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Rudder Roll Stabilization for Ships*

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Advanced control algorithms using LQG and adaptive control techniques enable the design of an economically attractive alternative for conventional fin stabilizers and have proved to be robust during simulation experiments and full-scale trials.

Key Words—Adaptive control; automatic gain control; nonlinear control systems; optimal control; ship control; stabilizers.

Abstract—This paper describes the design of an autopilot for rudder roll stabilization for ships. This autopilot uses the rudder not only for course keeping but also for reduction of the roll. The system has a series of properties which make the controller design far from straightforward: the process has only one input (the rudder angle) and two outputs (the heading and the roll angle); the transfer from rudder to roll is non-minimum-phase; because large and high-frequency rudder motions are necessary, the non-linearities of the steering machine cannot be disregarded; the disturbances caused by the waves vary considerably in amplitude and frequency spectrum.

In order to solve these problems a new approach to the LQG method has been developed. The control algorithms were tested by means of computer simulations, scale-model experiments and full-scale trials at sea. The results indicate that a rudder roll stabilization system is able to reduce the roll as well as a conventional fin stabilization system, while it requires less investments. Based on the results obtained in this project the Royal Netherlands Navy has decided to implement rudder roll stabilization on a series of ships under construction at this moment.

1. INTRODUCTION

BESIDES CONTROL of the heading, on some ships (for instance on ferries and naval ships) reduction of the roll motions is also desired. An attractive solution is **R**udder **R**oll **S**tabilization (**RRS**) where the rudder alone is used for controlling the heading as well as reducing the roll. The idea of rudder roll stabilization is not completely new. Cowley and Lambert (1972, 1975), Carley (1975) and Lloyd (1975) described it before. However, their attempts never resulted in successful applications; probably because at that time appropriate control algorithms were not yet available. The first successful full-scale trials were reported by Baitis (1980) who used the rudder for automatic roll stabilization, while the heading control was still done manually by the helmsman. A system which simultaneously controls the heading and the roll of a ship is described in this paper. Earlier results of this project can be found in van Amerongen and van Cappelle (1981) and van Amerongen *et al.* (1983, 1984). This paper summarizes the results of this project, including some results which were published, in part, in several recent papers (van Amerongen *et al.* 1986*b*; 1987*a*, *b*). Recent experimental results with a system similar to that of Baitis (1980) are reported by Källström *et al.* (1988).

Section 2 describes the mathematical models which are necessary for the design of a controller as well as for the first simulations.

Section 3 describes the design of the controller. Because of its simplicity the method of "optimal" LQG control has been used, although there are a few problems. These can be solved by introducing adaptive weighting factors in the quadratic criterion, followed by on-line computation of the controller gains. This results in a controller which gives the maximum possible roll reduction in high sea states, while it switches itself off when the roll angles are so small that roll reduction is not wanted anymore. Besides, it guarantees that the course-keeping performance hardly deteriorates.

Section 4 describes the experiments. Com-

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puter simulations were carried out in an early stage of the project to test the possibilities of rudder roll stabilization. These simulations were followed by experiments with an 8 meter long scale model and by several series of full-scale trials at sea. The conclusions are summarized in Section 5, where suggestions for further research have also been given.

2. MATHEMATICAL MODELS

2.1. *The ship's dynamics*

The model which describes the transfer from rudder angle to heading and from rudder angle to roll can be derived from the hydrodynamical models which are used by shipbuilding engineers (van Amerongen and van Cappelle, 1981). In this paper the model of Fig. 1 (van der Klugt, 1987) will be used, where

δ = the rudder angle
φ = the roll angle
ψ = the heading or yaw angle
v' = the sway velocity, caused by the rudder
w_φ, w_ψ = coloured noise with non-zero mean
w_φ describes the influence of the disturbances on the roll moment
w_ψ describes the influence of the disturbances on the yaw moment.

The parameters of this model were found from a series of full-scale modeling trials. They depend on such things as the ship design and the speed of the ship. A relation between these parameters and the hydrodynamical models can also be found (van der Klugt, 1987).

2.2. *The disturbances*

The disturbances acting on a ship are due to the wind, the waves and the current. When the current is supposed to be steady, uniform and horizontal it does not play a role in the control system considered here.

Wind can be modeled as a stochastic signal with non-zero mean. Only the mean value of the wind disturbance will be taken into account. The stochastic variations could be added as a white noise signal. The non-zero mean causes a constant roll angle as well as a stationary heading error. Because the constant roll angle cannot adequately be compensated for by the rudder-roll stabilization system, the mean value of the measured roll angle is suppressed by an appropriate high-pass filter. Variations in the roll angle and the heading are mainly caused by the waves. Waves can be described by means of a frequency spectrum, for instance the Bretschneider spectrum (Bhattacharyya, 1978). This frequency spectrum can be simulated by a summation of a series of sinusoidal signals with appropriate amplitudes or by using a coloring filter driven by white noise. The following filter gives a good approximation:

$$H = \frac{Ks}{s^2 + 2z\omega_f s + \omega_f^2}. \tag{2.1}$$

The disturbances can be added to the model of the ship dynamics by means of the signals w_φ and w_ψ as indicated in Fig. 1.

