Adaptive Steering of Ships—A Model Reference Approach*

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Model reference adaptive control, applied to automatic steering of ships, provides by means of direct adaptation, optimal control and adaptive state estimation, improved manoeuvring, and better fuel economy.

Key Words—Adaptive control; digital computer applications; optimal control; optimal filtering; parameter estimation; parameter optimization; ship control.

Abstract—This paper describes the application of model reference adaptive control (MRAS) to automatic steering of ships. The main advantages in this case are the simplified controller adjustment which yields safer operation and the decreased fuel cost. After discussion of the mathematical models of process and disturbances, criteria for optimal steering are defined. Algorithms are given for direct adaptation of the controller gains, applicable after setpoint changes, as well as for identification and adaptive state estimation, to be used when the input is constant. Solutions for applying MRAS to a certain class of nonlinear systems are dealt with. Full-scale trials at sea and tests with a scale model in a towing tank are described. It is shown that the autopilot designed indeed has the desired properties. Fuel savings up to 5% in comparison to conventional PID control are demonstrated. These savings are mainly possible because of the adaptive state estimator.

1. INTRODUCTION

AUTOMATIC steering of ships was introduced many years ago (Minorsky, 1922; Sperry, 1922); with developing technology, the hardware of autopilots changed from purely mechanical devices to electronic systems, but the controller concept itself has hardly changed. However, it may be expected that, in the near future, a new generation of autopilots, based on modern control techniques, will replace the present systems. The fast development of small and inexpensive microcomputers makes these autopilots practically realizable.

In principle, a conventional autopilot is nothing more than a PID controller extended with a limiter to limit its output signal (the desired rudder angle) and a dead band and a filter to smooth the controller output. Two major disadvantages of this type of controller are: (1) it is difficult to adjust manually because the operator, the watch officer, has many other tasks and lacks the insight into control theory; his adjustment will seldom be optimal and (2) the optimal adjustment varies and is not known by the user. Changing circumstances require manual readjustment of a series of settings of the autopilot. This holds not only for variations in the parameters of the process but also when due to a varying traffic situation the required performance changes.

Because of the changing environment it is not possible to simply design an optimal controller. Various operating conditions require different controller structures (course changing and course keeping) and varying traffic situations demand other definitions of optimal performance. The first problem to be solved is thus how the operator can be provided with the means which enable him to simply adjust the autopilot according to his actual demands, without the necessity of setting all the conventional settings. These demands must then be translated into a performance index to be minimized by an optimal control system. The second problem is that the optimal performance has to be maintained when the process characteristics change due to changing forward speed, load condition, water depth, etc. This requires adaptive control.

Since 1973, the continuously rising fuel prices have made the savings from applying more sophisticated control algorithms obvious. Recently, several proposals for adaptive autopilots have been published (Van Amerongen and Udink ten Cate, 1975; Van Amerongen and Van Nauta Lemke, 1978, 1979; Van Amerongen, 1982; Kallström and co-workers, 1979; Ohtsu, Horigome and Kitagawa, 1979; Reid and Williams, 1978; Kojima and

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Sugimoto, 1978; Herther and co-workers, 1980). Several techniques are used to achieve the automatic adjustment of the controller parameters. The autopilot described in this paper is based on the theory of model reference adaptive systems (MRAS). In general, the theory based on stability methods requires that the process and reference model be linear. The solutions given in this paper to deal with certain classes of nonlinearities are also applicable to other systems where saturation effects in actuators dominate the response. In general, continuous time techniques will be used to design the adaptive controller. Because of the relatively high sampling rate which can be chosen, the algorithms can easily be digitally implemented as well.

The paper is organized as follows: Section 2 describes the mathematical models of the process and the disturbances. Section 3 discusses criteria for optimal steering. Section 4 gives the algorithms used for direct adaptation of the controller parameters. Indirect parameter adjustment by means of on-line identification and controller optimization, as well as adaptive state estimation, are discussed in Section 5. In Section 6 results of a series of full-scale trials as well as tests with a scale model in a towing tank are described. Section 7 summarizes the conclusions.

