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GÖTEBORG

FURTHER STUDIES OF
PARAMETER IDENTIFICATION
OF LINEAR AND NONLINEAR
SHIP STEERING DYNAMICS

Report 1920-6



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FURTHER STUDIES OF PARAMETER IDENTIFICATION OF LINEAR AND NONLINEAR SHIP STEERING DYNAMICS

by

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1. INTRODUCTION

The possibilities to use system identification methods to determine linear ship steering dynamics were investigated in Åström, Källström, Norrbin and Byström (1975). It was shown that the linear dynamics could indeed be determined from free-steering experiments where the small perturbations from a straight line course were introduced by rudder changes. A powerful computer program, LISPID, was also developed to perform the necessary calculations. (See Källström, Essebo and Åström (1976).) In Åström et al (1975) it was also found that less encouraging results could sometimes be obtained, such as when trying to fit linear models to data obtained from a standard zig-zag test with large amplitudes.

The purpose of the present project was to apply the linear methods to more data and to explore the possibilities to extend the techniques to fit nonlinear models as well. A further task was to investigate a suitable equipment for routine identification experiments on ships at sea. Finally the techniques developed were to be applied to data obtained from model tests with free-running models.

For the identification of nonlinear systems a suitable model structure will be the necessary starting point. A common way to represent nonlinearities of ship dynamics makes use of formal Taylor series expansions of the hydrodynamic forces, involving odd functions in normal forces and yawing moments. These expansions suffer from lack of physical reality and their use is hampered by the large number of coeffi-

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cients and their strong interdependence. In SSPA predictions these odd functions have earlier been replaced by a few abs-square terms, reflecting the significance of the cross-flow drag and furnishing good approximations in turning circle manoeuvres; cf Norrbin (1970). It was now decided to develop a rational model based on the cross-flow drag concept, which should include a minimum of unknown parameters and which should be able to model all phases of a manoeuvre within the usual assumption of quasi-steadiness. Thus, approximate expressions have been derived for the normal force and yawing moment on a ship of simple geometry but arbitrary load condition; see Norrbin (1976). These expressions vary with the position of the pivoting point, and their application requires a record of sway and yaw velocities. A description of the model is given in Section 2 of this report, where other limitations to the linear theory are also discussed.

The nonlinear identification problem can be approached in many different ways. Several different methods were explored. It was finally decided to use an approximative method based on the facts that the functional form of the nonlinearity is known and that a good approximation of terms proportional to the nonlinear forces can be computed. This approach has the advantage of being comparatively simple. The required extensions have been made in the program LISPID. This is described in Section 3.

The techniques of linear and nonlinear system identification have been applied to many different ships. There are special reports which in great detail describe the results in each particular case. The results are also summarized in Section 4. The program LISPID allows for the possibility of using other criteria than to maximize the likelihood function. In particular there is the possibility to use the error when predicting the output T time units ahead as a criterion. In the maximum likelihood method T is simply the sampling interval. The possibility of changing T has been explored. It is now well understood what happens when T is changed. It has also been found that the results can be improved by an appropriate choice of T . The attempts to determine nonlinear models have given good results. It has been found that the coefficient which determines the cross-flow drag can easily be estimated.

Values that are reasonably close to those expected from physical arguments have been obtained. It has also been shown that the nonlinear model gives excellent results for data obtained from zig-zag tests with large excursions in heading. These are typical cases where the linear models have previously failed.

The results obtained will depend crucially on the precisions in the measurement of the yawing rates and the linear velocities. A review of the sensors that are normally available on ships and a proposal for a portable measurement rig is presented in Section 5 and Appendix A.

The installation of the special position tracking equipment in the wide basin of the new SSPA laboratory has been delayed. Therefore it has not been possible to perform the model tests as planned. A few measurements have recently been done, however, and they are briefly described in Section 6. The analysis is yet to be completed.

The conclusions drawn from the work done are summarized in Section 7.

2. THE REPRESENTATION OF NONLINEARITIES IN SHIP STEERING DYNAMICS

Some Features of Linear Dynamics

"Linearity" in the context of ship steering dynamics implies that the surge (or X-) equation be decoupled, that all hydrodynamic forces vary as ship speed squared, and that the controlling forces are proportional to the control actuator input. In an xy-plot the manoeuvre diagrams are independent of speed levels. Time constants vary inversely with speed, but their values are unique when expressed in ship lengths sailed. Drift angles and path curvatures will increase in proportion to rudder deflection.

Limitations of the Linear Equations

The simple and convenient model above is seriously distorted by the nonlinearities which are required to handle the more general case. These nonlinearities enter into the equations in several ways.

1:0 The hydrodynamic forces do not vary with the square of speed but the force coefficients are functions of the absolute value of the Froude number.

So, e g, the "resistance" ($X(u)$) due to forward speed increases much more rapidly in the range of high wave-making speeds - at the "economic speed limit" the speed exponent is often taken to be of the order of 2.2. A polynomial with two or three terms furnishes a good approximation.

Wave-making and change of trim also cause the linear force and moment derivatives (the "stability derivatives" Y_{uv} , N_{uv} , Y_{ur} and N_{ur}) to increase with Froude number - for most applications a linear dependence on $u^* = u/\sqrt{gL}$ will hold good (Norrbin 1965a, 1970). If speed variations are moderate it is often convenient to search for mean values only. (Parameter identification from tests at a higher speed will furnish results for a "more stable" ship.)

2:0 Propeller thrust $T(u, n)$ as well as the force on a rudder in the screw race $Y^R(u, n, \delta)$ varies with change of speed in a way which depends on the type of engine.

The "linear" approximation requires that propeller advance coefficient $J = V_a/nD$ be constant - to relax this condition the torque characteristics of engine and propeller must be included to give the new RPM (or n) balance, and thrust then follows from RPM and speed.

An observation that RPM during a manoeuvre will drop in proportion to drop of speed has been used to define a semi-empirical relation between thrust and speed. (Clarke 1976.) Approximations for thrust based on change of speed only may alternatively be found by assuming engine torque to be constant (diesel) or engine power to be constant (turbine). Further work along these lines is in progress.

Similarly, as force per degree of rudder depends on u and $T(u, n) \Rightarrow T(u)$ (Norrbin 1970) it may also be made a function of change of speed only. At the Danish Ship Research Laboratory the PMM test programs are designed for an analysis with respect to change-of-speed-dependent rudder derivatives. (Strøm-Tejsen and Chislett 1966.) Recent practice at SSPA includes measurement of propeller thrust in conjunction with captive as well as free-running model manoeuvring tests. When there are moderate deviations from a mean speed the rudder derivatives may be taken as constants, following the u -squared law. This is the most common approach. (From a free-running test analysis the rudder derivatives will then appear larger the larger the amplitudes of the motions.) Again, when RPM records are available together with speed a simple correction for the relative change of the advance coefficient may be worth while. (Norrbin 1965b).

3:0 Cross-coupled motions and large-value force nonlinearities put a limit to the linear representation.

Due to the drift angle experienced in any turning manoeuvre the outward centrifugal force has a component in the longitudinal direction, which is the main cause of the speed drop. This mass force ($m \cdot v \cdot r$) is further

increased by the hydrodynamic force coupling, and an adequate estimate of this latter force ($X_{vr} \cdot vr$) is essential to the prediction of tight manoeuvres. (Norrbin 1970.) It should be possible to deduce its value from parameter identification techniques applied to the X-equation, provided the thrust is also suitably modelled. (Cf above.)

In a turning manoeuvre the effective angle of attack on a rudder at a given angle of helm is modified by the local flow conditions at the stern. Obviously this correction would be equal to the local angle of drift if the rudder was protruding into the undisturbed water. In the practical cases the flow to the rudder is guided by hull flow and screw race, and the correction is likely to be smaller but more complex. It is common to make a Taylor expansion type of representation, using several higher "rudder derivatives" with respect to v and r as well as δ . (Strømtejsen and Chislett 1966, a.o.) Alternatively, an expression for effective angle of attack may be assumed using model force measurement results and a simple flow picture analysis. (Norrbin 1970.) The problem is considered to be of less importance as far as parameter identification is concerned.

The most important large-value nonlinearities appear in the normal force and yawing moment representations, $Y(u, v, r)$ and $N(u, v, r)$. The increase of yaw damping in progressively more narrow turning manoeuvres clearly violates the linear relation between helm angle and turning rate. Even more obvious is the fact that any ship which has been known to be dynamically unstable on a straight course has been seen to gain stability in a turn of moderate curvature. A first-order linear analysis of a finite amplitude low-frequency manoeuvre will usually provide a kind of "effective" time constant, which is positive and so suggests dynamic stability even for the initially unstable ship.

In view of the significance of these latter nonlinearities they were given priority for inclusion in the parameter identification model.

An Integral for Nonlinear Damping

The distribution of "linear" force load along a hull at a small angle of drift or side-slip, or in a gentle turn with forward speed, may be de-

rived from a consideration of impulse pressures required to displace the water around a frame contour which expands when penetrating a plane normal to the body axis. (Munk 1923, Norrbin 1965a, Clarke 1972.) In an ideal fluid the theory predicts zero total normal force in pure oblique translation, and the assumption of a three-dimensional viscous separation of boundary layer flow on the afterbody is made to explain the finite normal force and the loss of instability moment experienced for boat-tailed shapes in the real fluid.

The nonlinear contribution to hydrodynamic damping of the motion of a hull in yaw and/or sway may be attributed to section drag in two-dimensional cross-flow. (Fedyaevsky and Sobulev 1957, Martin 1961, Norrbin 1965a, 1965b.) This concept suggests that abs-square terms replace the odd terms of a formal Taylor expansion more commonly used to represent the large-value nonlinearities, and it has been shown that the use of these abs-square terms will let the linear derivatives be more correctly defined. A formally consistent set-up of second-order derivatives was included in "standard" equations for submarine dynamics. (Gertler and Hagen 1967.) Such a set-up, however, fails to account for the effect of pivoting point position; a new set up of derivatives or coefficients will be required as this point P moves into each one of three regions. (In the "bis" system the distance \overline{OP} is defined by $\overline{OP}/L = -v/r$.)

Within the present project the foundations for the cross-flow drag model have been re-examined, and the distribution of normal force has been integrated to yield explicit expressions for total force and moment for ships in arbitrary load conditions. (Norrbin 1976.) The local cross-flow drag coefficient certainly varies along the ship, being higher for deep and narrow sections in bow and stern. Such a variation is off-set by the three-dimensional end effects, and the assumption of a constant effect $C_D = C$ should be adequate for common hull forms. Then the expressions for nonlinear force ($Y''_{\text{nonlin}} \cdot mg$) and moment ($N''_{\text{nonlin}} \cdot mLg$) reduce to the forms given below:

$$\begin{aligned}
Y''_{\text{nonlin}} &= C \cdot \frac{L^2 T_m}{2V} \cdot r'' |r''| \cdot \left\{ -\frac{1}{12} - \left(\frac{v''}{r''}\right)^2 + \frac{\tau}{6} \cdot \frac{v''}{r''} \right\} & -\infty < -\frac{v''}{r''} < -\frac{1}{2} \\
Y''_{\text{nonlin}} &= C \cdot \frac{L^2 T_m}{2V} \cdot r'' |r''| \cdot \left\{ -\frac{1}{2} \frac{v''}{r''} - \frac{2}{3} \left(\frac{v''}{r''}\right)^3 + \right. \\
&\quad \left. + \tau \left[\frac{1}{32} + \frac{1}{4} \left(\frac{v''}{r''}\right)^2 - \frac{1}{6} \left(\frac{v''}{r''}\right)^4 \right] \right\} & -\frac{1}{2} < -\frac{v''}{r''} < \frac{1}{2}
\end{aligned} \tag{2.1}$$

$$Y''_{\text{nonlin}} = C \cdot \frac{L^2 T_m}{2V} \cdot r'' |r''| \cdot \left\{ \frac{1}{12} + \left(\frac{v''}{r''}\right)^2 - \frac{\tau}{6} \cdot \frac{v''}{r''} \right\} \quad \frac{1}{2} < -\frac{v''}{r''} < \infty$$

$$\begin{aligned}
N''_{\text{nonlin}} &= C \cdot \frac{L^2 T_m}{2V} \cdot r'' |r''| \cdot \left\{ -\frac{1}{6} \frac{v''}{r''} + \tau \left[\frac{1}{80} + \frac{1}{12} \left(\frac{v''}{r''}\right)^2 \right] \right\} \\
& & -\infty < -\frac{v''}{r''} < -\frac{1}{2}
\end{aligned}$$

$$\begin{aligned}
N''_{\text{nonlin}} &= C \cdot \frac{L^2 T_m}{2V} \cdot r'' |r''| \cdot \left\{ -\frac{1}{32} - \frac{1}{4} \left(\frac{v''}{r''}\right)^2 + \frac{1}{6} \left(\frac{v''}{r''}\right)^4 + \right. \\
&\quad \left. + \tau \left[\frac{1}{16} \frac{v''}{r''} + \frac{1}{15} \left(\frac{v''}{r''}\right)^5 \right] \right\} & -\frac{1}{2} < -\frac{v''}{r''} < \frac{1}{2}
\end{aligned} \tag{2.2}$$

$$\begin{aligned}
N''_{\text{nonlin}} &= C \cdot \frac{L^2 T_m}{2V} \cdot r'' |r''| \cdot \left\{ \frac{1}{6} \frac{v''}{r''} - \tau \left[\frac{1}{80} + \frac{1}{12} \left(\frac{v''}{r''}\right)^2 \right] \right\} \\
& & \frac{1}{2} < -\frac{v''}{r''} < \infty
\end{aligned}$$

The load condition is defined by mean draught, $T_m = \frac{1}{2}(T_S + T_B)$, and by relative trim, $\tau = 2(T_S - T_B)/(T_S + T_B)$. The effective cross-flow drag coefficient C should be expected to be of the order of $0.4 < C < 1.4$, say, typical values being 0.7 for a loaded tanker and 0.9 for a fine form displacement ship.

For parameter identification purposes the expressions above may be introduced in the form of additional inputs in a linear model, provided the records of sway velocity and yaw rate are accurate enough. These problems will be discussed in Section 3, and Section 4 will include results obtained from experiments at sea. These results suggest that the assumption of one effective cross-flow drag coefficient may be

justified, but it should be understood that this assumption is not essential to the method; it greatly facilitates the use of the model for prediction of realistic manoeuvres, however, including special effects in shallow water etc.