2.3. *The steering machine*

For the purpose of designing a controller and for simulation of the system the steering machine is sufficiently accurately described by the block diagram of Fig. 2. The rudder angle is either limited by the mechanical constraints of the steering machine (in general the rudder angle is always smaller than 35°), or intentionally at a lower value. The maximum rudder speed is

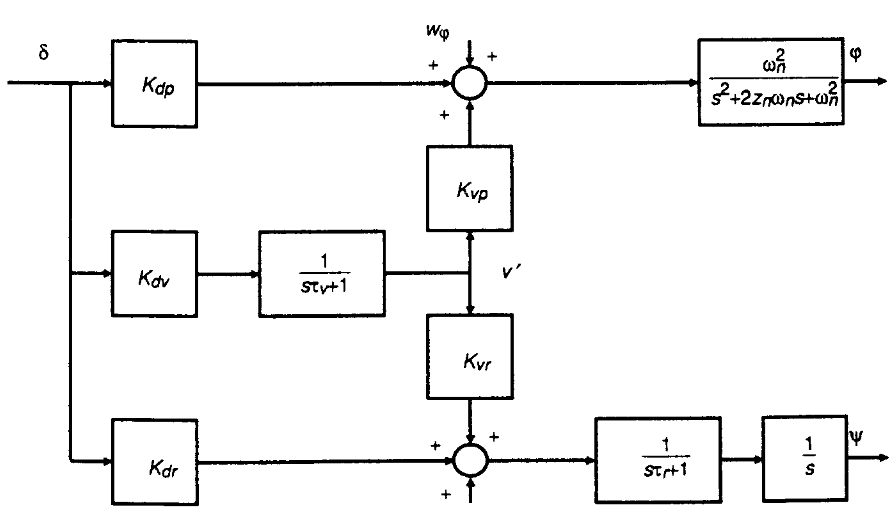

FIG. 1. Simplified dynamics between rudder and yaw and roll.

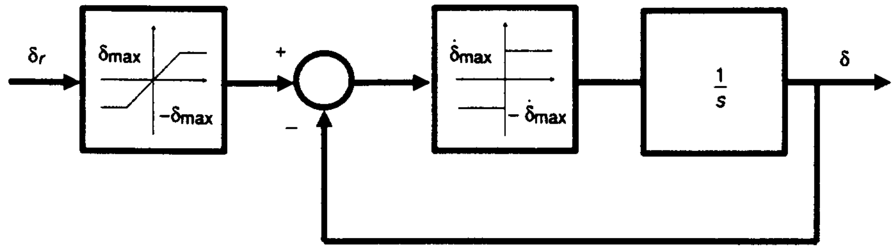

FIG. 2. The steering machine.

determined by the maximum capacity of the hydraulic pumps.

3. CONTROLLER DESIGN

The controller design will be done in two steps. First a controller will be designed for the system without a steering machine. The second step is to modify the controller in order to deal with the non-linear dynamics of the steering machine.

3.1. *The linearized system*

Let the process be described by the model of Fig. 1. A state-feedback controller for this process requires that the heading angle ψ, its derivative $d\psi/dt$, the roll angle φ, its derivative $d\varphi/dt$ and the signal v' be available to the controller. The heading angle and the roll angle can be measured with gyros. Their derivatives can be measured with rate-gyros or may be obtained from a state estimator. In general the signal v' can only be obtained from a state estimator. The system can be described by the following state-space equations:

$$\dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u} + D\mathbf{w} \tag{3.1}$$

where

$$\mathbf{x}^T = (\varphi,\ \dot{\varphi},\ v',\ \dot{\psi},\ \psi) \quad \text{and} \quad u = \delta.$$

A and B are described by

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ -\omega_n^2 & -2z_n\omega_n & \omega_n^2 k_{vp} & 0 & 0 \\ 0 & 0 & -1/\tau_v & 0 & 0 \\ 0 & 0 & k_{vr}/\tau_r & -1/\tau_r & 0 \\ 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

$$B = \begin{pmatrix} 0 \\ \omega_n^2 k_{dp} \\ k_{dv}/\tau_v \\ k_{dr}/\tau_r \\ 0 \end{pmatrix} \tag{3.2}$$

and

$$D = \begin{pmatrix} 0 & 0 & 0 & H_{wr}/\tau_r & 0 \\ 0 & H_{wp}\omega_n^2 & 0 & 0 & 0 \end{pmatrix}. \tag{3.3}$$

Application of the LQG method requires that a quadratic criterion be defined:

$$J = \lim_{T\to\infty} \frac{1}{T} \int_0^T (\mathbf{x}^T Q \mathbf{x} + \mathbf{u}^T R \mathbf{u})\, dt \tag{3.4}$$

where Q is a (semi-) positive-definite weighting matrix; R is a positive-definite weighting matrix.

A problem which remains is selection of the weighting factors in this criterion. This will be discussed later on in more detail. The feedback gains can be found by means of a computer program which solves the matrix Ricatti equations.

A model-reference adaptive state estimator (van Amerongen, 1984) is used to suppress high-frequency components in the heading and rate-of-turn signals. The low-frequency components of the roll angle are suppressed by means of an adaptive high-pass filter (van der Klugt, 1987). With this system large roll reductions can be obtained. However, the required rudder angles and rudder speeds are too large to be realistic. Therefore it is essential that the non-linearities of the steering machine be taken into account.

3.2. *The non-linear system*

The control system of Fig. 3 is considered.

The non-linear model of the steering machine has been given in Fig. 2. The maximum rudder angle limits the roll-reduction ability of the system directly. The limited rudder speed reduces the amplitude of the controller output, and introduces phase lag. This phase lag is not only a function of the frequency, but also of the amplitude of the controller signal. Even for small phase lags the performance of the system rapidly deteriorates and therefore it is essential that phase lag be prevented. Besides that the steering machine has to be redesigned in order to ensure higher rudder speeds, the controller must prevent the steering machine from saturating.

During this project three methods have been investigated to achieve this:

(1) Optimization of the controller gains by means of hillclimbing.