2. MATHEMATICAL MODELS

In the literature several mathematical models describing the steering dynamics of a ship are given. The most simple one is the first-order model of Nomoto (Nomoto and co-workers, 1957) which describes the transfer between the rudder angle $\delta$ and the rate of turn $\dot{\psi}$

$$\tau \ddot{\psi} + \dot{\psi} = K \delta$$  \hspace{1cm} (1)

where $\dot{\psi} = d\psi/dt$ and $\psi$ is the ship's heading.

The influence of the forward speed of the ship can be added in this model by the relations (Van Amerongen, 1982)

$$K = K^* (U/L)$$  \hspace{1cm} (2)

and

$$\tau = \tau^* (L/U)$$  \hspace{1cm} (3)

where $K^*$ and $\tau^*$ are dimensionless constants (with respect to speed variations) in the order of magnitude of 0.5–2.0; $U$ is the ship's speed and $L$ the length.

This very simple model, which is a simplification of the nonlinear model of Van Leeuwen (1970), does not describe, for instance, the nonlinear static relation between $\delta$ and $\psi$, but for the purpose of designing an adaptive controller it is suitable.

The rudder is actuated by means of the hydraulic steering machine which has nonlinear dynamics. Both its output, the rudder angle, and the rudder speed are limited. Common values are

$$\delta_{\text{max}} = 35^\circ$$  \hspace{1cm} (4)

and

$$\delta_{\text{max}} = 2–7 \text{ deg s}^{-1}.$$  \hspace{1cm} (5)

Compared with the limited rudder speed other time constants of the steering machine may be disregarded for the controller design.

Disturbances which play a role in ship steering are wind, waves and current. When only the ship's heading is controlled (no track control) a stationary current may be neglected. Wind causes a stochastic disturbance, with non-zero mean acting upon the hull. With respect to control of the heading only the moment caused by the wind plays a role. It can be added to the model of equation (1) by adding the moment of the wind to the moment excited by the rudder. This modifies (1) into

$$\tau \ddot{\psi} + \dot{\psi} = K(\delta + K_w)$$  \hspace{1cm} (6)

where $K_w$ represents the influence of the wind.

The moments caused by the waves may be described by one of the standard spectra available in the literature (for instance, the Bretschneider spectrum), recommended by the 12th International Towing Tank Conference. Some typical spectra of fully developed seas for various wind speeds, $V_w$ are given in Fig. 1.

The frequencies of the ship motions caused by this wave spectrum depend also on the angle between the direction of the waves and the heading of the ship and on the speed of the ship. Typical values for the peak frequency are 0.05–0.2 Hz. In the following the moments caused by the waves will be referred to as (high frequency) noise, added to the desired movements caused by the rudder.

![Fig. 1. Example of wave spectra.](image-url)
3. STEERING CRITERIA

To be able to design an optimal controller a performance index has to be defined. Factors which play a role in this particular problem are: (1) economy (fuel cost); (2) safety (related to accuracy and manoeuvrability); and (3) user preferences. Maximum economy and safety cannot be realized without taking into account what the user subjectively considers to be good steering because he is ultimately responsible for the ship. Information about the user's ideas was obtained from an inquiry held among officers of the Royal Netherlands Navy and the Dutch Merchant Navy (Van Amerongen and Prins, 1980). It appears necessary to distinguish between two steering modes: course changing and course keeping.

Course changing

The inquiry indicates that during course changing the 'optimal' performance can be most easily defined as a step response in the time domain which has the form of the response given in Fig. 2. Three phases may be distinguished: (1) start of the turn; (2) stationary turning; and (3) end of the turn.

The turn should have a start which clearly shows to other ships the intention of the manoeuvre. The stationary phase of the turn is determined either by limiting the rudder angle, by controlling the rate of turn or by controlling the turning radius. Conventional autopilots have only the rudder limiter. Rate control or radius control will be preferable in most cases. It follows from (1) and (2) that by limiting the rudder angle a kind of radius control is implicitly achieved. Finally, the turn should stop without overshoot of the heading.

From the user's point of view there is no need for controller adjustment for the phases 1 and 3. Only the stationary phase should be adjustable (in terms of slow and fast turning), depending on the traffic situation, etc. All the conventional settings should be automatically adjusted, when varying process dynamics necessitate this. The only setting chosen to be provided to the operator for course changing is the stationary rate of turn.