3. NONLINEAR IDENTIFICATION

There are several different ways to approach the nonlinear parameter estimation problem. Since all methods involve approximations and assumptions which are difficult to check there is no obvious choice. Some of the methods that were considered are discussed below.

Quasi-linearization

This method can be considered as an off-line version of extended Kalman filtering. Assume that the model can be described as

$$\frac{dx}{dt} = f(x, u, w) \quad (3.1)$$

where x is the state, u the input, and w a white noise disturbance with covariance $R_1 \delta(t)$. Furthermore assume that the measurements are obtained at discrete times t_0, t_1, \dots, t_N and that they are given by

$$y(t_n) = g(x(t_n)) + e(t_n), \quad n = 0, \dots, N \quad (3.2)$$

where $\{e(t_n)\}$ are measurement errors with covariance R_2 . The functions f and g as well as R_1 and R_2 may contain unknown parameters. The model given by (3.1) and (3.2) is obviously an extension of the linear model discussed in Källström, Essebo and Åström (1976). Unfortunately it is not possible to obtain a nice closed form expression for the likelihood function for the nonlinear model.

If the system can be approximated linearly between two sampling points the following approximation may be reasonable.

$$-2 \log L \approx \sum_{n=0}^N \log \det R(t_n) + \sum_{n=0}^N \varepsilon^T(t_n) R^{-1}(t_n) \varepsilon(t_n) + \text{const} \quad (3.3)$$

where

$$\varepsilon(t_n) = y(t_n) - \hat{y}(t_n)$$

$$\hat{y}(t_n) = g(\hat{x}(t_n))$$

$$\frac{d\hat{x}}{dt} = f(\hat{x}, u, 0) \quad t_n < t \leq t_{n+1}$$

$$\begin{aligned}
\hat{x}(t_{n+}) &= \hat{x}(t_n) + K(t_n) \varepsilon(t_n) \\
K(t_n) &= P(t_n) g_x^T(\hat{x}(t_n)) R^{-1}(t_n) \\
R(t_n) &= R_2 + g_x(\hat{x}(t_n)) P(t_n) g_x^T(\hat{x}(t_n)) \\
\frac{dP}{dt} &= f_x(\hat{x}) P + P f_x^T(\hat{x}) + f_v R_1 f_v^T \quad t_n < t \leq t_{n+1} \\
P(t_{n+}) &= [I - K(t_n) g_x(\hat{x}(t_n))] P(t_n)
\end{aligned} \tag{3.4}$$

The equations above reduce to the equations given in Källström, Essebo and Åström (1976) for the linear case. It is, however, extremely difficult to analyse the consequences for the approximations made. The approximations made above are analogous to those made when deriving the extended Kalman filter. Since the scheme discussed above is an off-line procedure it does not suffer from the instability problems which are sometimes encountered when using the extended Kalman filter. The approximation given above can easily be incorporated in the program LISPID. It is only required to write a subroutine which evaluates the Jacobians f_x and g_x . The computing times using this approximation will, however, be substantial because of the short step length required and the linearizations. For this purpose other simpler schemes have been investigated.

Innovations Representation

A considerable simplification is obtained by directly postulating a nonlinear model which is an innovations representation, i.e.

$$\begin{aligned}
\frac{d\hat{x}}{dt} &= f(\hat{x}, u) \quad t_n < t \leq t_{n+1} \\
\hat{x}(t_{n+}) &= \hat{x}(t_n) + K \varepsilon(t_n) \\
\varepsilon(t_n) &= y(t_n) - g(\hat{x}(t_n))
\end{aligned} \tag{3.5}$$

where f , g contain the unknown parameters and the matrix K is also unknown. In the linear case the likelihood function is then given by (3.3) provided that the process is in steady state. This means among other things that the sampling period must be constant and that no measurements can be missing. The approach is attractive because it

gives simple computations. The method has been tried to fit linear models. Difficulties to estimate all parameters in K were then encountered. The method was therefore discarded in the present investigation. The procedure is, however, a good candidate when new measurements are planned.

A Special Technique

The method that was finally chosen is based on the fact that the nonlinearities in the particular case have a very special structure. The nonlinear models discussed in Section 2 give terms in the equations of motion which are proportional to $r|r|$, $v|r|$ etc. If accurate measurements of v and r are available the problem can then be handled simply by introducing the nonlinear force and moment as additional inputs in the existing linear model. The results obtained are somewhat improved if filtered values are used instead. The approximation is similar to the approximations involved in the quasi-linearization.

The filter used is described by

$$\begin{aligned}\hat{x}(t+T) &= A \hat{x}(t+) + B u(t) \\ \hat{x}(t+) &= \hat{x}(t) + K \varepsilon(t) \\ \varepsilon(t) &= y(t) - C \hat{x}(t) - D u(t)\end{aligned}\tag{3.6}$$

where the sampling interval T is assumed to be constant. If no process noise is included then $K=0$ in (3.6). The filter (3.6) is exactly the same filter that is used in LISPID for a linear, time-invariant model with measurements equally spaced in time (cf. Model 1 in Åström et al (1975)).

The current implementation of the nonlinear identification procedure thus assumes that a time-invariant model is used and that the sampling interval is constant. There are, however, possibilities to extend the procedure by e.g. changing (3.6) to a time-varying filter.

The state vector \hat{x} of (3.6) contains filtered values \hat{v} , \hat{r} , and $\hat{\psi}$ of the sway velocity, the yaw rate, and the heading, resp. The filtered values \hat{v} and \hat{r} are used to compute the nonlinear force and moment as described in Section 2. The nonlinear force and moment are then introduced as additional inputs of the linear model (Model 1 in Åström et al (1975)). This technique has the great advantage that only small modifications of LISPID are necessary.

4. RESULTS FROM EXPERIMENTS AT SEA

The technique described in the previous sections has been applied to experiments on many different ships. Linear models for the container ship Atlantic Song and the oil tanker Sea Splendour were determined in Aström et al (1975) and Aström and Källström (1976). A detailed description of the results of the Sea Splendour experiments is given in Källström (1977a). Linear models for the ferry Bore I, the tanker AK Fernström, and the cargo ship USS Compass Island, which is a Mariner Class ship, were also obtained in Aström et al (1975). The experiments on the AK Fernström and the USS Compass Island have now been analysed using the nonlinear model. These results will be summarized in this section. New experiments on the tankers Sea Scout, Sea Swift, Sea Scape, Norseman and a military patrol boat have also been analysed within the project. A summary of the main results are given below.

The Sea Scout and Sea Swift Experiments

Seven identification experiments were performed on the oil tankers Sea Scout and Sea Swift in connection with the STU project "A Method for Adaptive Control of Ships" (see Källström et al (1977), STU projects number 734187 and 744127). The experiments are described in detail in Källström (1974) and (1975). Both linear and nonlinear models were fitted to the data. However, the experiments were mainly designed to determine the linear ship steering dynamics, which means that only small excursions were performed. The differences between the linear and nonlinear models obtained were thus small, and it was difficult to determine the parameter C which characterizes the cross flow drag in the nonlinear model. The results of fitting linear models only to the data are summarized in this section, but a detailed description of all results for the Sea Scout is given in Källström (1977c). A detailed report describing the results of the Sea Swift experiments is also planned. Some of the Sea Swift results have been published in Gustavsson, Ljung and Söderström (1977).

The Sea Scout and Sea Swift are both 255 000 tdw oil tankers built for the Salén Shipping Companies in Stockholm by Kockums Shipyard in

Malmö. They are sister ships to the Sea Splendour. The ship characteristics are summarized in Appendix B.

The Sea Scout experiments were performed in 1973, off the west coast of Africa in the Gulf of Guinea. The tanker was ballasted and it had a displacement of $142\,000\text{ m}^3$. The draught at bow was 8.55 m and the draught at stern 11.45 m. The speed was approximately 17 knots. The wind speed was less than 6 m/s and the waves were small. All experiments were performed by using a PRBS as rudder disturbances and by measuring the sway velocities at bow and stern, the yaw rate, the heading, the forward speed, and the number of propeller revolutions. The data were punched on paper tape. The onboard process computer made it possible to record the data with a precise, constant sampling interval. The sampling interval was chosen to 10 s in the first experiment (E1) and to 5 s in the other two experiments (E2 and E3). Only small excursions from the desired heading were made in the experiments E1 and E3, but a gentle manoeuvre was performed in experiment E2 because of the presence of another ship. However, this manoeuvre seems not to have excited the nonlinearity of the steering dynamics to such an extension that a nonlinear model is appropriate to the data.

The results of applying a straightforward maximum likelihood method to the three experiments are shown in Table 4.1. The time horizon was thus 10 s in experiment E1 and 5 s in experiments E2 and E3. The initial parameter estimates also shown in Table 4.1 are adjusted values from model tests with a similar tanker. The models obtained from experiments E2 and E3 are not good. The magnitude of the values obtained for the rudder derivatives $Y''_{cc\delta}$ and $N''_{cc\delta}$ is too small and even incorrect signs are obtained from experiment E3. This means that the rudder motions almost are neglected in the models and that the effects of the disturbances are enlarged. Since the model obtained from experiment E1, where the sampling interval was 10 s, not suffered from these problems, was it concluded that the time horizon of 5 s used in the ML identifications of experiments E2 and E3 was too short.

	Initial estimates	Final estimates				
		E1	E2		E3	
		ML	ML	Prediction error	ML	Prediction error
Sampling interval [s]		10	5	5	5	5
Time horizon [s]		10	5	10	5	10
$1 - Y_{\dot{v}}''$	1.67					
$x_G'' - Y_{\dot{r}}''$	0.050					
$x_G'' - N_{\dot{v}}''$	0.040					
$k_{zz}'' - N_{\dot{r}}''$	0.100					
Y_{uv}''	-1.21	-0.92	-0.98	-1.04	-1.19	-0.84
$Y_{ur}'' - 1$	-0.525	-0.681	-0.896	-0.774	-0.992	-0.703
N_{uv}''	-0.180	-0.093	-0.021	-0.029	0.010	-0.029
$N_{ur}'' - x_G''$	-0.256	-0.089	-0.029	-0.088	0.021	-0.083
$\frac{1}{2} Y_{cc\delta}''$	0.210	0.134	0.028	0.163	-0.046	0.152
$\frac{1}{2} N_{cc\delta}''$	-0.100	-0.064	-0.013	-0.078	0.023	-0.073
K'	-0.74	-3.70	-1.36	-1.25	-1.65	-1.30
K_V'	0.49	2.89	1.27	1.09	1.34	1.27
T_1'	2.03	9.96	9.38	1.92	-4.92	2.59
T_2'	0.38	0.85	1.78	1.25	2.12	1.27
T_3'	1.10	1.57	1.71	1.60	1.50	1.95
T_{3v}'	0.24	0.30	0.27	0.27	0.27	0.30

Table 4.1 - Estimated hydrodynamic derivatives ('bis' system) and transfer function parameters ('prime' system) from maximum likelihood and prediction error identifications of a linear model to the Sea Scout experiments E1, E2, and E3.

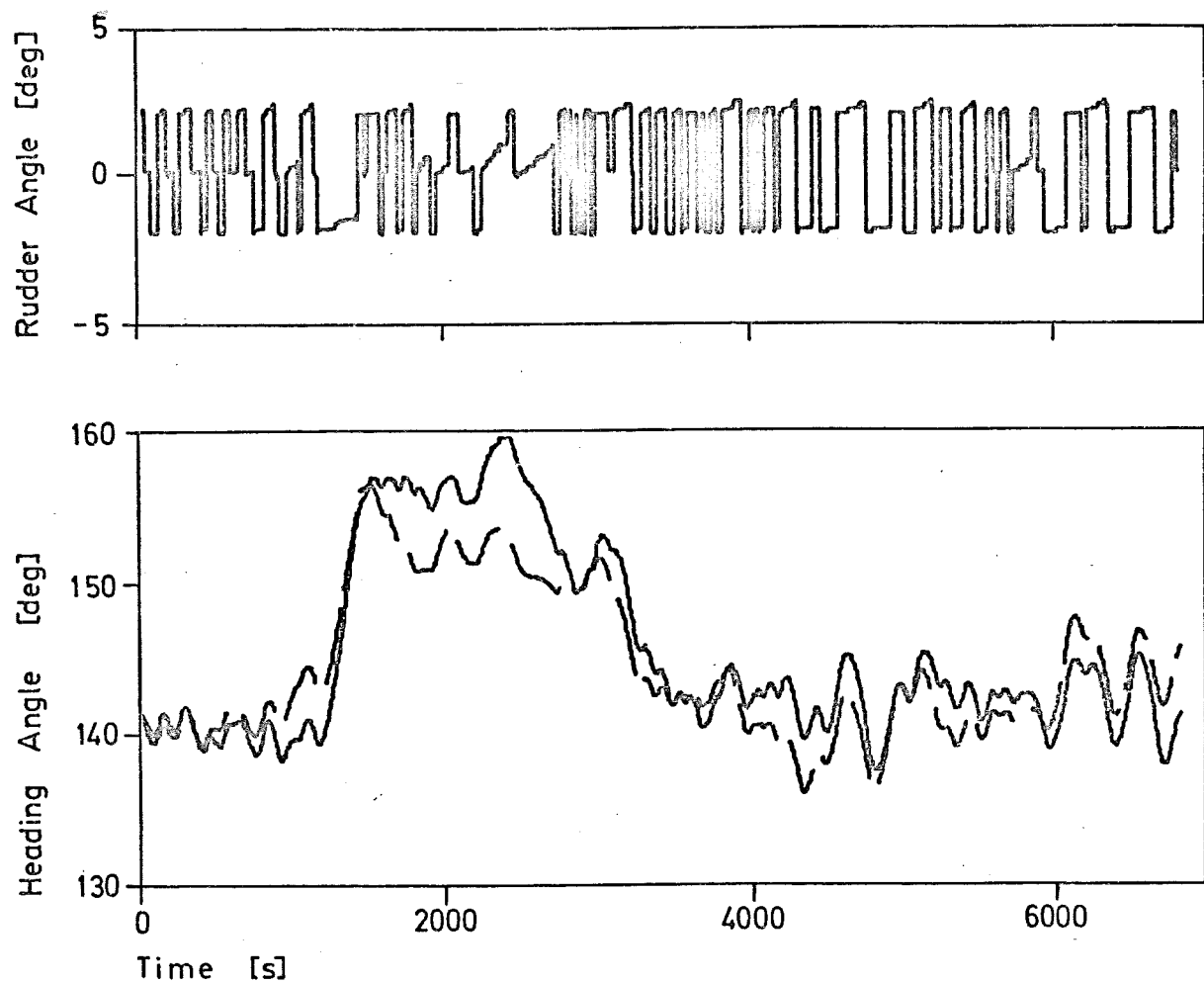


Fig. 4.1 - Result of prediction error identification of a linear model to the Sea Scout experiment E2. The only measurement signal shown is the heading angle (the continuous line). The dashed line is the model output.