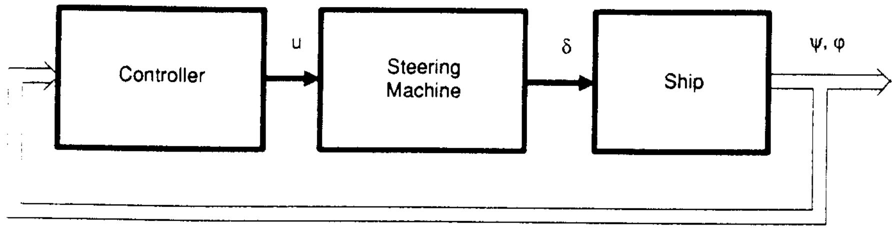

FIG. 3. The RRS-control system including the steering machine.

(2) Introduction of automatic gain control.
(3) Introduction of an adaptive criterion.

3.2.1. *Optimization by means of hillclimbing.* The system given in Fig. 3 has been simulated, using the simulation package PSI (van den Bosch, 1981). This package enables optimization of a system by means of a hillclimbing procedure. Its use is not restricted to linear systems nor to quadratic criteria. This makes it possible to use more appropriate criteria (van Amerongen *et al.*, 1984) and to take into account the non-linear steering machine dynamics.

This method has been used in the first stage of the project, to determine values of the maximum rudder speed, necessary for realizing the required roll reduction. The Rudder Roll Stabilization system was developed in parallel with the design of a new series of ships of the Royal Netherlands Navy. This made it possible to formulate demands for the ship design, with respect to the required rudder speed as well as with respect to the ship's dynamics.

Because of the non-linear nature of the problem it is not possible to find one set of controller parameters for all situations. But the method may be used to determine a gain-scheduling table, which contains the controller gains as a function of the amplitude and dominating frequency of the disturbances. This table can be used for manual adjustment of the controller during the experiments or, when estimates of the amplitude and frequency of the waves are available, for automatic gain scheduling. The problem which remains is to measure or estimate the amplitude and frequency of the disturbances during normal operation. A Kalman-filter type of observer was designed for this purpose. It gave good results in simulations but it did not perform satisfactorily during the full-scale trials. The results obtained with a controller designed with this method are given in the Sections 4.1–4.3.

3.2.2. *Introduction of automatic gain control.* The method described in Section 3.2.1 gives the best controller for each situation and for an arbitrary criterion. A disadvantage is that generation of the gain-scheduling table necessitates a lot of computations for each particular situation. In addition, the method does not guarantee that saturation of the rudder speed will be prevented.

It will be shown later that saturation of the rudder speed as well as saturation of the rudder angle can be prevented by changing the weighting factors of the criterion used for LQ-optimization. In order to achieve the maximum possible roll reduction in a changing environment, the weighting factors, and thus the controller gains should be continuously readjusted. Because this takes too long a time when high rudder speeds are suddenly demanded, another mechanism was developed. This mechanism reduces the output of the controller, automatically and instantaneously, as soon as the rate of change of the controller output is so large that this would cause saturation in the steering machine. The mechanism hardly affects the shape of the rudder signal and the introduced phase lag is kept to a minimum. When there is no further risk for saturation the gain is gradually increased until the standard value of 1 is reached again. The result of application of such a mechanism is in fact that the rudder speed limiter is removed from the control loop, and therefore its phase lag is no longer able to cause the performance of the system to deteriorate. This patented "Automatic Gain Controller" (AGC) has proven to be a robust and simple algorithm.

The AGC can be compared with the automatic gain control used in audio equipment. The latter prevents non-linear distortion by adjusting the gain of the amplifier. The difference is that the AGC prevents the rudder speed from becoming too large, rather than the rudder angle.

The AGC can be explained with the aid of Fig. 4, where

u = the controller output
δ = the setpoint of the rudder
$\dot{\delta}_{max}$ = the maximum rudder rate
y = the maximum of three signals:
(1) the maximum rudder rate
(2) the absolute value of the derivative of u
(3) the output of a memory function

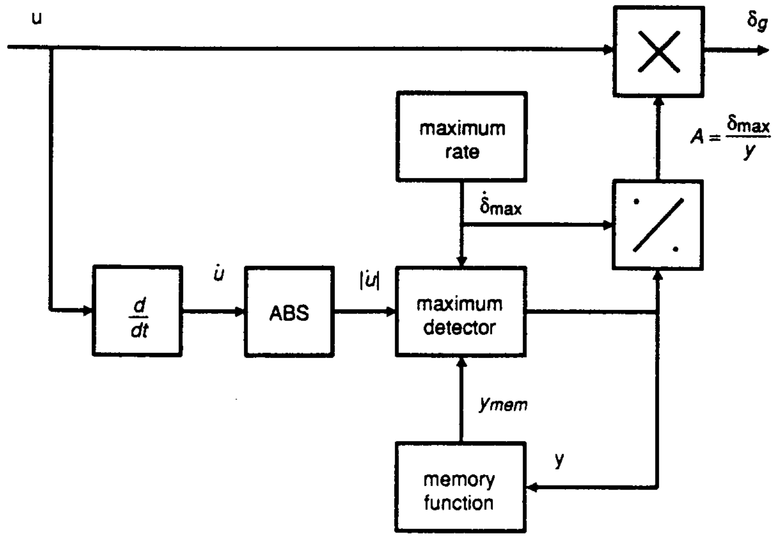

FIG. 4. The Automatic Gain Controller.

A = The gain needed to adjust the controller output
$(0 < A \leq 1)$
$= \dot{\delta}_{max}/y$.