Course keeping

Optimization of the course-keeping controller is a more difficult problem. In confined waters with dense traffic the controller has to be above all accurate. This can be realized by selecting high controller gains. However, these gains are limited by the dynamics of the system.

On the ocean minimization of fuel cost will be the main goal. Assuming constant cruising speed this is realized by minimizing the extra drag due to steering. In other words, the loss of speed due to steering actions and the 'loss of speed' due to course errors (the elongation of the distance to be sailed) has to be minimized. There is no direct relation between fuel consumption and controller settings. Because of the difficult and inaccurate measurements involved, this problem cannot be solved by applying experimental optimization methods aimed at directly optimizing the fuel consumption. Attempts to define a more simple performance index have led to the criterion (Motora and Koyama, 1968; Norrbin, 1972)

\[ J = \frac{1}{T} \int_{0}^{T} (\epsilon^2 + \lambda \delta^2) \, dt \]  

(7)

where \( \epsilon \) is the heading error, \( \lambda \) is a weighting factor, and \( \delta \) is the rudder angle.

When the steering machine dynamics are neglected a state-feedback controller for the process of (1) is described by

\[ \delta = K_p \epsilon - K_d \psi + K_i. \]  

(8)

The factor \( K_i \) has been added to compensate for the slowly varying moment of the wind, \( K_w \). When the sum of \( K_p \) and \( K_w \) is supposed to be zero the optimal feedback gains can be straightforwardly computed using standard LQ theory (see also Fig. 3)

\[ K_p = \frac{1}{\sqrt{\lambda}} \]  

(9)

\[ K_d = \frac{1}{K} \left\{ \sqrt{\frac{1}{1 + \frac{K \tau}{\sqrt{\lambda}}}} - 1 \right\}. \]  

(10)

The integrating action \( K_i \), which should compensate for the slowly varying disturbance \( K_w \), can be

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**Fig. 2.** Course-changing manoeuvre.

**Fig. 3.** Course-keeping control system.
separately computed by simply taking the mean of the rudder angle necessary for zero rate of turn

$$K_i = \frac{1}{T} \int_0^\tau \delta \, dt$$

(11)

where $T$ is in the order of 100 s.

In the literature there is no consensus about the value of $\lambda$. Values suggested range from 0.1 to 10. Van Amerongen and Van Nauta Lemke (1980) suggest the following extremes

$$\lambda = 0.1$$

for accurate steering

$$\lambda = 4$$

for small ships in high sea states.

and

$$\lambda = 0.1$$

for large ships

$$\lambda = 4$$

for small ships in a calm sea

This choice is based, among other things, on observations made during full-scale trials, towing-tank experiments and the previously mentioned inquiry.

It has also been shown that optimization of criterion (7) does not suffice to reach maximum economy. The frequencies of the ship motions caused by waves are so high that it makes no sense to try to compensate them by rudder movements. The latter will only cause extra loss of speed and, especially when the level of the ‘noise’ caused by the waves is high, the rudder movements will enlarge the motions of the ship, rather than reduce them: the steering machine introduces a considerable phase lag for large and fast rudder movements.

The presently commonly applied dead band is not the right solution. It is essential that a low-pass filter be designed to remove the high-frequency noise from the rudder signal. Because the noise frequencies are not too far from the bandwidth of the system, the filter must be carefully designed in order to avoid introducing stability problems. For optimal performance the amount of filtering should also be adaptive with respect to the level of the noise.

For optimal course-keeping performance it is thus essential to design a noise-reduction filter and to optimize criterion (7). The only setting chosen to be provided to the operator is the choice between maximum accuracy and maximum economy. This setting influences the value of $\lambda$ and the amount of filtering. For maximum accuracy $\lambda$ is small and there is a minimum amount of filtering. For maximum economy $\lambda$ is large and, if necessary, the maximum amount of filtering is permitted. Corresponding to the foregoing $\lambda$ is also influenced by the level of the noise.

4. COURSE-CHANGING CONTROLLER

The knowledge of the previous sections about mathematical models and steering criteria enables us to design the controller. During course changing the optimal performance has been defined as a step response with constant slope (rate of turn control). A suitable structure for realizing such a response is given in Fig. 4 (De Keizer, 1976). The heading-control system itself is preceded by a series model which modifies the heading reference, generating the type of response in Fig. 2. The slope of this response, the rate of turn, can be adjusted by the user.