It was thus decided to try a prediction error method on experiments E2 and E3. A time horizon of 10 s was then chosen. The results are shown in Table 4.1. A good consistency between the ML model from experiment E1 and the prediction error models from E2 and E3 are now obtained, since a time horizon of 10 s is used in all cases. The hydrodynamic derivatives obtained do not differ very much from the initial estimates. The rudder angles and the measured heading angles from experiment E2 are shown in Fig. 4.1 together with the heading output from the prediction error model.

Four experiments on the Sea Swift were performed in 1974. They were carried out in the Mozambique Channel, which separates Madagascar from Africa. The tanker was fully loaded which means that the displacement was $284\,300\text{ m}^3$. The draught at bow and stern was 20.2 m. The speed was approximately 17 knots. The wind speed was less than 4 m/s during all experiments and the wave disturbances were negligibly small. The Sea Swift has the same equipment as the Sea Scout, which means that the experiments were carried out in the same way as the Sea Scout experiments and that the same measurement signals were recorded. Two experiments, E1 and E4, were performed in open loop by using a PRBS as rudder disturbances. During the experiments E2 and E3 a simple P-regulator was keeping the ship on the desired course. Extra rudder disturbances were introduced in experiment E2 by use of a PRBS, while two different gains of the P-regulator were used in experiment E3 instead of extra rudder disturbances. The sampling interval was 10 s during all experiments. Only small excursions from the desired heading were made during the experiments, which means that linear models only will be considered.

The analysis of the Sea Swift experiments is not finished, but the results of applying the output error identification method to experiments E3 and E4 are shown in Table 4.2. The initial estimates of the hydrodynamic derivatives are, as before, adjusted values from model tests with a similar tanker. A good consistency between the initial estimates and the final estimates from experiments E3 and E4 is obtained. Notice especially the small differences between the hydrodynamic derivatives obtained from experiment E4 and the initial

	Initial estimates	Final estimates	
		E3	E4
$1 - Y_{\dot{v}}''$	1.87		
$x_G'' - Y_{\dot{r}}''$	0		
$x_G'' - N_{\dot{v}}''$	0		
$k_{zz}'' - N_{\dot{r}}''$	0.108		
Y_{uv}''	-0.892	-0.568	-0.997
$Y_{ur}'' - 1$	-0.723	-0.297	-0.694
N_{uv}''	-0.463	-0.517	-0.421
$N_{ur}'' - x_G''$	-0.189	-0.220	-0.235
$\frac{1}{2} Y_{cc\delta}''$	0.187	0.220	0.208
$\frac{1}{2} N_{cc\delta}''$	-0.088	-0.104	-0.098
K'	0.99	6.01	3.19
K_V'	-0.60	-2.75	-2.01
T_1'	-3.09	-16.86	-9.78
T_2'	0.39	0.42	0.36
T_3'	1.00	1.12	0.99
T_{3v}'	0.20	0.30	0.19

Table 4.2 - Estimated hydrodynamic derivatives ('bis' system) and transfer function parameters ('prime' system) from output error identifications of a linear model to the Sea Swift experiments E3 and E4.

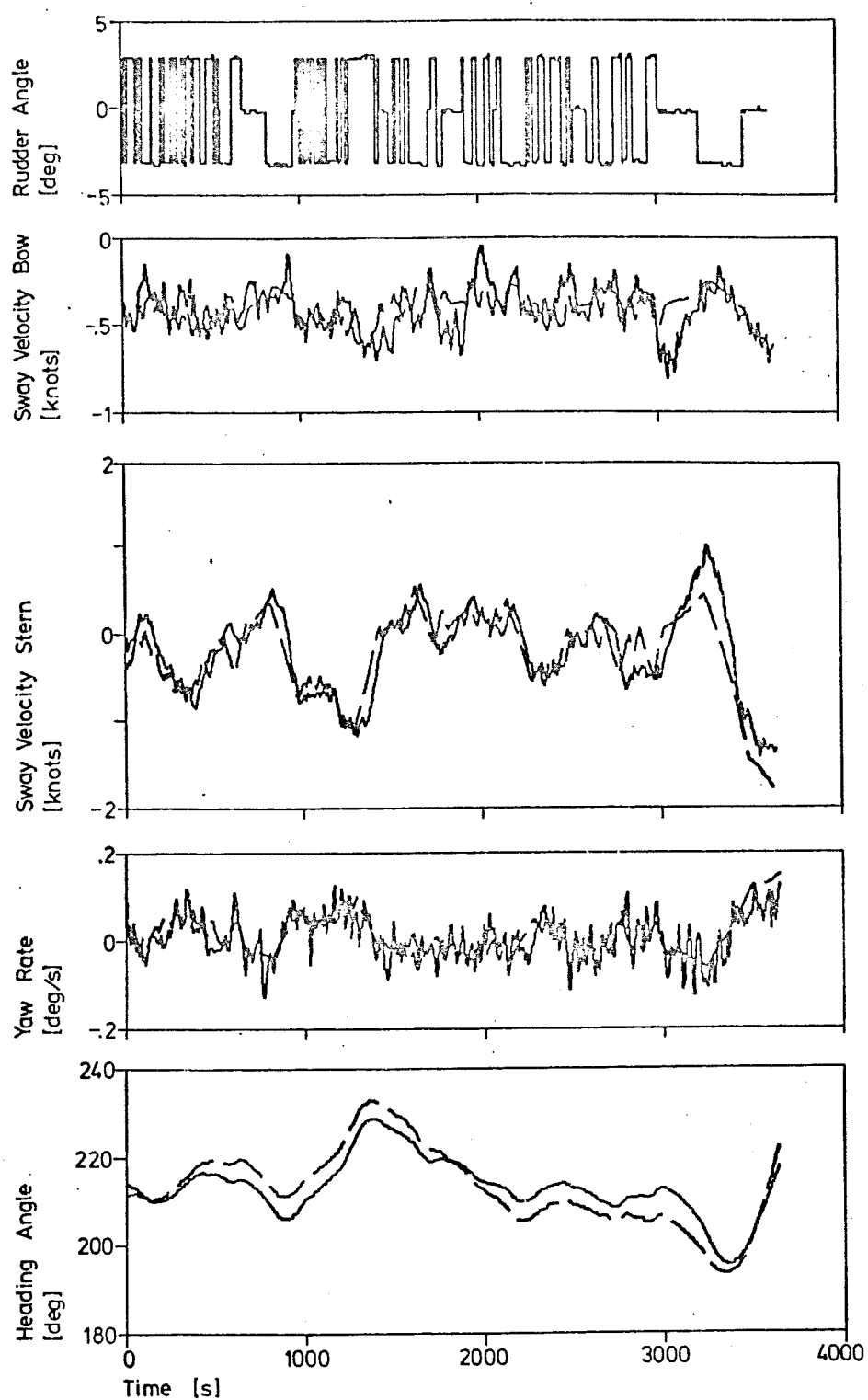


Fig. 4.2 - Result of output error identification of a linear model to the Sea Swift experiment E4. The continuous lines are the measurement signals and the dashed lines are the model outputs.

estimates. Fig. 4.2 shows the result of the output error identification to the data from experiment E4.

The output error method can approximately be described as a prediction error method with an infinite time horizon. Results presented in Åström et al (1975) show that models obtained from output error identifications sometimes are good and sometimes are bad. It is necessary to analyse more data to get a deeper insight into the problem of choosing a suitable time horizon. It is the intention also to apply the maximum likelihood method and the prediction error method to the data obtained from the Sea Swift.

The USS Compass Island Experiments

Both linear and nonlinear models have been fitted to three $20^0/20^0$ zig-zag tests on the USS Compass Island by use of the output error method and the maximum likelihood method. The approach speed of the different zig-zag tests was 10, 15, and 20 knots which resulted in an average speed during each experiment of 8.75, 12, and 16.5 knots, respectively. The experiments are described in Morse and Price (1961). The USS Compass Island is a converted 13 400 tdw cargo ship of the Mariner Class. The ship characteristics are given in Appendix B. The displacement of the ship was $16\,650\text{ m}^3$ during the tests, and the draught at bow and stern was 6.86 and 8.08 m, respectively. The experiments were performed in calm sea. The rudder angles, the sway velocities, the yaw rates and the headings from each experiment were obtained from diagrams in Morse and Price (1961). A sampling interval of 6 s was used when the curves were digitalized.

It was concluded in Åström et al (1975) that nonlinear effects were present during a $20^0/20^0$ zig-zag test. The application of the new nonlinear model to the USS Compass Island experiments was thus one of the main purposes of the project. A detailed description of all results obtained from the USS Compass Island zig-zag tests is given in Källström (1977b).

The experiment performed at the approach speed of 20 knots and the average speed of 16.5 knots will be used to illustrate the power of

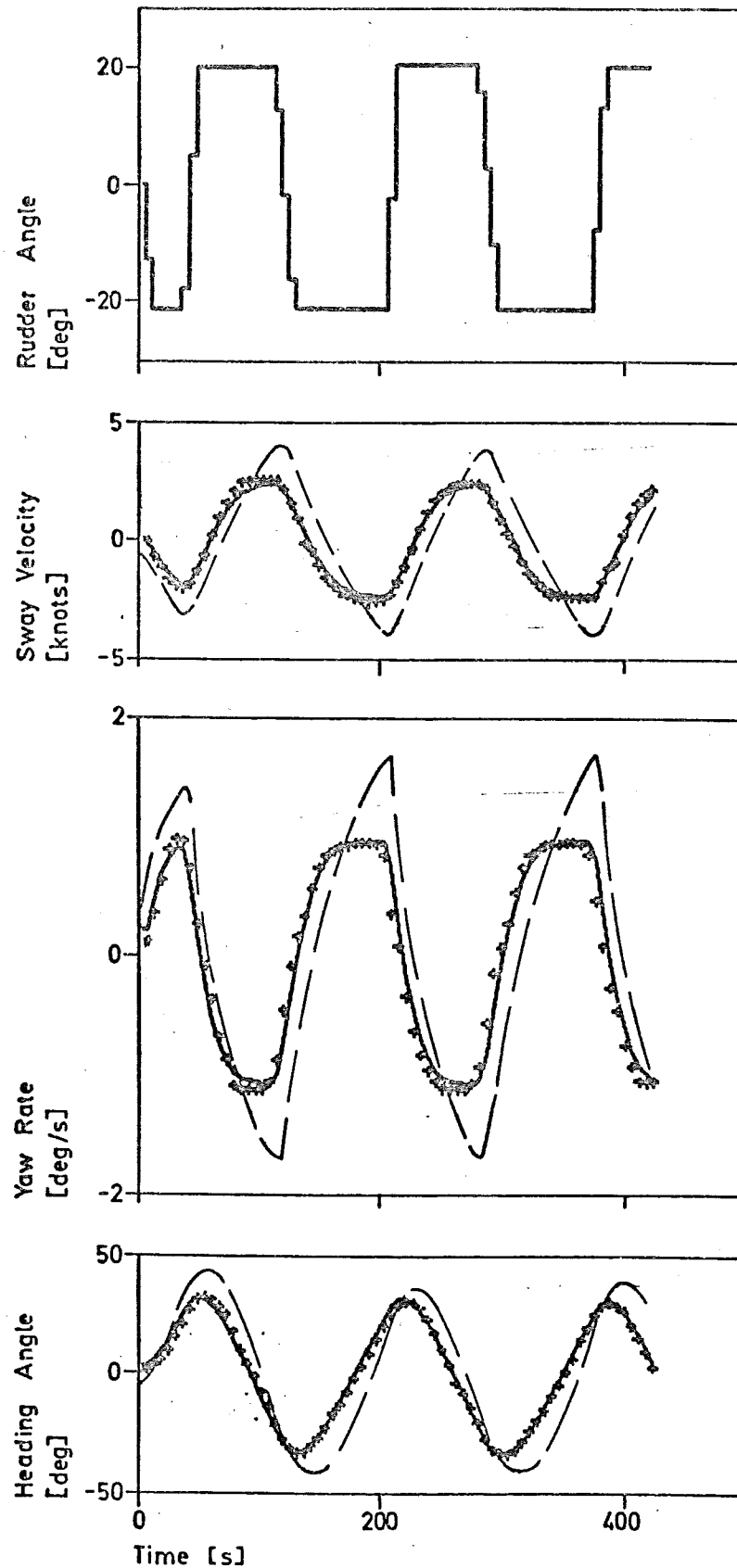


Fig. 4.3 - Simulations of HyA's linear model (the dashed lines) and the nonlinear model with the linear part fixed to HyA's model and $C = 0.67$ (the continuous lines). Data from a $20^\circ/20^\circ$ zig-zag test performed at an average speed of 16.5 knots on the USS Compass Island are used (the dots).