The automatic gain control is achieved by multiplying the controller output u with a factor A ($A \leq 1$) such that:

$$\delta_g = Au$$

with

$$A = \frac{\dot{\delta}_{max}}{y}.$$

When the memory function is disregarded, y is the maximum of two signals: $\dot{\delta}_{max}$ and $|du/dt|$:

$$y = \dot{\delta}_{max} \quad \text{if } \dot{\delta}_{max} \geq \left|\frac{du}{dt}\right|$$

$$y = \left|\frac{du}{dt}\right| \quad \text{if } \dot{\delta}_{max} < \left|\frac{du}{dt}\right|$$

where du/dt is the rudder speed demanded by the controller, computed by numerical differentiation of u.

This mechanism, without the memory function, takes care that δ_g is reduced as long as $|du/dt| > \dot{\delta}_{max}$. Without further measures the shape of the rudder signal would still be distorted and phase lag would be introduced. This can be improved by introducing the memory function. When y no longer increases, the output of the memory function gradually decreases:

$$y_{mem}(k) = \alpha y_{mem}(k-1)$$

where α is a constant close to 1 ($\alpha < 1$) which determines the rate of change of y_{mem}. As long as:

$$y_{mem} > \dot{\delta}_{max} \quad \text{and} \quad y_{mem} > \left|\frac{du}{dt}\right|$$

the maximum selector makes

$$y = y_{mem}$$

and thus:

$$y(k) = \alpha y(k-1).$$

This implies that when the absolute value of du/dt is no longer too large, the memory function takes care for a slow increase of A. This memory function is the major reason that the phase lag introduced by the steering machine is reduced to a minimum.

The performance of the AGC can be judged from Fig. 5. A sinusoidal signal with increasing amplitude forms the input u. Without the AGC the rudder angle δ_w shows the typical triangular shape caused by the rate limiter. With the AGC δ_w remains a sinusoidal signal, with a constant maximum amplitude. The smaller phase lag when the AGC is applied is clearly visible in this figure.

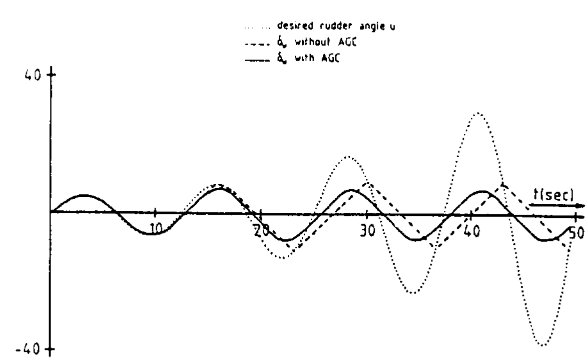

FIG. 5. Influence of the AGCC with increasing controller output u.

Although the AGC is able to solve the problem of the limited rudder speed in a robust way, it does not realize an optimum controller. Its effect on the controller can be expressed as a reduction of all the feedback gains simultaneously and with the same rate. This is not necessarily an optimum solution.

3.3. *Adaptive LQG-method*

3.3.1. *Introduction of an adaptive criterion.* Because optimization of the controller gains with the aid of a gain-scheduling mechanism did not give good results in practice, another adaptation mechanism had to be sought. In addition, the AGC is primarily a safety mechanism which may yield a non-optimal controller.

In this section the idea of an "Adaptive Criterion" combined with the LQG approach will be introduced. This method will be further referred to as Adaptive LQG, or ALQG. It enables the definition of criteria which are more appropriate for a particular problem than the otherwise necessary, quadratic criteria.

Let a process, described by the following state-space equations, be given by:

$$\begin{aligned} \dot{\mathbf{x}} &= A\mathbf{x} + B\mathbf{u} + D\mathbf{w} \\ \mathbf{y} &= C\mathbf{x}. \end{aligned} \tag{3.5}$$

Without loss of generality for the method mentioned below it is assumed that $\mathbf{w}$ denotes white noise with a zero mean.

If the process is time invariant, the "optimal" controller, with respect to criterion (3.4), can be calculated off-line (see for instance Kwakernaak and Sivan, 1972):

$$\mathbf{u} = -K\mathbf{x} \tag{3.6}$$

where the feedback gains K may be computed from the steady-state solution of the Ricatti equation:

$$\begin{aligned} K &= R^{-1}B^TP \\ 0 &= A^TP + PA + C^TQC - PBK. \end{aligned} \tag{3.7}$$

When the parameters of the process (A, B, C and D), or the weighting factors (Q and R) change, new optimal controller gains have to be computed. Van Amerongen *et al.* (1986a) propose a robust real-time method to calculate the optimal controller. It is based on the translation of equation (3.7) to the non-linear "innovation process" (3.8) which has as inputs u_m the weighting factors of criterion (3.4). This method can be used to compute the controller gains when the process parameters or the weighting factors in the criterion vary slowly:

$$\begin{aligned} \dot{x}_m &= A_m x_m + B_m u_m \\ y_m &= C_m x_m \end{aligned} \tag{3.8}$$

where

$$\begin{aligned} &\dot{x}_m && \leftrightarrow \dot{P} \\ &A^TP + PA - PBK && \leftrightarrow A_m x_m \\ &C^TQC && \leftrightarrow B_m u_m \\ &R^{-1}B^TP && \leftrightarrow C_m x_m. \end{aligned}$$

On-line simulation by means of numerical integration yields, as outputs (y_m) of the innovation process, the optimal controller gains, K.

When the process parameters are known by on-line parameter identification or by gain scheduling (for instance, as a function of the ship's speed) the proposed mechanism takes care of the adaptive controller adjustment.

But also changing the weighting factors of the criterion, for instance if the steering machine is saturating, will gradually result in another "optimal" controller. By multiplying each element of dx_m/dt with a scaling factor l_i, the rate of convergence of this innovation process (and thus the speed of adaptation) can be controlled.