The control algorithm of the actual autopilot is given by (8). The series model is shown in the block diagram of Fig. 5. In this figure $\psi_m$ is the ‘heading’ of the series model, $\psi_r$ is the modified input signal for the course control loop, and $\psi_r$ and $\psi_f$ will be defined later. At this stage $\psi_f$ is set to one.

The time constant $\tau_m$ is chosen approximately 2–3 times smaller than the dominating time constant of the ship at cruising speed [$\tau_c$]. This choice results from the following consideration: a reasonable course controller will have a rate-feedback gain $K_r$, which makes the time constant of the ship 2–3 times smaller than was the case for the open system. By choosing a similar time constant for the series model this guarantees that the process can follow the model. $K_{pm}$ follows from the desired damping ratio of the system after the rate-of-turn limiter is neglected

$$K_{pm} = 1/(4z^2\tau_m).$$

When the actual heading control system is sufficiently tight the desired response will be realized. If the controller gains were not limited for reasons of stability, mainly due to the limited rudder speed, this could be achieved by selecting high controller gains. In practice, the controller gains should be carefully tuned to their maximum allowable values.

If the process parameters were constant and known this would not be a problem but when the circumstances change, this requires adjustment of the controller gains. When the influences of external variations on the process parameters are known this adjustment can be obtained by scheduling the controller gains. For example, to compensate for variations in the ship's speed, (2) and (3) may be used. However, this is only possible for a limited number of variables whose influence on the controller gains is well established. Other parameter variations can be dealt with by applying a second, parallel, reference model, according to Fig. 6.

A straightforward design of MRAS based on stability theory requires that process and parallel

![Fig. 4. Course-changing controller.](image-url)
reference model be linear and of the same order and structure. It has been shown by Van Amerongen, Nieuwenhuis and Udink ten Cate (1975) and by Johnson (1982) that for nonlinear ship’s dynamics a stable MRAS can also be designed. For practical application, however, the proposed algorithms are too sensitive for small structural differences between process and reference model.

Without special precautions it is impossible to meet these requirements of linearity. The ship’s dynamics themselves are nonlinear, but it has been shown (Van Amerongen, Nieuwenhuis and Udink ten Cate, 1975) that this is not a serious problem as long as simple adaptive algorithms are used. The major problems are introduced by the rudder limit (either as a controller parameter or as the absolute maximum of the rudder angle) and by the limited rudder speed. Because both nonlinearities are well known or easily measurable this problem can be circumvented by some minor modifications of the series model. When the series model only generates signals which saturate neither the rudder limiter nor the rudder-speed limiter, the influence of the steering machine has been removed from the inner control loop. This can be achieved as follows.

When the rudder limiter is known, the ratio between the maximum rudder angle $\delta_{\text{max}}$ and the desired rudder angle $\delta$ can be computed. When this ratio is smaller than 1 the factor $f$ in Fig. 5, which was earlier disregarded by setting it to the value 1, is replaced by

\[
f = \frac{\delta_{\text{max}}}{|\delta|} \quad (12)
\]

with $f \leq 1$. Similar measures can be taken to introduce the effects of the limited rudder speed into the series model. Suppose that the actual rudder angle is $\delta$ and the desired rudder angle is $\delta_i$. The time needed to move the rudder from $\delta$ to $\delta_i$ is then approximately

\[
\tau_\delta = \frac{|\delta - \delta_i|}{\delta_{\text{max}}} \quad (13)
\]

where $\delta_{\text{max}}$ is the maximum rudder speed. When the earlier defined factor $f$ of the series model is extended by a first-order transfer function

\[
H_\delta = \frac{1}{s \tau_\delta + 1} \quad (14)
\]

with variable time constant $\tau_\delta$ according to (13), the influence of the limited rudder speed is added to the series model as well.

The result of these measures is that there is in fact no more saturation of the steering machine: the process is thus linearized. This means that a linear parallel reference model of the same order and structure as (1) may be chosen. For the closed loop this yields the transfer function

\[
\frac{\psi_m}{\psi_i} = \frac{K_{pm}/\tau_m}{s^2 + s/\tau_m + K_{pm}/\tau_m} \quad (15)
\]

where $\psi_m$ is the ‘heading’ of the parallel reference model $K_{pm}$ and $\tau_m$ are chosen similarly to the series model. Note that $\psi_i$ is used as input signal.