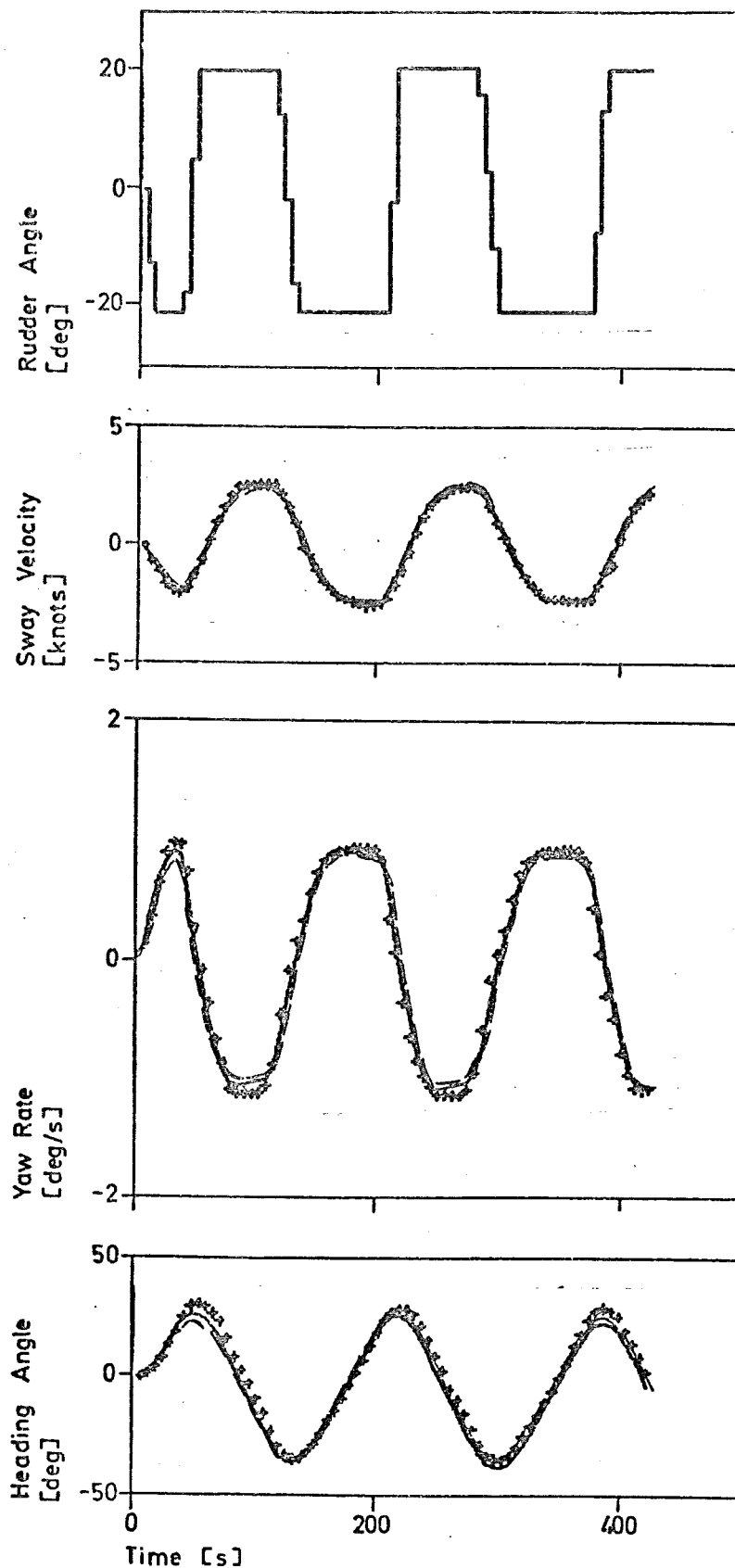


Fig. 4.4 - Results of maximum likelihood identification of a linear model (the dashed lines) and a nonlinear model (the continuous lines) to the USS Compass Island data from a $20^\circ/20^\circ$ zig-zag test performed at an average speed of 16.5 knots. The dots are the measurements.

	Initial estimates (HyA's model)	Final estimates	
		Linear model	Nonlinear model
$1 - Y_{\dot{v}}''$	1.94		
$x_G'' - Y_{\dot{r}}''$	0.033		
$x_G'' - N_{\dot{v}}''$	0.015		
$k_{zz}'' - N_{\dot{r}}''$	0.10		
Y_{uv}''	-1.45	-3.04	-1.86
$Y_{ur}'' - 1$	-0.66	-1.26	-1.10
N_{uv}''	-0.36	0.15	-0.15
$N_{ur}'' - x_G''$	-0.23	-0.03	-0.08
$\frac{1}{2} Y_{cc\delta}''$	0.35	0.16	0.22
$\frac{1}{2} N_{cc\delta}''$	-0.17	-0.08	-0.11
C	-	-	0.79
K'	-3.90	-0.81	9.39
K_V'	2.01	0.39	-5.41
T_1'	5.70	} complex poles	-13.54
T_2'	0.37		0.60
T_3'	0.89	0.72	0.90
T_{3v}'	0.22	0.19	0.20

Table 4.3 - Estimated hydrodynamic derivatives ('bis' system) and transfer function parameters ('prime' system) from maximum likelihood identifications of a linear and a nonlinear model to the USS Compass Island 20°/20° zig-zag test performed at an average speed of 16.5 knots.

the nonlinear model. A linear model obtained from the planar motion mechanism tests performed by the Hydro- and Aerodynamics Laboratory (HyA, now SL), Denmark, is first investigated. The hydrodynamic derivatives of the model are shown in Table 4.3. The model tests were performed at a speed corresponding to 15 knots. Fig. 4.3 shows the measurements from the zig-zag test (dots) and the outputs from HyA's linear model (dashed lines). The consistency is bad. Fig. 4.3 also illustrates the result obtained when the nonlinear model was fitted to the data by fixing the linear model to HyA's model (cf. Table 4.3) and only adjusting the parameter C (the continuous lines). The value of C was estimated to 0.67. A very good consistency between the measurements and the outputs from the nonlinear model is shown in Fig. 4.3.

The results of applying the maximum likelihood method to the data are shown in Fig. 4.4. The dashed lines are the outputs from the identified linear model and the continuous lines are the outputs from the identified nonlinear model. The model outputs do not differ much from the measurements. The estimated hydrodynamic derivatives are shown in Table 4.3. It is concluded that the values obtained by fitting a linear model are very bad, although the consistency between model outputs and measurements was good. The parameter values obtained by fitting the nonlinear model do not differ very much from HyA's values.

The Sea Scape Experiment

The Sea Scape is a single screw tanker built by Kockums Mekaniska Verkstads AB in Malmö with main dimensions and hull characteristics according to Appendix B.

The experiment, a $10/10^0$ zig-zag test, was carried out in connection with the delivery trials with

Draught bow	22.3	m
Draught stern	22.3	m
Initial speed	15.4	knots
Mean speed	12.8	knots
Sea state	1	on the Beaufort Scale
Wind	W2	m/s

cf Byström (1977a).

During the tests rudder angle, heading, speed and Decca coordinates were recorded every 20 seconds. From heading and Decca coordinates the sway velocity was calculated and used in the identifications below.

The experiment was first analysed with all linear derivatives fixed to initial estimates. Thus only the nonlinear coefficient C and bias parameters were determined. The result of the identification shows that very good agreement is obtained and consequently the initial estimates are quite reliable, see Table 4.4.

An identification of the hydrodynamic derivatives using a linear model was not quite successful, as the cross correlation functions are outside the 95% confidence limits. This is probably due to the motions being too large to be described by a linear model. The nonlinear identification, however, gives a valid model.

As is seen from the coefficients K , K_V , T_1 , T_2 , T_3 and T_{3V} in Table 4.4 (model with process noise) of the transfer functions relating yaw rate - rudder angle and sway velocity - rudder angle the dynamics are now close to the expected, i.e. a clearly unstable ship. Thus in spite of the individual coefficients being different, the dynamics of the two models are essentially the same.

The A K Fernström Experiment

The A K Fernström is a single screw tanker built by Öresundsvarvet AB in Landskrona. Main dimensions and hull characteristics are given in Appendix B.

The experiment, also a $10/10^0$ zig-zag test, performed in the Skagerrack during the delivery trials with

	Initial estimates	Linear without process noise	Linear with process noise	Nonlinear without process noise	Nonlinear with process noise
$1 - Y_v''$			-1.82		
$x_G'' - Y_r''$			0.0		
$x_G'' - N_v''$			0.0		
$k_{zz}'' - N_r''$			0.103		
Y_{uv}''	-0.700	-1.268	-2.008	-1.224	-0.988
$Y_{ur}'' - 1$	-0.820	-0.674	-1.060	-0.650	-0.700
N_{uv}''	-0.350	-0.973	-0.985	-0.949	-1.082
$N_{ur}'' - x_G''$	-0.163	-0.510	-0.518	-0.478	-0.527
Y_δ''	0.176	0.573	0.350	0.584	0.378
N_δ''	-0.083	-0.269	-0.165	-0.274	-0.178
C	0.52	-	-	0.17	0.49
K'	0.69	96.54	158.75	27.77	2.47
K_v'	-0.56	-50.86	-83.58	-14.28	-1.36
T_1'	-2.56	-113.90	-270.04	-31.24	-4.64
T_2'	0.42	0.18	0.16	0.19	0.17
T_3'	1.26	0.55	0.44	0.56	0.55
T_{3v}'	0.19	0.12	0.10	0.13	0.12

Table 4.4 - Estimated hydrodynamic derivatives and transfer function parameters from a $10/10^0$ zig-zag test ($T_B/T_S = 22.3/22.3$ m) with the Sea Scape.

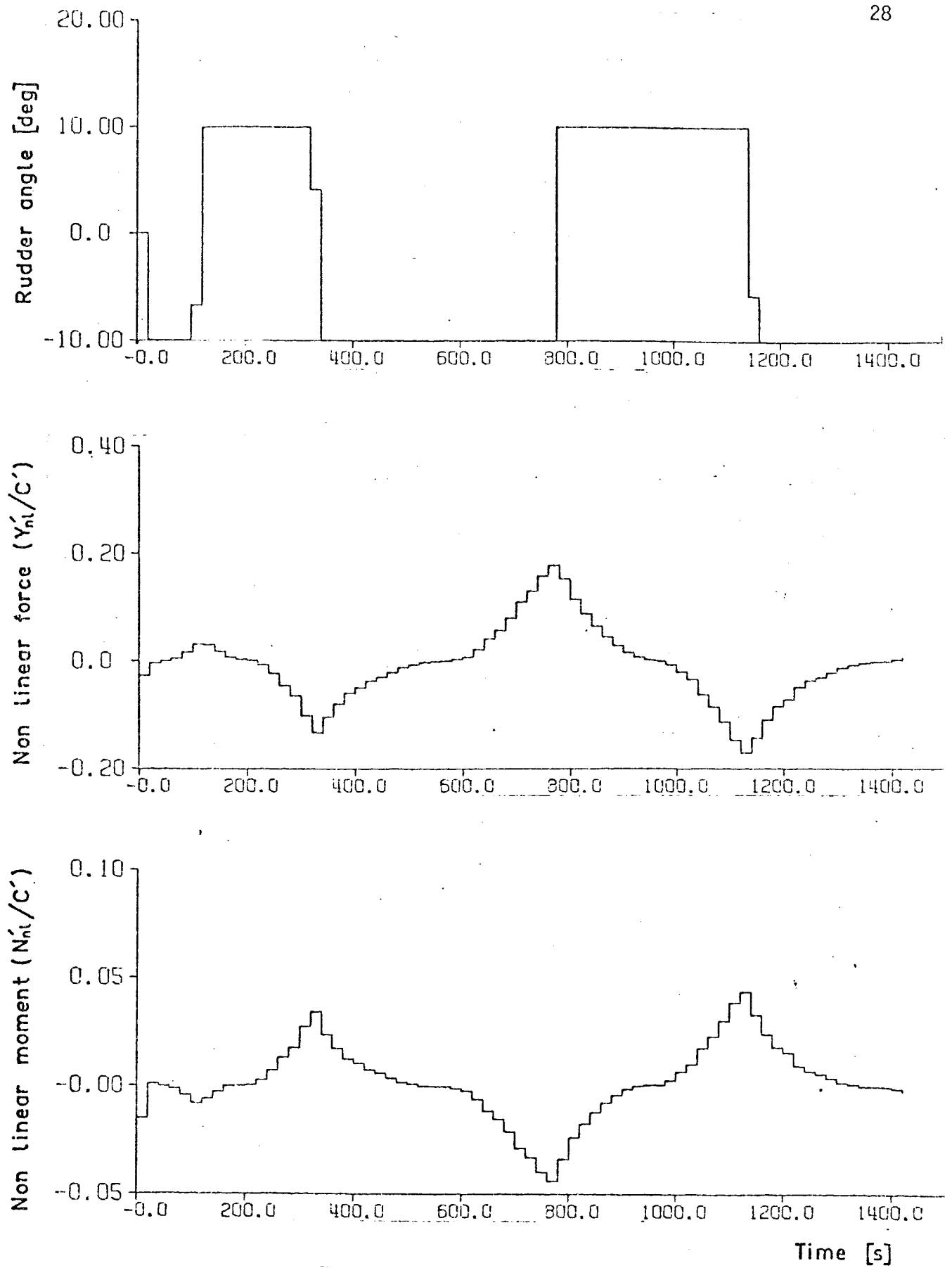


Fig 4.5 - Result of identification of the hydrodynamic derivatives and the nonlinear coefficient C from a $10/10^\circ$ zig-zag test ($T_B/T_S = 22.3/22.3$ m) with the Sea Scape.

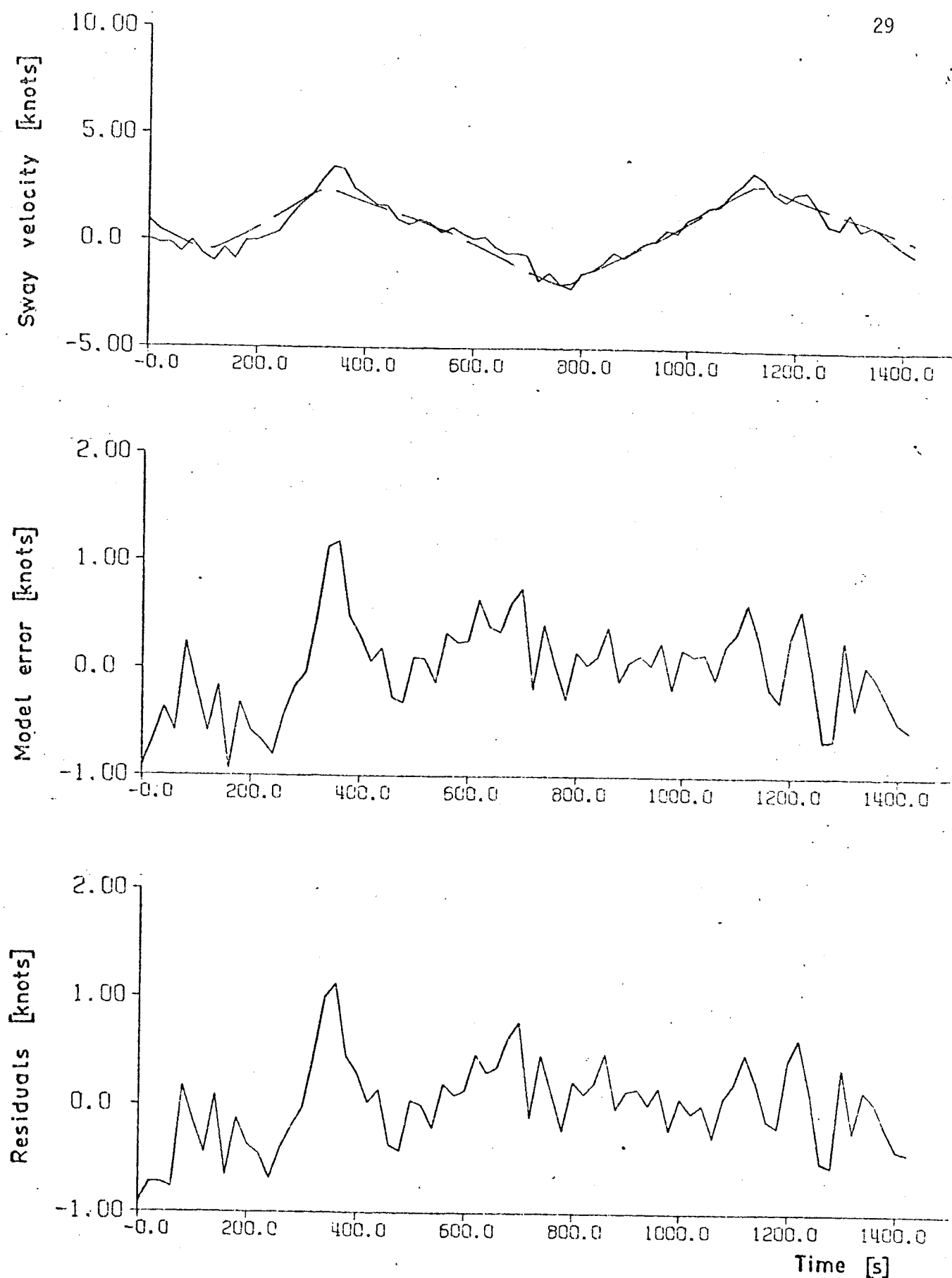


Fig 4.6 - Result of the identification of the hydrodynamic derivatives and the nonlinear coefficient C from a $10/10^\circ$ zig-zag test with the Sea Scape. The dotted line is the model output.