3.3.2. *Adaptation of the criterion.* The word "optimal" in relation to the LQG method is more an indication for the method than a guarantee of optimum performance. This is even more true when an adaptive criterion is used. Apparently, there is a criterion behind the quadratic criterion which really defines the optimum performance. Van Amerongen *et al.* (1986a) describe a suitable adjustment mechanism for various types of non-linear elements, such as a dead band, a limiter and a rate limiter. The latter is most relevant for rudder roll stabilization.

In practice, it is not possible to solve this problem with a single linear controller. A controller which gives satisfactory results for small roll angles, may give no roll reduction when the roll angles are large, in rough weather. Furthermore, the operational requirements may change; a ship's operator may want to have as much roll reduction as possible even if that introduces larger heading deviations, or he may be satisfied if the heading error and roll angle stay below a certain limit. This indicates that it is not possible to define one criterion which covers all conditions to be met in practice. The criterion has to change with the conditions. Furthermore, it should be possible for the operator to easily change the criterion based on the operational demands. The desired performance of the rudder roll stabilization system can be defined as a series of demands:

Demand 1. The roll angle is not allowed to exceed a certain value, set by the ship's operator.

Demand 2. The demanded rudder speed is not allowed to be larger than the limitation posed by the steering machine.

The Automatic Gain Controller described in Section 3.2.2 prevents the system's performance from deteriorating if this constraint is temporarily not met. This mechanism does not give the solution to the actual problem, i.e. the controller is based on a wrong criterion; however it does allow some time for a slower mechanism to solve that problem.

Demand 3. Under some conditions roll stabilization by the rudder might increase the heading deviations. If these deviations reach a certain limit (set by the ship's operator) more weight should be given to a good course-keeping performance.

Demand 4. If the roll remains below a certain limit (set by the ship's operator) less weight should be given to roll reduction in order to reduce the wear and tear of the steering machine.

Demand 5. The controller design, indicated in Section 3.2.3, will result in a stable system. However, due to non-linear and unmodeled dynamics, problems may occur. Therefore, to avoid stability problems, the controller parameters are not allowed to become too large.

Demand 6. The adjustment of the controller parameters should be slow enough to follow only weather changes.

For given disturbance conditions, sufficient knowledge is available (whether *a priori* or from meaurements) to derive a proper criterion. Only if the disturbance conditions change is criterion adjustment necessary.

If a ship is considered with the rudder as its only actuator criterion 3.4 may be rewritten as

$$J = (q_\varphi J_\varphi + J_\psi) \tag{3.9}$$

where

$$J_\varphi = \sum_{i=1}^{3} q_i E[y_i \cdot y_i] + E[\delta_\varphi \delta_\varphi] \tag{3.10}$$

describes the influence of the roll motions on the criterion while J_ψ is selected to be similar to the course-keeping criterion, given by van Amerongen (1984).

δ_φ indicates the components of the rudder angle needed for roll reduction.

q_i corresponds to the elements of the weighting matrix Q in criterion (3.4).

$$y_i^T = (\varphi, \dot{\varphi}, v').$$

Further simplification is obtained by choosing fixed values for the weighting parameters q_i. Therefore, it remains only necessary to choose the weighting parameter q_φ depending on the weather conditions. With q_φ it is possible to exchange the roll reduction against the course-keeping performance.

The above-mentioned demands can easily be translated into a rate of change Δ_q of the weighting parameter q_φ. The resulting rate of change Δ_q of parameter q_φ, incorporating the demands which were mentioned above, is chosen to be:

$$\Delta_q = \Delta_{q1} + \Delta_{q2} + \Delta_{q3} + \cdots. \tag{3.11}$$

For some of the demands the adjustment of Δq_i is illustrated in Fig. 6.

In this figure the following holds:

Δ_{qi} = the rate of change of weighting parameter q_φ with respect to demand i

$\dot{\delta}_g$ = the demanded rudder speed

$\dot{\delta}_{max}$ = the maximum rudder speed

σ_φ^2 = the variance of the roll angle φ

$\sigma_{\varphi g}^2$ = the allowed variance of the roll angle

σ_ψ^2 = the variance of the heading deviations ψ

$\sigma_{\psi g}^2$ = the allowed variance of the heading deviations

$q_{\varphi g}$ = the maximum allowable value of q_φ.

The weighting parameters q_φ will be adjusted according to:

$$q_\varphi = q_0 + a \int \Delta_q \, dt \tag{3.12}$$

where "a" is a parameter which is introduced to determine the speed of the adaptation.

The weighting parameters q_φ and q_i are used as the input variables of the "innovation" process mentioned in Section 3.2. The outputs of this process approach the desired controller parameters. If the weather conditions change slowly, compared to the convergence speed of the "innovation" process, the resulting controller will be optimal with respect to the demands stated above.

The results obtained with this method are described in Sections 4.4–4.5.

The proposed method of translating operational requirements into a criterion function is related to the theory of fuzzy sets (see for instance van Amerongen *et al.*, 1977). This theory might offer some better tools for such a translation.