Because the process is now linearized, the design of the adaptive controller is straightforward (Van Amerongen and Van Nauta Lemke, 1978, 1979; Landau, 1974, 1979). This yields the adjustment laws for the controller gains

\[
dK_p/dt = \beta(p_{12}e + p_{22}e)e \quad (16)
\]

\[
dK_d/dt = -\alpha(p_{12}e + p_{22}e)\dot{\psi} \quad (17)
\]

\[
dK_i/dt = \gamma(p_{12}e + p_{22}e) \quad (18)
\]
where $e$ is defined as

$$ e = \psi_m - \psi \quad (19) $$

and

$$ \dot{e} = \dot{\psi}_m - \dot{\psi} \quad (20) $$

$\alpha$, $\beta$, and $\gamma$ are 'arbitrary' positive constants and $p_{12}$ and $p_{22}$ are elements of the matrix $P$. $P$ can be solved from

$$ A_m^TP + PA_m = -Q \quad (21) $$

where $Q$ is an arbitrary positive definite matrix and $A_m$ is the system matrix of the reference model according to (15), the states of the reference model being defined as $x_1 = \psi_m$ and $x_2 = \dot{\psi}_m$. The stability of the overall system can be proved, for instance with Liapunov's stability theory.

By computing $K_i$ during course changing in an adaptive manner, according to (18), it is not necessary to stop the integration during course changing, which is common practice in conventional autopilots.

Because of the noise being present both on the signals, $\dot{\psi}, \dot{\psi}_2, e$, and $\dot{e}$, the adjustment laws according to (16) and (17) require that measures be taken to prevent the controller gains from drifting away (Van Amerongen and Van Nauta Lemke, 1978, 1979). In the present design the concept of decreasing adaptive gains has been applied and the adaptation is totally switched off a certain period of time after a setpoint change. Decreasing adaptive gains are obtained by dividing the adaptive gains $\alpha$ and $\beta$ by $(1 + T)$, where $T$ is the time after the last setpoint change.

5. COURSE-KEEPING CONTROLLER

Parameter estimation

It has been shown in Section 2 that optimal course keeping can be achieved by optimizing criterion (7) and filtering noisy signals. The optimization procedure requires the parameters $K_i$ and $\tau$ to be known. When scheduling of the gains does not suffice in view of the influence of changing load conditions, water depth, etc., an additional on-line identification procedure is required. For this purpose MRAS can be applied as well. This leads to the structure according to Fig. 7.

A simple first-order adjustable model is placed parallel with the transfer between $\delta$ and $\dot{\psi}_m$

$$ \tau_m \ddot{\psi}_m + \dot{\psi}_m = K_m(\delta - K_{i,m}) \quad (22) $$

where $K_{i,m}$ is the rudder off-set. Defining

$$ e = \dot{\psi}_m - \dot{\psi} \quad (23) $$

yields the simple adjustment laws

$$ \frac{d(K_m/\tau_m)}{dt} = -\beta e(\delta - K_{i,m}) \quad (24) $$

$$ \frac{d(1/\tau_m)}{dt} = \alpha e \dot{\psi}_m \quad (25) $$

$$ \frac{d(K_{i,m})}{dt} = -\gamma e. \quad (26) $$

In this case there are no problems with nonlinearities and biasing due to noise. Stability can again be proved by applying the theory of Liapunov. Instead of (26) equation (11) could be used to compute $K_{i,m}$, but it appears that best results are obtained with (26).

![Fig. 7. Basic structure for parameter identification.](image-url)
State estimation