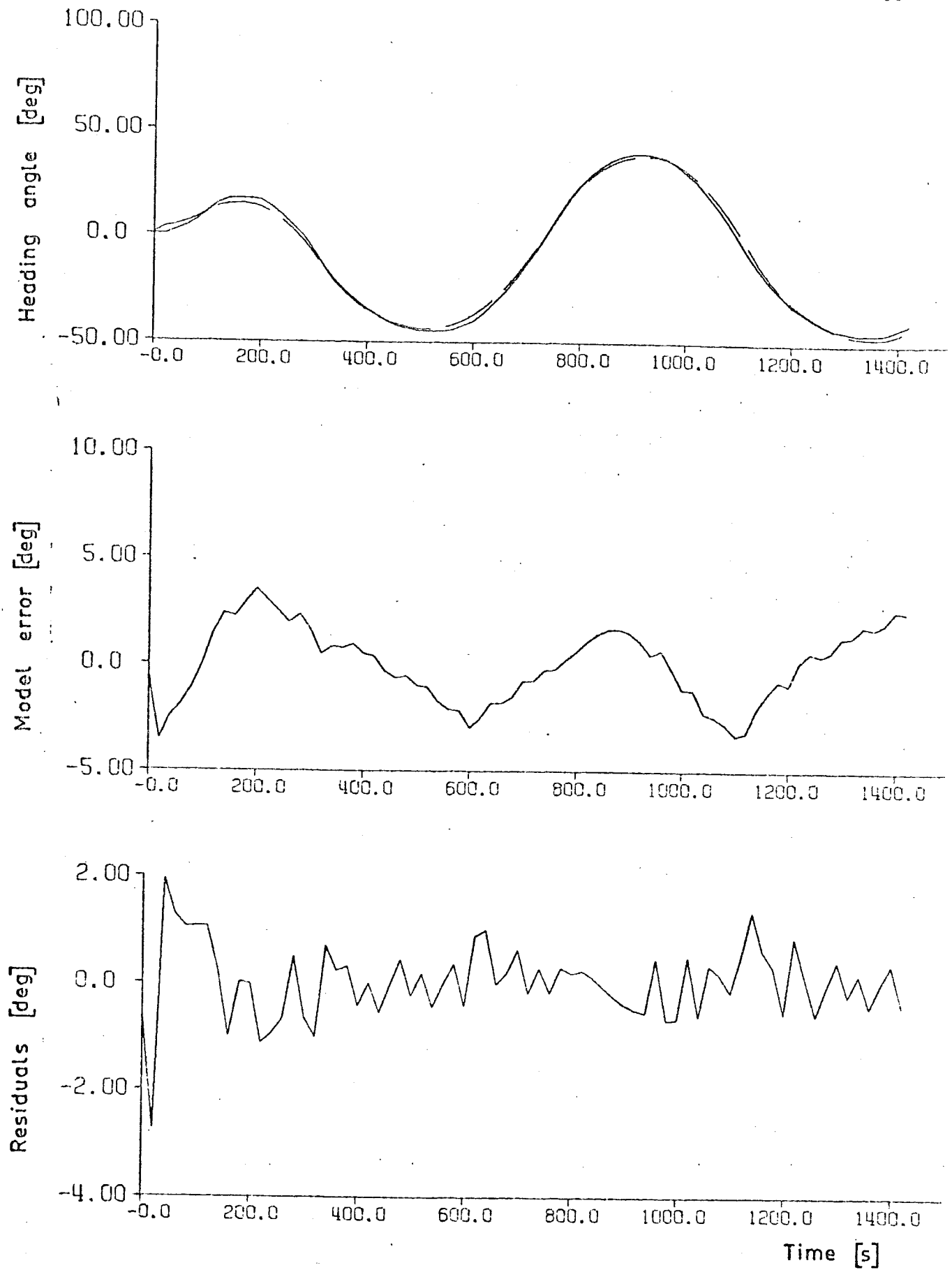


Fig 4.7 - Result of the identification of the hydrodynamic derivatives and the nonlinear coefficient C from a $10/10^0$ zig-zag test with the Sea Scape. The dotted line is the model output.

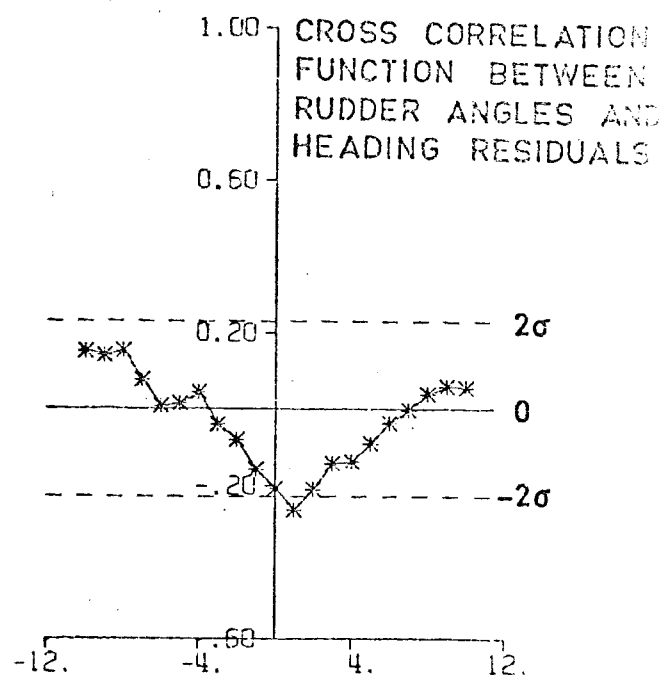
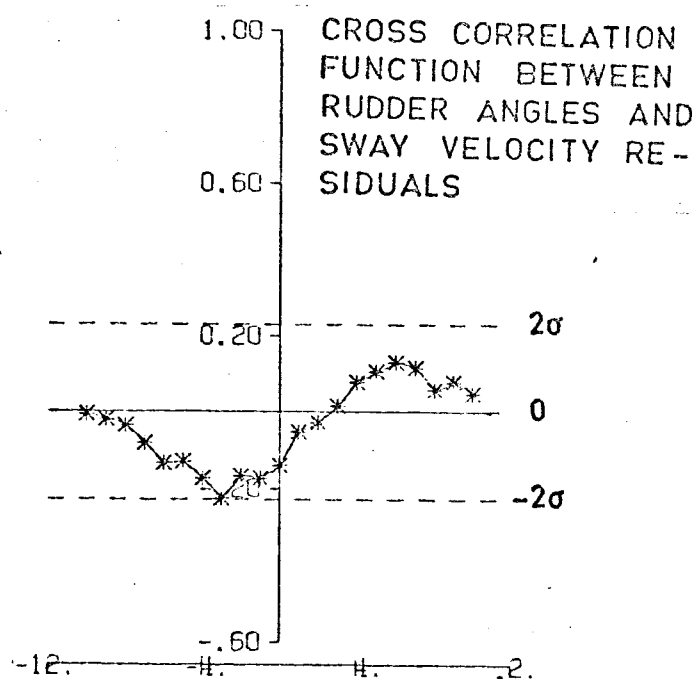
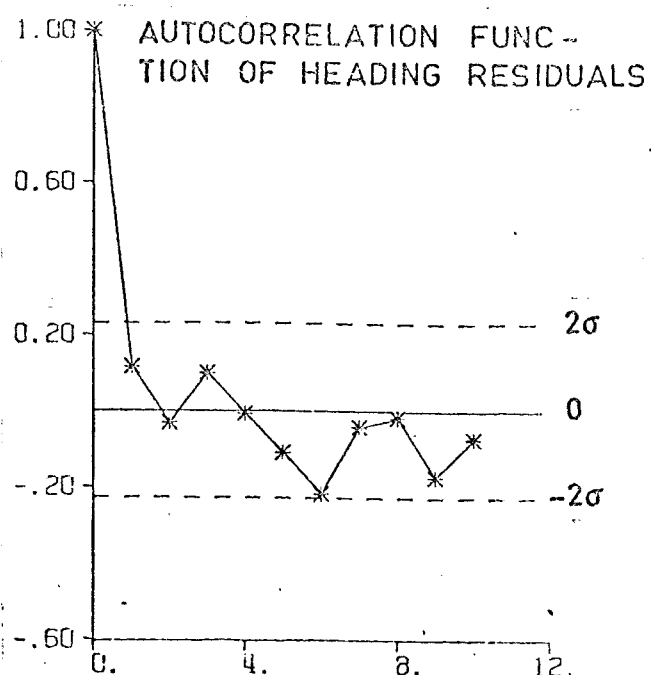
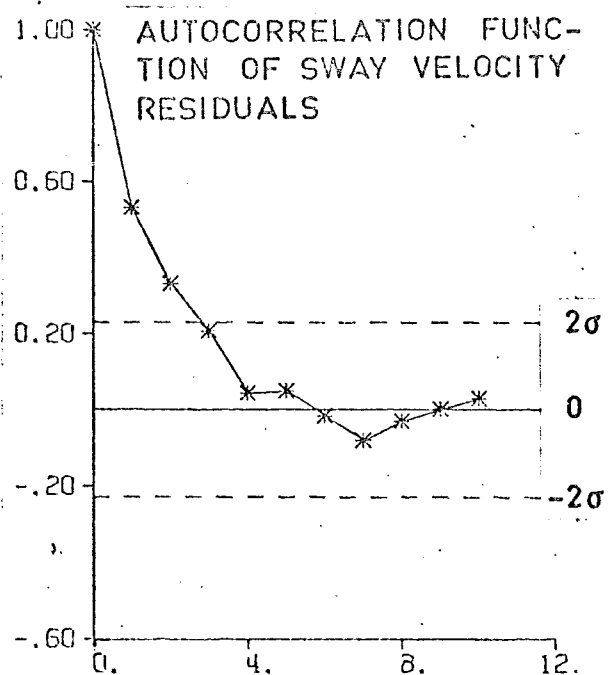


Fig 4.8 - Result of the identification of the hydrodynamic derivatives and the nonlinear coefficient C from a $10/10^\circ$ zig-zag test with the Sea Scape.

Draught bow	14.4	m
Draught stern	14.4	m
Initial speed	16.0	knots
Mean speed	14.2	knots
Sea state	1	on the Beaufort Scale
Wind	W2	m/s

cf Byström (1977a).

Whereas the initial estimates in this case were not established as well as those of the Sea Scape, the results of the estimation of the nonlinear coefficient C with the hydrodynamic derivatives fixed to initial estimates gave a reasonable value of C , see Table 4.5. The values of the coefficients from the linear analysis are quite close to the initial estimates, especially the rudder derivatives. However, the initial estimates indicate a more unstable ship.

The correlation functions of the linear analysis are within the confidence limits. Hence, the linear analysis gives a valid model.

The coefficients obtained from the nonlinear analysis differ very little from those obtained above, but the degree of instability is closer to the expected in the nonlinear case. Consequently a linear model is sufficient, but a nonlinear model probably gives more reliable values of the hydrodynamic derivatives. This was also the case with the Sea Scape experiment.

The Norseman Experiment

Three different experiments of half an hour each were carried out with different draught and at different weather conditions according to

Experi- ment No	Draught stern (m) bow (m)		Speed (knots)	Wind (m/s)
1	13.41	9.45	15.0	17-18
2	9.93	7.09	17.6	8-10
3	12.91	11.27	18.1	0- 2

	Initial estimates	Linear without process noise	Linear with process noise	Nonlinear without process noise	Nonlinear with process noise
$1 - Y_{\dot{v}}''$	2.0				
$x_G'' - Y_{\dot{r}}''$	0.062				
$x_G'' - N_{\dot{v}}''$	0.055				
$k_{zz}'' - N_{\dot{r}}''$	0.120				
Y_{uv}''	-1.200	-0.873	-0.871	-0.831	-0.817
$Y_{ur}'' - 1$	-0.750	-0.705	-0.571	-0.715	-0.673
N_{uv}''	-0.450	-0.193	-0.193	-0.239	-0.227
$N_{ur}'' - x_G''$	-0.230	-0.123	-0.123	-0.124	-0.111
Y_{δ}''	0.230	0.243	0.243	0.237	0.227
N_{δ}''	-0.108	-0.114	-0.114	-0.111	-0.107
C	0.45	-	-	0.52	0.54
K'	3.79	128.76	48.99	2.19	2.24
K_V'	-2.17	-103.63	-31.85	-1.60	-1.56
T_1'	-9.12	-280.56	-103.79	-5.02	-5.09
T_2'	0.42	0.65	0.76	0.69	0.75
T_3'	0.98	1.65	1.65	1.58	1.63
T_{3v}'	0.26	0.31	0.38	0.32	0.35

Table 4.5 - Estimated hydrodynamic derivatives and transfer function parameters from a 10/10° zig-zag test ($T_B/T_S = 14.4/14.4$ m) with the A K Fernström

cf Byström (1977b).