4. EXPERIMENTAL RESULTS

4.1. *Simulation*

In an early stage of the project, the controllers designed by the hill-climbing optimization, described in Section 3.2.1 where tested during

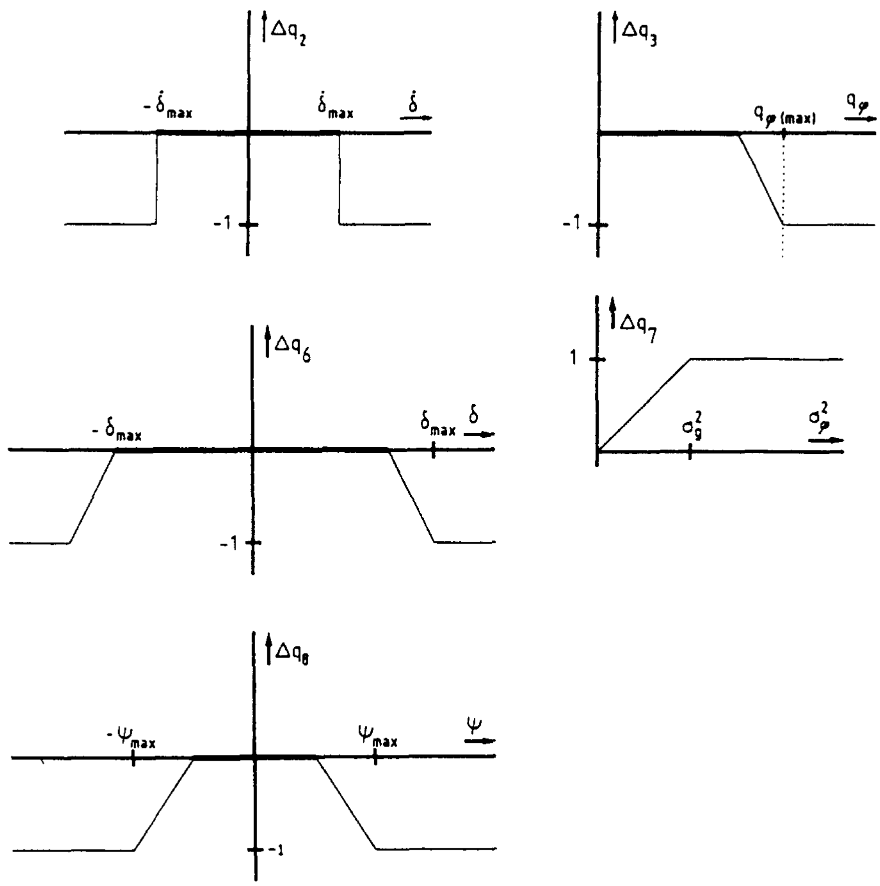

FIG. 6. The controller design demands.

extensive computer simulations. Besides simulations with the model according to Fig. 1, a series of simulations were carried out with a more extensive model available at the computer of the Maritime Research Institute in the Netherlands (MARIN).

The MARIN model is based on a hydrodynamical approach and describes other ship motions as well. During these simulations the controller itself was implemented in a second computer. Both computers were coupled by AD- and DA-converters, in order to simulate as realistic a situation as possible. The main purpose of these experiments was to determine the required rudder speed for a rudder roll stabilization system as well as to do a sensitivity analysis for variations in the controller gains. It could be concluded that for the naval ship simulated during the experiments, a rudder speed of 15 deg s^{-1} would be appropriate (van Amerongen *et al.* 1984). This rudder speed is considerably higher than the usual rudder speeds. The latter are in the range 3–7 deg s^{-1}. Based on this result the ship's designers could select an appropriate steering machine.

In addition, the sensitivity analysis showed that it is important that the controller gains are not selected too large as this leads to saturation of the rudder-speed limiter. This causes deterioration not only of the roll reduction, but also of the course-keeping performance. Large, low-frequency heading deviations are observed in this situation.

4.2. *Scale-model experiments*

After the simulation experiments a series of trials with an 8 meter long scale were carried out. Because of the length of the model and the duration of each run it was not possible to carry out the experiments in a towing tank. A suitable location for the trials seemed to be in the Harvingvliet, a former sea arm in the South West of the Netherlands; the distance from shore to shore was 3 km, while a measurement post of the Royal Netherlands Navy was available to install the equipment. Furthermore, the waves were expected to represent sea waves with respect to the model.

The model was propelled by a diesel engine and equipped with gyros and a speed log in order to measure yaw, yaw rate, roll, roll rate and the ship's speed. Radio communications channels were used to send these data to the shore where the computer with the autopilot was installed. The desired rudder angle as well as the signals used to control the diesel engine were

FIG. 7. Impression of the scale model.

transmitted from the shore to the ship. The photos of Fig. 7 give an impression of the model.

The trials lasted 7 days. The constantly changing weather conditions made it difficult to obtain good results and to verify the earlier simulation results. Only at the end of the series of experiments could roll reductions be demonstrated. However, the trials were still very useful. The main benefit of the trials was that several realistic situations which were not foreseen during the simulations were encountered. The steering problems related to these situations were recognized and had to be solved by modifications or extensions of the controller algorithms. This resulted in the research towards the Automatic Gain Controller.

4.3. *Full scale trials*

The controller, extended with the AGC was tested in several series of full-scale trials. These trials have been described extensively by van Amerongen *et al.* (1984). The AGC mechanism appeared to contribute a great deal to the success of these trials. During the first series of trials the parameters of the state feedback controller were adjusted manually, based on an off-line optimization procedure (hill-climbing). Because the ship which was used had a rudder