Besides estimates of the process parameters the adjustable model also produces an estimate of the actual rate-of-turn signal. When the actual rate of turn signal is corrupted by `noise`, due to the influence of the waves, the estimate will be much smoother. The filtering problem is thus solved simultaneously. However, this filter is not the best possible one. When the level of the noise is low, it is not necessary to rely on the output of the adjustable model alone. The prediction may be updated, based upon the measurements. In order not to influence the identification process a second adjustable model is introduced whose parameters are adjusted simultaneously with the first model. The output of the second model is updated every sampling interval with the latest measurements. The weighting between prediction and measurements is determined by the relation between the low-frequency components of the error signal, which should not be filtered, and the high-frequency components which should be suppressed (Van Amerongen, 1982). This is not a straightforward Kalman filter because it does not distinguish between system noise and observation noise but between the low-frequency and high-frequency components of the system noise. Observation noise is supposed to be totally absent. The adaptive filter gains are computed on-line as follows: define

\[ e = \hat{\psi} - \psi \quad (27) \]

where \( \hat{\psi} \) is the output of the second adjustable model. By means of a low-pass filter, \( e \) is split into a low-frequency and a high-frequency component

\[ e_{lf} = \frac{1}{\tau_f + 1} e \quad (28) \]

\[ e_{hf} = e - e_{lf}. \quad (29) \]

Averaging yields the mean variances \( \sigma_{\hat{\psi}}^2 \) and \( \sigma_{hf}^2 \) of the low-frequency and high-frequency components of \( e \). A gain factor \( \zeta \) is now computed

\[ \zeta = \frac{\sigma_{\hat{\psi}}^2}{\sigma_{\hat{\psi}}^2 + \sigma_{hf}^2} \quad (30) \]

which is used to update the predictions. In discrete form this yields

\[ \hat{\psi}(k + 1/k + 1) = \hat{\psi}(k + 1/k) + \zeta [\psi(k + 1) - \hat{\psi}(k + 1/k)] T / \tau_m \quad (31) \]

where \( \hat{\psi}(k + 1/k) \) is the output of the adjustable model; \( \psi(k + 1/k + 1) \) is this output, updated with the measured value \( \psi(k + 1) \) at \( t = (k + 1) T \); \( T \) is the sampling interval; and \( \tau_m \) is the time constant of the adjustable model.

The upper limit of \( \zeta \) is 1, and the lower limit is influenced by the desired course-keeping accuracy. In a similar way estimates of the ship's heading can be obtained

\[ \hat{\psi}(k + 1/k) = \hat{\psi}(k/k) + \hat{\psi}(k + 1/k + 1) T \quad (32) \]

\[ \hat{\psi}(k + 1/k + 1) = \hat{\psi}(k + 1/k) + \xi [\psi(k + 1) - \hat{\psi}(k + 1/k)] T. \quad (33) \]

6. PRACTICAL RESULTS

Most of the algorithms given above were continuous time algorithms, which can easily be combined with the proposed gain scheduling. However, practical realization is more robust and simple by using a digital computer. Because the sampling time of the computer can be chosen small (0.25 s), compared with the system's bandwidth the continuous-time algorithms can be used unmodified in the digital computer (sampling frequency > 25 rad/s, closed-loop bandwidth <0.1 rad/s). The algorithms of the previous sections have been implemented in a digital computer in order to test the system under real-life conditions. A DECLA B 11/03 system with 28K words of memory, dual floppy disk and appropriate interfaces is used for control as well as data logging (Onkenhout, 1979). Up to 16 variables can be monitored on a graphical display unit and are stored on floppy disk for analysis afterwards. Full-scale tests on three different ships have been carried out, as well as experiments with a scale model in a towing tank. During these trials it had to be demonstrated whether the control algorithms which were derived for a simplified mathematical model also gave a satisfactory performance in practice.

In general, the adaptive autopilot, further referred to as ASA (from the Dutch: Adaptieve Stuur Automaat), showed the behaviour that might be expected from hybrid simulation experiments, which were carried out before the sea trials at the laboratory (Van Amerongen, 1982). Some modifications were necessary, however, mainly because the disturbances at sea differed from the disturbance models used in the simulation, leading to a low course-keeping accuracy. The values of \( \lambda \) suggested before result from these experiences. It was also necessary to use narrower bounds for the filter gains than previously expected.

Some typical results are given in the Figs 8–13. Figure 9 shows the course-changing performance under ASA control of H.NL.M.S. Tijdenman, the oceanographic survey vessel of the Royal Netherlands Navy (Fig. 8). The length of this ship is about 100 m. A standard series of course alterations is automatically carried out. In Fig. 9 the desired rate
Fig. 8. H.N.I.M.S. Tydeman (photograph courtesy of Royal Netherlands Navy).

Fig. 9. Course-changing performance of ASA.
of turn was set to 0.5 and 1.0 deg/s. The performance of the adaptive state estimator can also be judged from this figure.