In the experiments with the Norseman, with main dimensions and ship characteristics according to Appendix B, the rudder angle was perturbed and the yaw rate observed. The rudder angle was in principle chosen as a PRBS-input (Pseudo Random Binary Signal) with a peak-to-peak variation of 10^0 . A slight modification was sometimes necessary to match a heading bias, especially at the first experiment, when the weather conditions were bad. The yaw rate was measured with a pneumatic gyro and the rudder angle with a potentiometer applied to the rudder stock. The measurements were recorded on magnetic tape and later sampled every ten seconds.

The relation between the yaw rate $\dot{\psi}$ and rudder angle δ may be written

$$T_1 T_2 \ddot{\psi} + (T_1 + T_2) \dot{\psi} + \dot{\psi} = K \delta (1 + T_3 \dot{\delta})$$

or in transfer function form

$$G_{\psi\delta} = \frac{K(1 + sT_3)}{(1 + sT_1)(1 + sT_2)}$$

Using yaw rate and rudder angle the coefficients above are identifiable, cf Åström and Källström (1973). The estimated parameters of the transfer function $G_{\psi\delta}$ without process noise are given in Table 4.6.

Experim No	T_S/T_B (m)	K'	T_1'	T_2'	T_3'
1	13.41/9.45	-2.24	2.78	0.31	0.51
2	9.93/7.09	-2.27	2.82	0.46	0.83
3	12.19/11.27	-2.71	4.40	0.33	0.50

Table 4.6 - Estimated parameters (normalized in the "prime" system) of the transfer function relating yaw rate and rudder angle for the Norseman. (Model without process noise.)

With process noise included the parameters of $G_{\psi\delta}$ are estimated as shown in Table 4.7

Experi- ment No	T_S/T_B (m)	K'	T_1'	T_2'	T_3'
1	13.41/9.45	-7.08	9.08	0.26	0.62
2	9.93/7.09	-1.91	1.91	0.16	0.28
3	12.19/11.27	-	-	-	-

Table 4.7 - Estimated parameters (normalized in the "prime" system) of the transfer function relating yaw rate and rudder angle for the Norseman. (Model with process noise.)

In the third experiment the process noise appeared to be very small. This led to considerable convergence problems and therefore the process noise was not estimated.

The parameters of the third experiment are of course the most reliable as the weather conditions were most favourable at this experiment. Comparing the conditions of the second experiment with those of the third, it appears that the draught is smaller but the stern trim larger. Therefore the stability lever should be larger in the second case, i.e. $-K'$ and T_1' should decrease as in the Tables above. The time constants T_2' and T_3' may either increase or decrease depending on the actual change of the hydrodynamic coefficients. In the first experiment the stern trim is larger but the difference in draught is rather small compared to the third. However, due to weather conditions the speed was only 15 knots and thus the water speed past the rudder was relatively larger. This may be the reason for the large $-K'$ and T_1' values obtained in Table 4.7. The result of the identification of the first experiment is, however, somewhat questionable as the autocorrelation function is not independent, probably due to the rolling motion disturbing the measuring of the yaw rate.

The High Speed Patrol Boat Experiment

The experiments with the high speed patrol boat consist of a 10/20° zig-zag test and two turning tests with rudder angles of 20° and 30°. The

trial conditions at the zig-zag test were

Draught bow	2.2	m
Draught stern	1.4	m
Initial speed	20.0	knots
Mean speed	19.0	knots
Sea state	2-3	
Wind	S6	m/s

The turning tests were performed according to

Rudder angle (°)	Mean speed (knots)	Stat speed (knots)	Stat turn rate (°/s)
20	18.0	16.0	4.0
30	18.3	17.5	4.4

cf Byström (1977a).

The main dimensions and hull characteristics are given in Appendix B.

The initial estimates for this ship were taken from PMM-tests with a scale model of a patrol boat of a similar size. These estimates, however, proved to be too bad to be used at a determination of the C value. Therefore such an estimation was not carried out. The linear analysis also gives values of the coefficients, which differ considerably from the initial estimates.

The nonlinear analysis results, see Table 4.8, in almost the same values of the coefficients as in the linear case. Furthermore the C values are very small and even negative. This indicates that the nonlinear effects are small and that the linear analysis is sufficient.

The turning tests were analysed using the nonlinear model, see Table 4.9. First the nonlinear coefficient C was determined with the hydrodynamic derivatives fixed to the values obtained from the zig-zag test. Again very small values of C were obtained in both turning tests. Also the estimation of all coefficients gave low values of C . Moreover, the derivatives do not differ much from those of the zig-zag test, i.e. the linear model is sufficient also for the turning tests. This is actually not surprising with regard to the curvature L/R being as low as 0.29.

	Initial estimates	Linear without process noise	Linear with process noise	Nonlinear without process noise	Nonlinear with process noise
$1 - Y_v''$			1.697		
$x_G'' - Y_r''$			-0.060		
$x_G'' - N_v''$			0.070		
$k_{zz}'' - N_r''$			0.089		
Y_{uv}''	-1.931	-0.972	-0.808	-0.954	-0.991
$Y_{ur}'' - 1$	-0.110	-1.832	-1.538	-1.618	-1.592
N_{uv}''	0.123	-0.013	-0.030	-0.012	-0.019
$N_{ur}'' - x_G''$	-0.381	-0.118	-0.181	-0.203	-0.194
Y_δ''	1.066	0.131	0.209	0.251	0.219
N_δ''	-0.460	-0.053	-0.090	-0.108	-0.095
C	-	-	-	-0.0068	-0.020
K'	-1.00	-0.58	-0.78	-0.61	-0.60
K_V'	0.61	1.22	1.75	1.30	1.19
T_1'	0.86	complex	1.89	complex	complex
T_2'	0.23	"	0.82	"	"
T_3'	1.13	1.85	2.12	1.90	1.80
T_{3v}'	0.19	0.070	0.075	0.070	0.072

Table 4.8 - Estimated hydrodynamic derivatives and transfer function parameters from a 10/20° zig-zag test with a high-speed patrol boat

	20° turning test		30° turning test	
	Estimation of C	Nonlinear without process noise	Estimation of C	Nonlinear without process noise
$1 - Y_v''$		1.697		
$x_G'' - Y_r''$		-0.060		
$x_G'' - N_v''$		0.070		
$k_{zz}'' - N_r''$		0.089		
Y_{uv}''	-0.991	-0.919	-0.991	-0.994
$Y_{ur}'' - 1$	-1.592	-1.431	-1.592	-1.326
N_{uv}''	-0.019	-0.027	-0.019	-0.021
$N_{ur}'' - x_G''$	-0.194	-0.228	-0.194	-0.131
Y_δ''	0.219	0.219	0.219	0.149
N_δ''	-0.095	-0.094	-0.095	-0.064
C	-0.0005	0.001	0.0056	0.008
K'	-0.60	-0.54	-0.60	-0.65
K_v'	1.19	1.09	1.19	1.01
T_1'	complex	1.60	complex	complex
T_2'	"	0.57	"	"
T_3'	1.80	1.89	1.80	1.79
T_{3v}'	0.072	0.075	0.072	0.090

Table 4.9 - Estimation of the nonlinear coefficient C (linear coefficients fixed to values obtained from the nonlinear analysis of the 10/20° zig-zag test) and hydrodynamic derivatives from turning tests

5. EXPERIMENTAL EQUIPMENT

This section summarizes the measuring equipment that has been used in the experiments analysed so far. It also gives some recommendations for equipment suitable for future experiments.

The USS Compass Island

The USS Compass Island experiments (Morse and Price (1961)) were performed using an inertial navigation system which makes it possible to measure all angular rates and all velocities with high precision and high resolution. Inertial quality gyroscopes have e.g. drift rates of the order of $0.01^\circ/\text{h}$ ($= 3 \times 10^{-6}^\circ/\text{s}$). Typical short term resolutions in velocity are 0.1 m/s .

The inertial system also gives measurements in all three axes. Unfortunately we did not have access to the raw data from the USS Compass Island experiments. Instead we had to generate the data by converting graphs to digits. Naturally a lot of the precision inherent in the data are lost when this is done. In spite of this the estimated parameters from the USS Compass Island were very good. This clearly indicates the potential of experiments based on inertial sensors.

The Sal  n Tankers

The experiments on the Sal  n tankers Sea Splendour, Sea Scout, and Sea Swift were also made using good measurement equipment. The experiments were easy to perform because the ships had an onboard computer which was used to generate rudder perturbations. In these experiments the primary sensors were the Sperry gyrocompass, the ATEW rate gyro, and a doppler sonar equipment type Ametek Straza for measuring the velocity components. A gyrocompass typically has a resolution of $1/6^\circ$. The quality of the rate gyro signal varies with sea conditions and the way the gyro is mounted. Typical drift rates for the rate gyro given by the manufacturer are $3^\circ/\text{h}$. The doppler sonar may have a bias but resolutions are typically of the order of 0.01 m/s . The resolution

of the sensors are thus at least two orders of magnitude less than those obtained from an inertial navigation system. In spite of this the results of the parameter estimations have been reasonable. There are however some indications that the resolutions of the sensors give a limit to the results. It has for example been found in some cases that when increasing the model from second to third order the model attempts to fit sensor round off instead of higher order ship dynamics (see Aström et al (1975) and Aström and Källström (1976)).

Practical Aspects

In all experiments made the measurement equipment has been tailored to the special situation for each particular ship. This is costly and time consuming and difficult to do on a routine basis. It is therefore of practical interest to discuss how identification measurements can be done on a routine basis.

A Measurement System Based on Inertial Navigation

Since installation of measurement equipment is both tedious and costly the ideal situation is of course to have a small self-contained box that contains all necessary equipment. Ideally this box should contain an inertial navigation system and a minicomputer. It is then sufficient to connect the signal to the rudder servo only. The inertial navigation system offers a very high resolution. Since it also admits direct measurement of the accelerations it can be expected that very good estimates can be obtained from such experiments. The major drawback with the inertial navigation system is the cost of the order of 0.5 Mkr. There may, however, be possibilities to borrow or rent a system for shorter test periods from SAS or FMV.

A Measurement System Based on Sensors Available on the Ship and a Minicomputer

Another alternative is to use existing sensors available on the ship together with a minicomputer and a flexible interface. A list of typical sensors and their signals are given in Appendix A. It is not difficult to design a flexible interface which can convert these

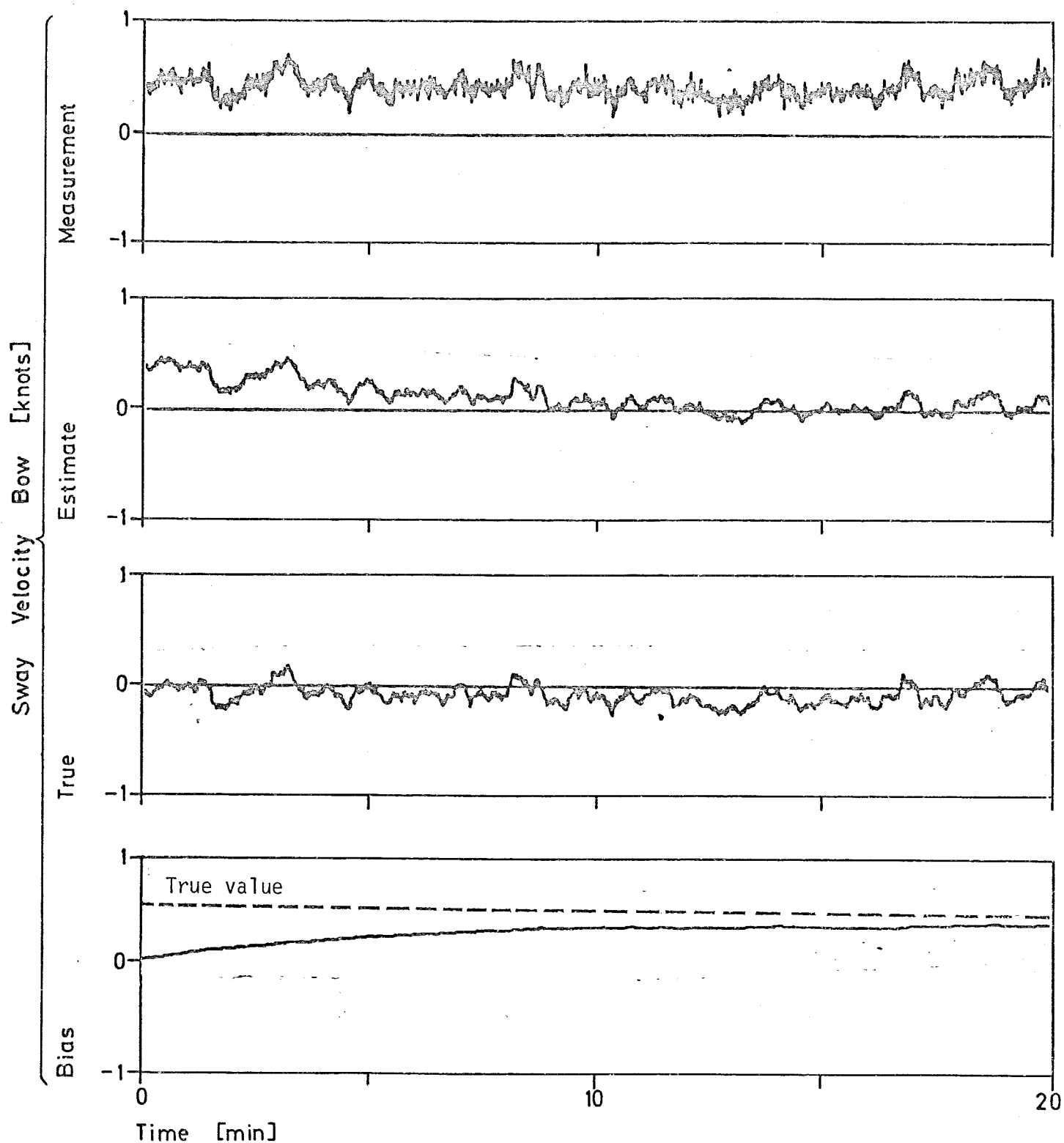


Fig. 5.1 (a) - Primary measurement signal of sway velocity at bow, filtered signal from a Kalman filter, true signal and estimated measurement bias obtained in a wind speed of 11-14 m/s. The simulation is adopted from Källström (1976).