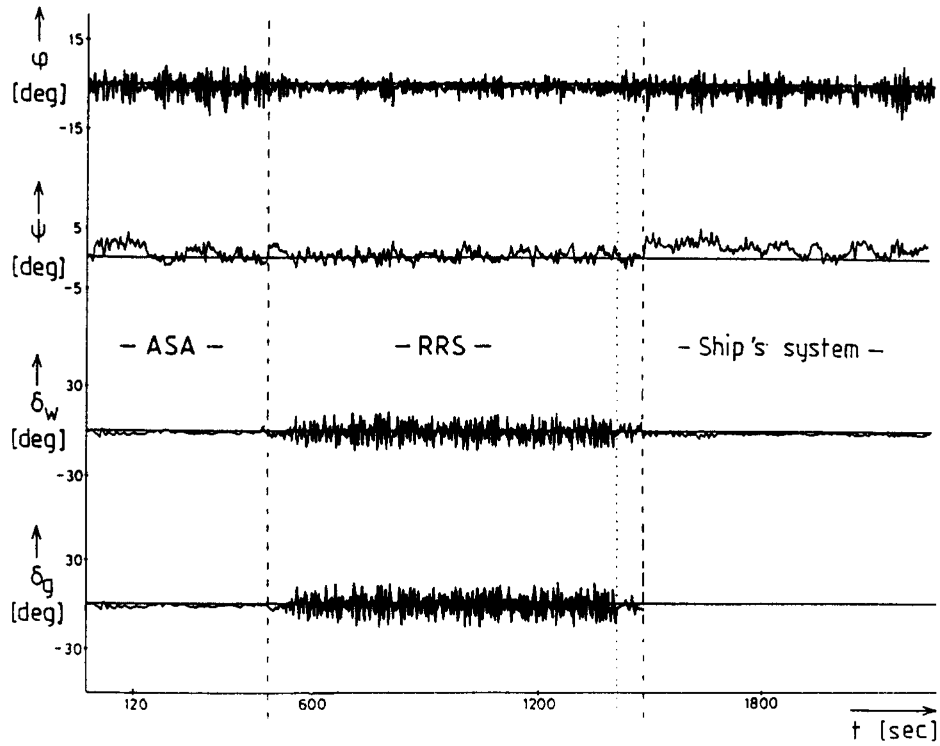

FIG. 8. Rudder Roll Stabilization during full-scale trials.

speed of only 7 deg s^{-1}, the achievable roll reduction was limited. A typical example of these trials is given in Fig. 8.

The Rudder Roll Stabilization autopilot (RRS) is compared with an adaptive autopilot (ASA) and with the ship's standard autopilot. The roll angle (φ), the heading error (ψ) and the actual and desired rudder angle (δ_w and δ_g) are shown. Even with this "slow" rudder, the roll reduction is clearly visible, while the variance of the heading error does not increase when rudder roll reduction is applied. By comparing the results of the full-scale trials with those of the simulations, it may be concluded that the roll reduction with a rudder 15 deg s^{-1} will be at least as good as the reduction which can be obtained with the present fin stabilizer system.

4.4. *Simulations with the adaptive LQG method*

The performance of this method will be illustrated with some simulations. The following conditions were simulated:

—the wave spectrum is chosen such that roll angles of about 10 degrees occur if no roll stabilization is applied. The angle of incidence of the waves is 90 degrees.

—The following criterion is used:

$$J = \lim_{T\to\infty} \frac{\lambda}{T} \int_0^T (q_\varphi(\varphi^2 + \dot{\varphi}^2/\omega_n^2) + \psi^2/\lambda + \delta^2)\, dt \qquad (4.1)$$

where

$\lambda = 0.5$

ω_n = the natural roll frequency of the ship

—the maximum rudder speed = 15 deg s^{-1}
the maximum rudder angle = 22 deg
the ship's speed = 20 knots.

Figure 9 compares a ship with roll stabilization (solid lines) and the same ship without roll stabilization. Figure 10 shows the fluctuations of the controller parameters during this simulation. After approximately 20 s the controller gains K_3,

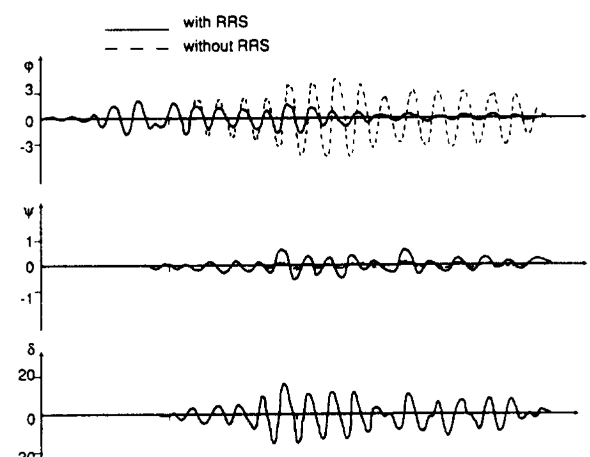

FIG. 9. Roll reduction with the adaptive criterion (rudder 15 deg s^{-1}).

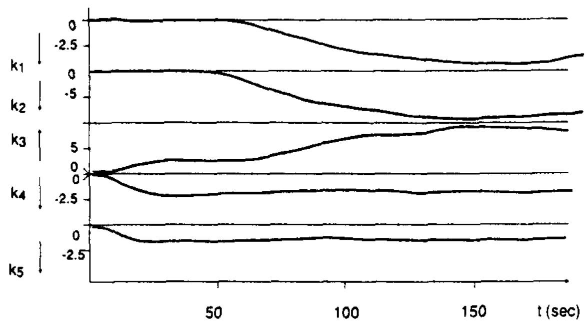

FIG. 10. Adaptation of the controller parameters.

K_4 and K_5 (feedback of v', ψ and $\dot{\psi}$) reach the desired value. After approximately 30 s it is detected that roll reduction is needed; the criterion is adjusted, resulting in a change of the controller gains K_1, K_2 and K_3 (feedback of φ, $\dot{\varphi}$ and v').