A comparison between the course-keeping performance of ASA, a conventional autopilot and an experienced helmsman is shown in Fig. 10. It can clearly be seen that both autopilots are superior to the helmsman and that ASA performs better than the conventional autopilot. The rudder is most smooth when steering with ASA.

The performance criterion (crit) which is shown in Fig. 10 is the criterion (7) with $\lambda = 10$. Criterion (7) is only an approximation of the real criterion: minimum fuel consumption. Attempts have been made to measure the latter in a more direct way.

Because the instrumentation necessary to measure the propeller thrust was not available, only the mean speed with a constant number of revolutions could be measured. During 8 h a fixed heading was sailed and after every hour control was switched from ASA to the conventional autopilot and back. During these trials, with sea state 4 (corresponding with a wave height of about 3 m), the mean speed during control by ASA was about 0.5% higher than with conventional control. Similar experiments in another area, with a sea state 3 (wave height approximately 2 m) indicate an increased speed between 0.3 and 1.5% in favor of ASA, depending on the direction of the waves. In terms of fuel consumption the savings are even bigger if the increased performance is used to decrease the propeller thrust and to maintain a constant speed.

The increased speeds were mainly obtained due to the smoother rudder movements. This will also lead to less wear and tear of the steering equipment. Figure 11 gives an illustration of the frequency spectra of both autopilots. The spectra in this figure were obtained after fast fourier transformation of the heading, rate-of-turn and rudder signals. For ASA the estimated rate-of-turn signal is also transformed. Because this signal is very smooth, the rudder spectrum also contains fewer high frequencies during control by ASA.

Because the performance measurements are difficult at full scale, it was decided to carry out additional experiments in a towing tank (Van Amerongen and co-workers, 1980). By measuring not only the ship's mean speed, but also the propeller torque and its number of revolutions, a more accurate measure of the fuel consumption was obtained. A model of a ship of 180 m length was used and tested in different sea states, generated by wave generators. Controllers with high gains and controllers with low gains, both with and without the adaptive filter, were tested. The improved performance, due to filtering in terms of increased speed, was between 0.3 and 1.5% for the high-gain controllers and between 1.5 and 5.6% for the low-gain controllers. During the experiments only pure head seas and pure following seas could be generated. Additional experiments are necessary to investigate the performance with other wave angles and to compare the high-gain and low-gain controllers.

During experiments with H.Ni.M.S. Poolster, a

![Fig. 10. Course-keeping performances.](image-url)
This performance was not recorded during a special experiment, but it shows the normal use by the crew of the recently installed conventional autopilot. The conventional autopilot, which was adjusted for normal course keeping, was not re-adjusted before the RAS operation, where, due to the interaction of the other ships, a much tighter control is required. Because of the too-low accuracy the heading error became too large and the helmsman was ordered to take over the control. Although the heading error thereafter remained within the safety limits, the helmsman's control can also be qualified as poor. After defining 'RAS-settings' the conventional autopilot performed much better, as shown in Fig. 14. Control by ASA, easily adjusted for accurate steering, was a further improvement.

7. CONCLUSIONS

It has been shown that adaptive control enables the design of an autopilot with the following features: easier adjustment, course changing with predictable manoeuvres, and improved fuel economy. Full-scale experiments confirm the simulation results and demonstrate the practical usefulness of the autopilot designed.

The advanced filter algorithm, combining MRAS with the ideas of Kalman filtering, provides the major
contribution to improved fuel economy. During full-scale trials the speed increase has been shown to be 0.5–1.5%. When the reduced drag is used to reduce the thrust, this leads to fuel savings between 1 and 3%. During model tests, where the ship’s speed could be corrected for variations in the thrust, increased speeds up to 5% were demonstrated. The improved fuel economy is of growing importance because of the drastic increase of fuel prices since 1973.

In general, the users were enthusiastic about the features of the adaptive autopilot. In various cases the controlled rate-of-turn steering was purposefully used. During the experiments it was demonstrated several times that the users lack the insight and time to optimally adjust a conventional autopilot. All these features became practically realizable due to the availability of small and inexpensive digital hardware. Therefore, it may be expected that in the near future an increasing number of adaptive autopilots will be available on the market.

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