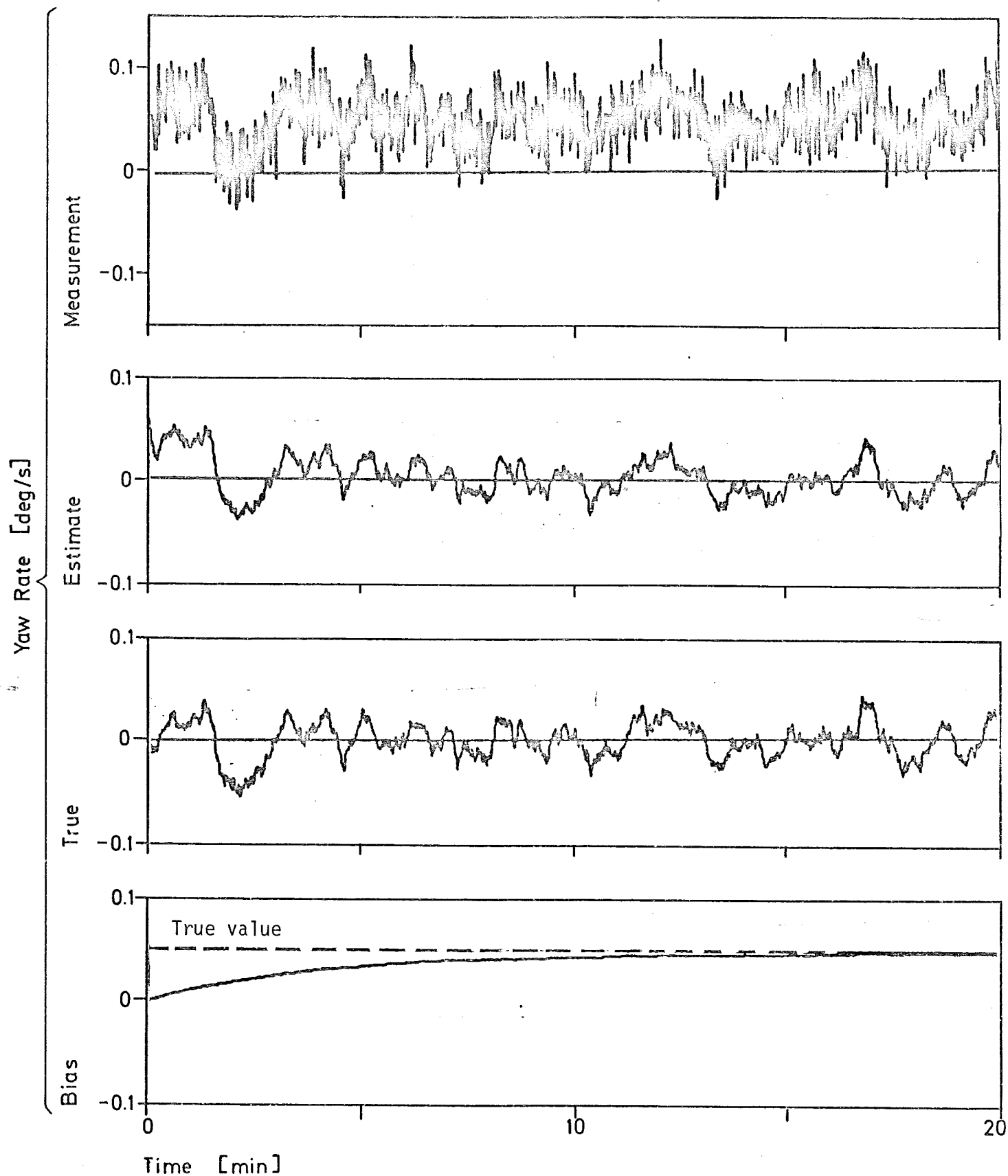


Fig. 5.1 (b) - Primary measurement signal of yaw rate, filtered signal from a Kalman filter, true signal and estimated measurement bias obtained in a wind speed of 11-14 m/s. The simulation is adopted from Källström (1976).

signals to digital form. A minicomputer, e.g. LSI-11, can then generate the desired rudder perturbation and store the data on tape. A small process control system developed for teaching at LTH could be a first prototype. This system needs to be extended with respect to flexibility of accepting different signal levels. This is, however, easily done. A substantial advantage of using a minicomputer is that the raw data can be filtered efficiently using a Kalman filter which means that measurement disturbances can be rejected efficiently. Studies reported in Källström (1976) and Källström et al (1977) show that a substantial reduction of disturbances can be achieved. Compare Fig. 5.1 from which it also can be concluded that measurement biases can be estimated efficiently by using a Kalman filter. The computational requirements for a Kalman filter on the process computer PDP 15 have been estimated in Källström and Aström (1971). A straightforward FORTRAN implementation required 140 memory cells for the code and $n_x(n_x+2n_u+n_y+1)+n_u+n_y$ cells for the data, where n_x , n_u , and n_y are the number of states, inputs, and outputs, resp. For the Kalman filter designed in Källström (1976) and Källström et al (1977) $n_x = 9$, $n_u = 1$, and $n_y = 5$, which means that 300 cells are required totally. An execution time of approximately 0.04 s is then obtained on the PDP 15 if software floating point arithmetic is used. The execution time is approximately halved with hardware floating point arithmetic.

Recursive Estimation

If a measuring equipment with a minicomputer is available it can also be attempted to use the computer to arrive at approximative parameter estimates. This can be done by using some recursive parameter estimation procedure. A preliminary investigation of the feasibility of an extended Kalman filter, see Jazwinski (1970), has been explored. The possibilities to determine the parameters in the nonlinear first-order model

$$\frac{d^2\psi}{dt^2} + a_1 \frac{d\psi}{dt} + a_2 \left| \frac{d\psi}{dt} \right| \frac{d\psi}{dt} = b \delta + e \quad (5.1)$$

were investigated. The result of one simulation is shown in Fig. 5.2.

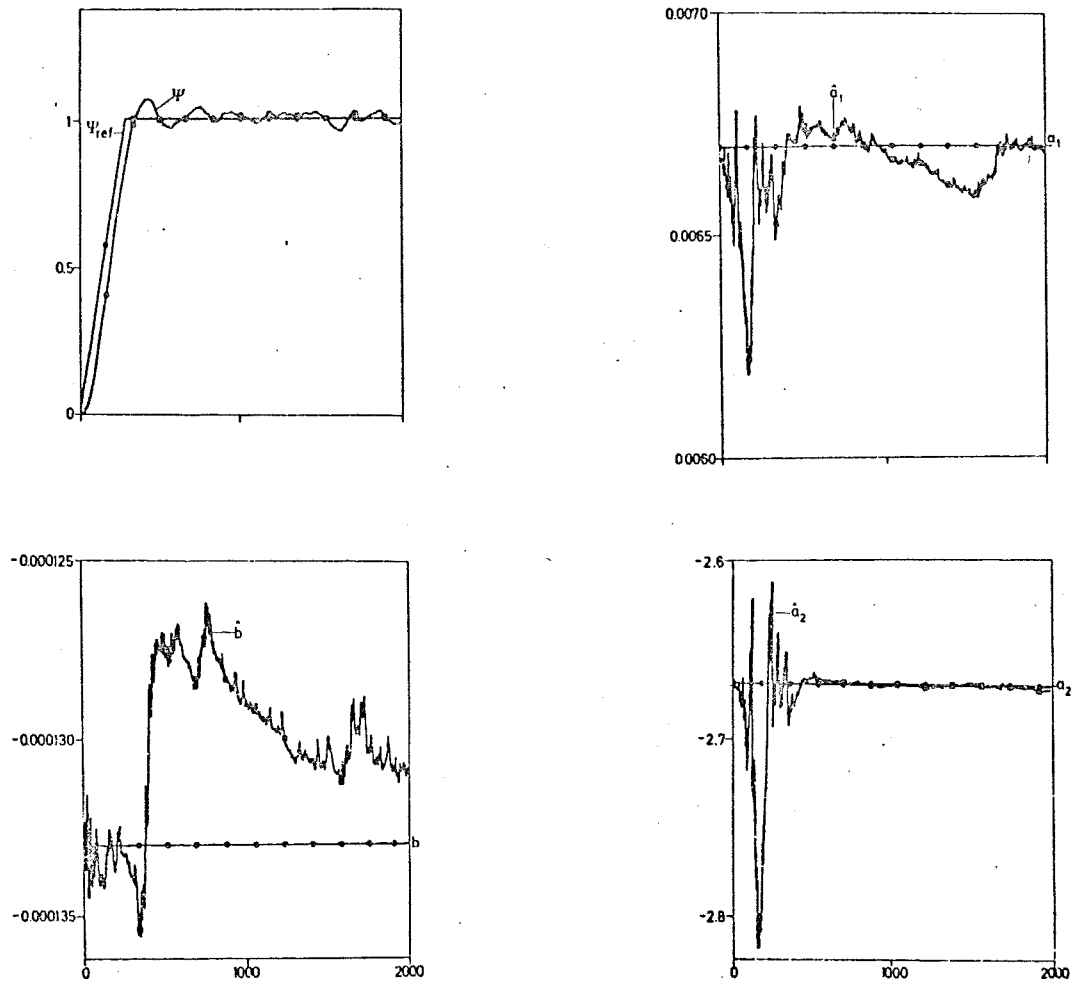


Fig. 5.2 - Simulation of an extended Kalman filter for estimating the parameters a_1 , a_2 , and b_0 of a nonlinear first-order model (5.1).

It was also attempted to apply the extended Kalman filter to fit the model (5.1) to measured data. These results were not successful probably because the model is too simple.

6. MODEL TESTS

Model tests with a free-running scale model of the Svealand have been carried out in the new Maritime Dynamics Laboratory at SSPA. The main dimensions and ship characteristics of the Svealand are

L_{pp}	= 321.6 m	L/B	= 5.89
B	= 54.6 m	B/T	= 2.52
T_{CWL}	= 21.7 m	L/T	= 14.82
∇_{CWL}	= 312 200 m ³	$L/\nabla^{1/3}$	= 4.74

The experiments, performed in full load condition, comprised a large number of zig-zag-, turning, and PRBS-tests in two different shallow water conditions.

Due to the limited space the scale model is accelerated to the initial speed of a test with a catapult. During the tests the measurements were made as stated below.

- position	overhead photography system, position measuring system using infra-red rays
- rudder angle	potentiometer
- number of revolutions	tachometer
- rudder force	strain gauge dynamometer
- speed	pitot tube
- drift angle	vane type sensor
- heading, yaw rate	rate gyro
- rolling angle	horizontal gyro

Examples of results are given in Figs 6.1, 6.2 and 6.3. In Figs 6.1 and 6.2 two 20/10⁰ zig-zag tests at different water depths ($h = 28$ and 50 m) are presented. Note the marked shallow water influence on the sway velocity. The amplitude is smaller in Fig 6.1 due to the stabilizing effect of the lower water depth. Finally an example of a turning test with full star-board rudder at a water depth of 28 m is shown in Fig 6.3. Further results and analyses including parameter estimations will be presented in Byström (1977c).

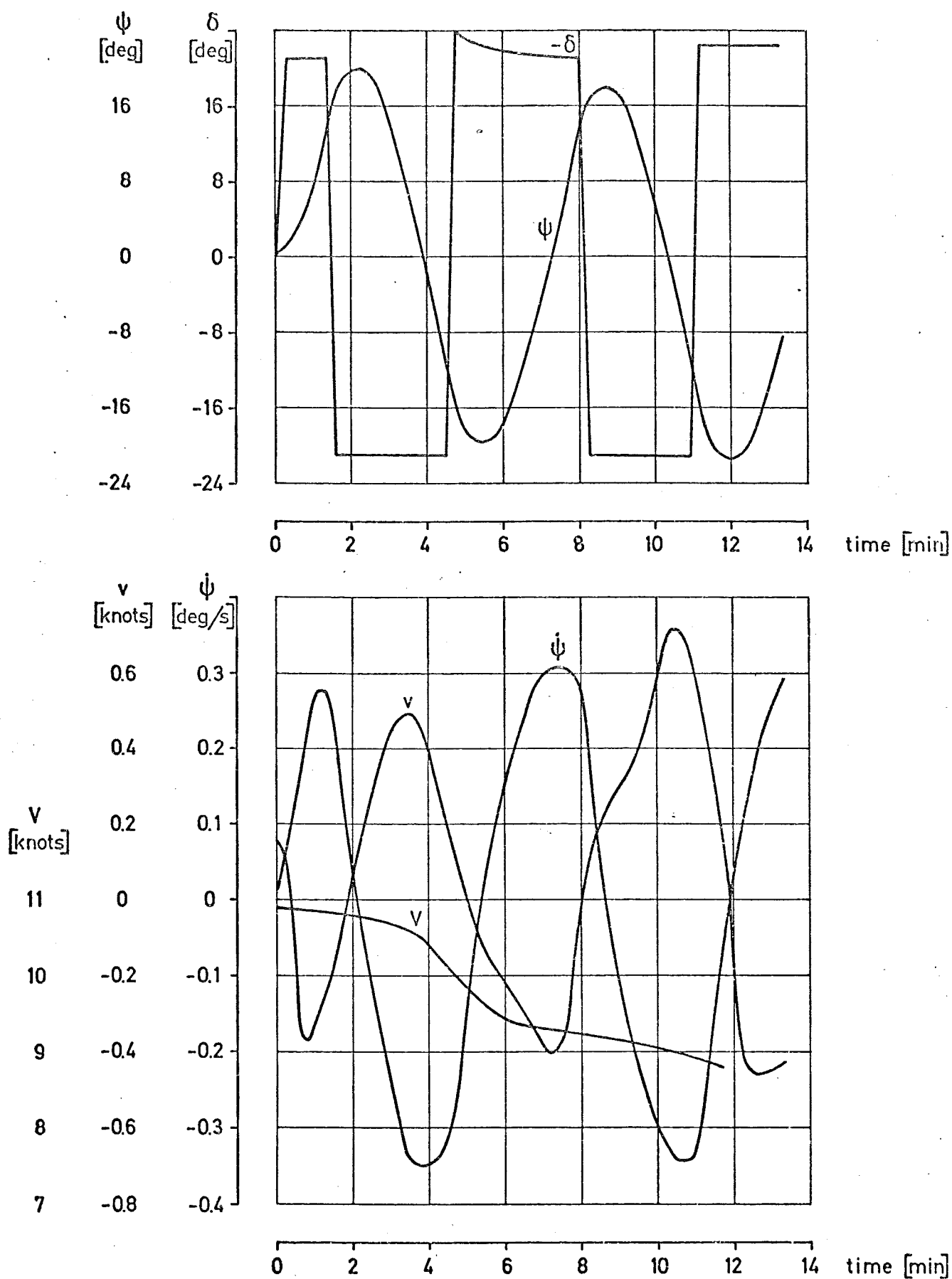


Fig 6.1 - Results of a 20/10° zig-zag test with a scale model of the Svealand in shallow water ($h = 28$ m) with initial speed 10.9 knots. Top heading (ψ) and rudder angle (δ). Below speed (V), sway velocity (v) and yaw rate ($\dot{\psi}$)