Figure 9 clearly demonstrates the roll reduction. The course deviations remain small. When the disturbances would be much larger or when the rudder would be much slower, the controller should be adjusted. This is demonstrated with Fig. 11 where the experiment of Fig. 9 is repeated, for a rudder with a maximum rudder speed of 5 deg s^{-1}. A rudder speed as low as this normally results in a system which, without precautions, is highly non-linear, even in low sea-state conditions. The performance of the Adaptive LQG method can therefore be demonstrated by simulating the rudder of 5 deg s^{-1}. In the first experiment the controller parameters were kept on the values which were optimal for a rudder of 15 deg s^{-1}. Instead of being reduced, the roll angles increase, just as the course deviations do. In a second experiment under the same conditions the adaptation of the

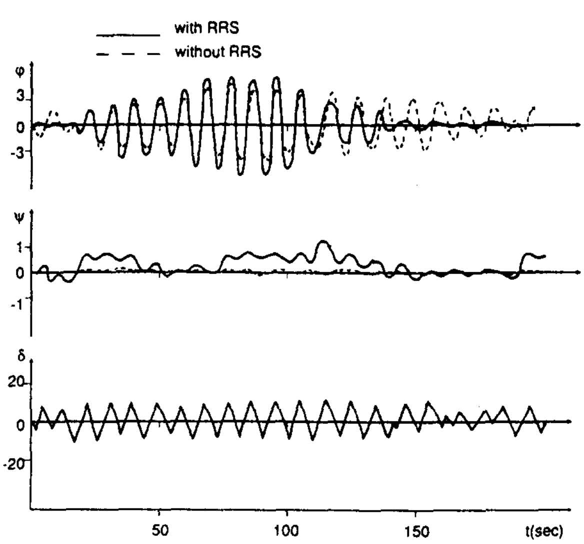

FIG. 11. Performance with a fixed controller (rudder 5 deg s^{-1}, controller adjusted for a rudder of 15 deg s^{-1}).

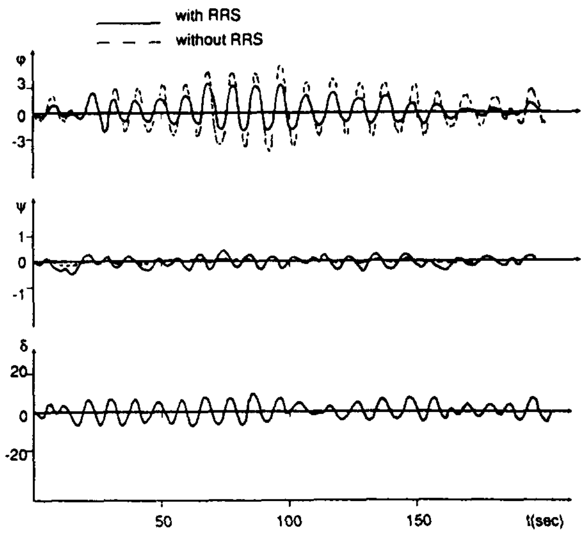

FIG. 12. Performance with the adaptive criterion (rudder 5 deg s^{-1}).

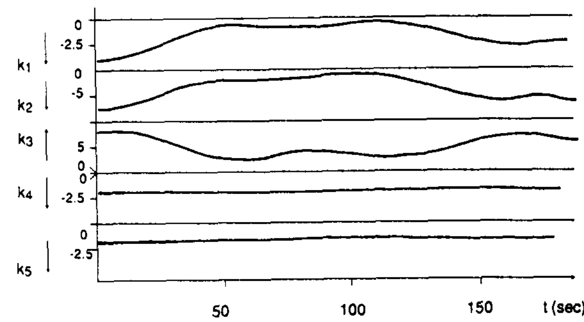

FIG. 13. Adaptation of the controller parameters.

criterion is switched on again. Figure 12 demonstrates that in this case roll reduction is possible, although with lower controller gains and of course with less reduction, especially for the larger roll angles. The controller parameters belonging to Fig. 12 are shown in Fig. 13.

No manual adjustments of the controller were made when the rudder speed changed from 15 to 5 deg s^{-1}. This demonstrates the robustness of the method. Neither is it very sensitive to variations in the parameters of the mathematical model. However, whether the performance can be improved by on-line estimation of the process parameters is still being investigated.

4.5. *Full-scale trials with the adaptive LQG method*

Due to unfavorable weather conditions, the adaptive controller could not yet be fully tested in rough weather conditions at sea. The experiments which were possible showed a good correspondence with the simulation experiments. The experiments with an extensive hydrodynamical model, similar to those described above, indicate that the performance of the adaptive controller is close to the performance of the optimally and manually adjusted controller which was tested at sea. The latter required careful tuning, while the adaptive controller requires no manual adjustments to compensate for a changing environment.

5. CONCLUSIONS AND SUGGESTIONS

Linear control techniques are no longer applicable when saturation type of non-linearities are dominating the behaviour of the process. This paper demonstrates the applicability of various new control algorithms. They can be used to control non-linear processes, based on easy-to-define operational demands, rather than using a quadratic criterion. These methods were developed in order to realize an autopilot for rudder roll stabilization of ships.

The Automatic Gain Control algorithm prevents the rate of change of the actuator input from becoming too large. Full-scale experiments with this algorithm have demonstrated its usefulness and robustness. Because it reduces all controller gains simultaneously, the resulting controller will not be an optimal controller. It should only be applied as a safety mechanism.

The adaptive adjustment of the weighting factors of the criterion in combination with the on-line calculation of the "optimal" controller solves this problem. The adaptation mechanism is based on a series of simple rules, which translate the operational demands into the weighting factors themselves.

Simulation results have demonstrated that this method is robust against variations of the characteristics of the disturbances and of the process parameters, including variations in the non-linearity.

During the experiments with the ALQG method it was assumed that the parameters of the process were known. (The influence of variations of the ship speed on these parameters was taken into account by a gain scheduling table.) Large variations in these parameters were made in order to determine the sensitivity of these variations. Although no serious problems were encountered, the addition of an on-line parameter estimator may improve the performance.

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