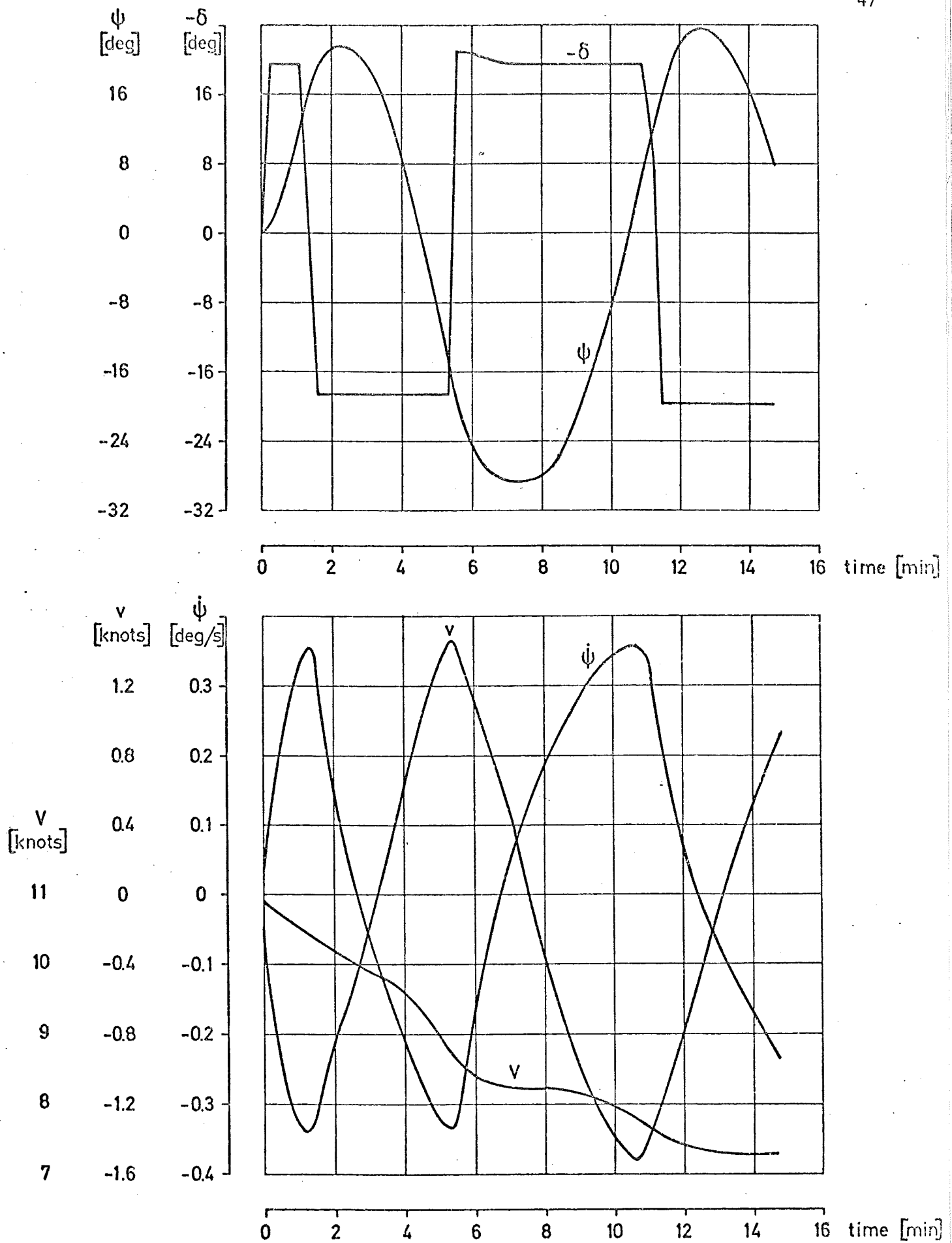


Fig 6.2 - Results of a 20/10° zig-zag test with a scale model of the Svealand in shallow water ($h = 50$ m) with initial speed 10.9 knots. Top heading (ψ) and rudder angle (δ). Below speed (V), sway velocity (v) and yaw rate ($\dot{\psi}$)

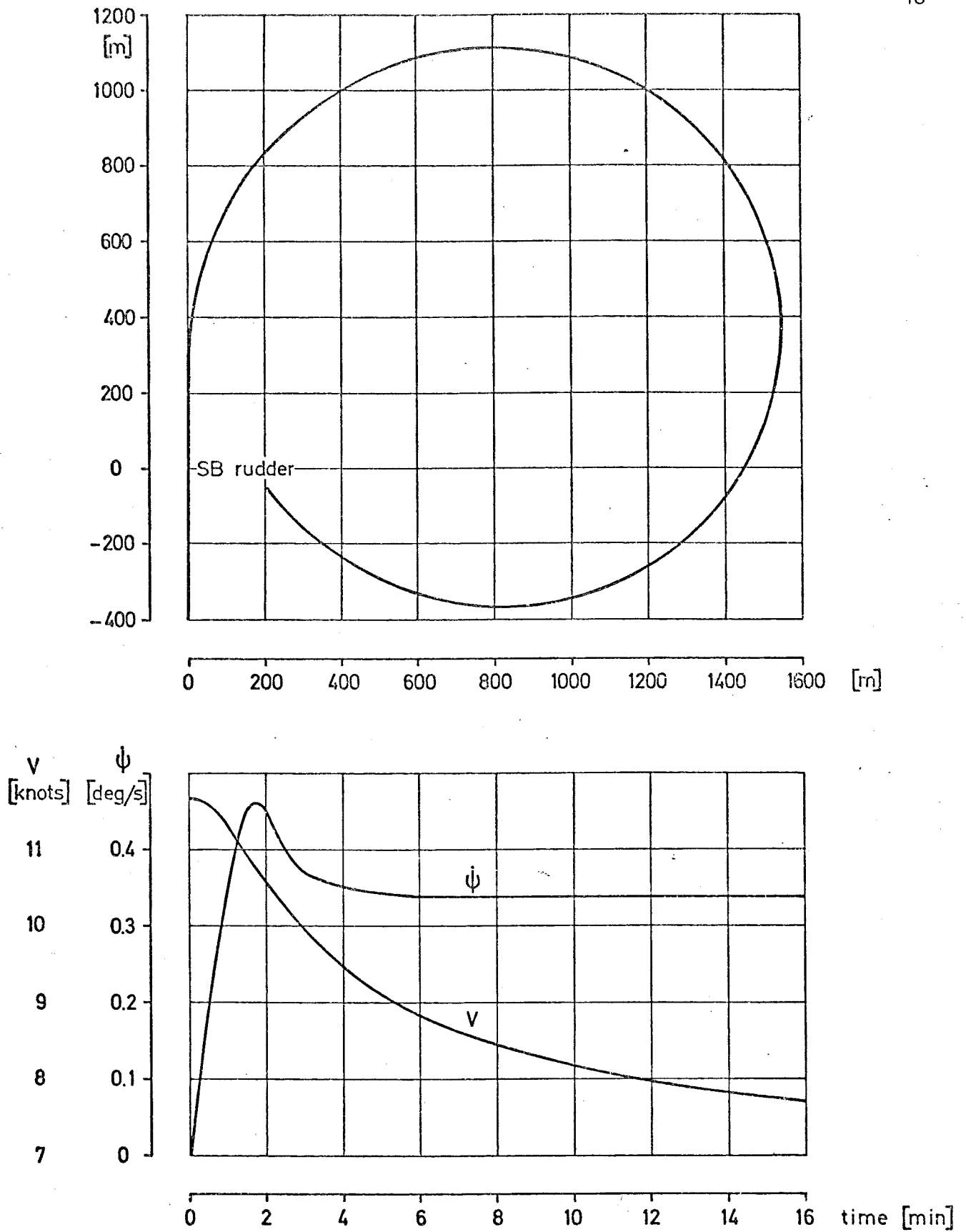


Fig 6.3 - Turning test with a scale model of the Syealand ($\delta = -35^\circ$ and $V = 10.9$ knots) in shallow water ($h = 28^0\text{m}$). Top x_0 -, y_0 -coordinates. Below yaw rate (ψ) and speed (V)

7. CONCLUSIONS

The results of this project do support the earlier conclusions given in Åström, Källström, Norrbin and Byström (1975) that system identification methods form a powerful tool for determining models for ship steering. The analysis of the linear models has shown that it may be advantageous to use other criteria than that of maximizing the likelihood function. For data with sampling intervals which are significantly shorter than the dominating time constants it has been found desirable to use a prediction error method with a time horizon that is larger than the sampling interval and sometimes of the same magnitude as the dominating time constant.

The attempts to fit nonlinear models have been very successful. It has been shown that the nonlinear model proposed can describe the nonlinear effects very well, as far as normal ship forms are concerned. The method proposed to estimate the single unknown parameter in the nonlinear model also works very well. For ships of extreme form the method may be modified to include a three-parameter model for the longitudinal variation of effective cross-flow drag.

Based on the experiences obtained we can now recommend the following procedure to determine the ship dynamics from free-steering experiments. First determine the linear dynamics from a PRBS type of experiment using small perturbations and an experiment length corresponding to several hundred ship lengths. To estimate the hydrodynamic derivatives the use of a prediction error criterion with a prediction horizon somewhat shorter than the dominating time constants of the ship is recommended. If it is desired to model the stochastic properties also the stochastic parameters can then be determined using a prediction error criterion, possibly with a shorter time horizon. To determine the nonlinear parameter it is necessary to have an experiment that well excites the nonlinear modes, such as a zig-zag test with large excursions. When determining the parameter characterizing the nonlinear motion the linear parameters can be kept at the values obtained from the linear experiment. There is reason to study the potentials of alternative experiments with regard to accurate estimates of

the parameter characterizing the cross-flow drag. Among existing standard manoeuvres the circle test with subsequent "pull out" may offer some possibilities.

Portable equipment suitable for future experiments at sea has also been considered. Undoubtedly a measurement system built up around an inertial platform will be the best choice. Possibilities of testing such equipment should be explored. Since the inertial equipment is quite expensive, however, a cheaper alternative has also been investigated. This equipment uses sensors already available onboard the ship. A flexible interface and a minicomputer with tape is then sufficient. Such equipment can easily fit into 4 panel heights of a 19" rack.

Much work still remains before the procedures can be accepted for routine use. The linear and, especially, the nonlinear model should be fitted to more data. A serious drawback with the existing models is that the computations are still costly. Methods to simplify the computations should be explored. Other methods to estimate the parameters of the nonlinear models should also be studied. It seems highly desirable to evaluate the possibilities of inertial sensors because of their high accuracy. Another important issue is the comparison of parameter estimates from free-running scale model experiments and compatible full scale experiments; plans are well advanced for such a correlation.

When performing experiments with large excursions required to obtain data suitable for the nonlinear identification, the speed is decreased. The possibility of modelling the equation describing the forward speed in a way that is suitable for the purpose of identification should be explored. This equation is basically nonlinear, which means that the different methods for nonlinear identification reviewed in this report could be investigated in more detail in connection with a more sophisticated nonlinear model for the steering dynamics.

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APPENDIX A

List of typical sensors

Below is given a list of typical sensors and their signals on modern ships. The list is based on information from Uddevallavarvet AB, but it should apply to ships from other builders as well.

<u>Forward speed</u>	Doppler speed log giving 200 pulses/nautical mile of water track. By means of a relay a suitable level of the pulses may be obtained
<u>Lateral speed</u>	One or two speed logs as above, usually placed at bow and/or stern
<u>Heading</u>	Main gyro compass with a step by step motor (35V DC). One pulse represents $1/6^{\circ}$
<u>Yaw rate</u>	Main gyro derivative signal (0-3V DC, 3V = $1^{\circ}/s$)
<u>Number of revolutions</u>	Tachometer generator (0-24V DC)
<u>Rudder angle</u>	Selsyn signal from transducer on steering engine (115V, 60 Hz). The selsyn signal may be converted to continuous voltage in several different ways. A somewhat expensive, but probably the most suitable way is to use a synchro analog converter

Note: It should be pointed out that Decca position measuring system is available on most ships and that extensive use of Decca readings has been made in earlier identifications, cf Åström et al (1975)

APPENDIX B

Main dimensions and hull characteristics of ships in Section 4Sea Scout and Sea Swift

Lpp	= 329.2	m	L/B	= 6.35
B	= 51.8	m	B/T	= 2.58
T _{CWL}	= 20.1	m	L/T	= 16.38
∇ _{CWL}	= 285 000	m ³	L/∇ ^{1/3}	= 5.00

USS Compass Island

Lpp	= 161.1	m	L/B	= 6.94
B	= 23.2	m	B/T	= 2.55
T _{CWL}	= 9.1	m	L/T	= 17.70
∇ _{CWL}	= 20 840	m ³	L/∇ ^{1/3}	= 5.85

Sea Scape

Lpp	= 350.0	m	L/B	= 5.83
B	= 60.0	m	B/T	= 2.69
T _{CWL}	= 22.3	m	L/T	= 15.70
∇ _{CWL}	= 389 100	m ³	L/∇ ^{1/3}	= 4.79

A. K. Fernström

Lpp	= 243.9	m	L/B	= 6.27
B	= 38.9	m	B/T	= 2.61
T _{CWL}	= 14.9	m	L/T	= 16.37
∇ _{CWL}	= 121 500	m ³	L/∇ ^{1/3}	= 4.92

Norseman

Lpp	= 310.9	m	L/B	= 6.47
B	= 48.1	m	B/T	= 2.36
T _{CWL}	= 20.4	m	L/T	= 15.24
∇ _{CWL}	= 256 400	m ³	L/∇ ^{1/3}	= 4.89

High speed patrol boat

L_{pp}	= 33.85 m	L/B	= 5.46
B	= 6.20 m	B/T	= 3.71
T_{CWL}	= 1.67 m	L/T	= 20.27
∇_{CWL}	= 145 m ³	$L/\nabla^{1/3}$	= 6.44