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ADAPTIVE CONTROL ASPECTS OF A RUDDER ROLL STABILIZATION SYSTEM

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Abstract. This paper gives a survey of the design of an autopilot for rudder roll stabilization for ships which 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 nonlinearities 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 computer simulations, scale-model experiments and full-scale trials at sea have been carried out. Besides, a new approach to the LQG method has been developed. The results obtained so far, 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.

Keywords. *Adaptive Control, Optimal Control, Non-linear Systems, Stabilizers, Ships.*

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 **Rudder Roll Stabilization (RRS)** where the rudder alone is used for controlling the heading as well as reducing the roll.
The idea of rudder roll stablization 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), Van Amerongen, Van der Klugt and Van Nauta Lemke (1983) and Van Amerongen, Van der Klugt and Pieffers (1984). A comparison of various roll stabilization systems has been described by Källström (1981).

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.
Furthermore, Section 3 describes the computer simulations which 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 4, where also suggestions for further research have 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 figure 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 = white noise with non-zero mean
$H_{w\varphi}$ describes the influence of the disturbances on the roll moment
$H_{w\psi}$ 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, amongst others, on the ship design and the speed of the ship. A relation between these parameters and the hydrodynamical models can also be found.

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 doesnot 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

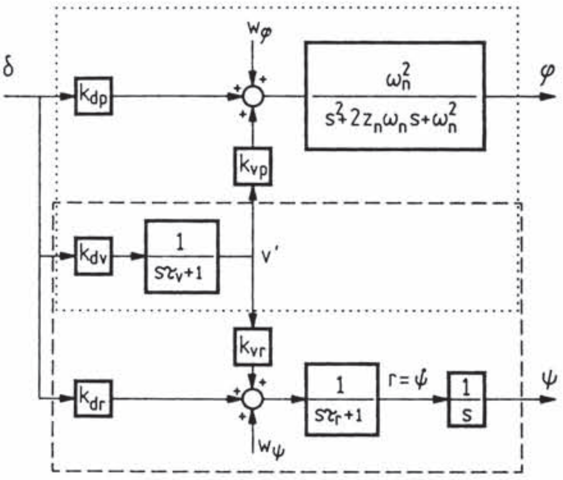

Fig. 1. Simplified dynamics between rudder and yaw and roll

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 filters $H_{w\varphi}$ and $H_{w\psi}$ as indicated in figure 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 figure 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 degrees), or intentionally at a lower value. The maximum rudder speed is determined by the maximum capacity of the hydraulic pumps.

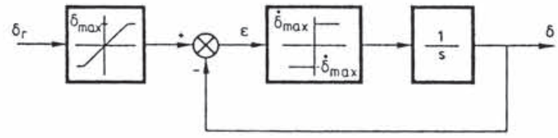

Figure 2 The steering machine

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 figure 1. A state-feedback controller for this process requires that the heading angle ψ, its derivative dψ/dt, the roll angle ψ, its derivative dφ/dt and the signal v' be available to the controller. The heading angle and the roll angle can be measured with gyro's. Their derivatives can be measured with rate-gyro's 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:

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

where

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

A and B are described by

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -\omega_n^2 & -2z_n\omega_n & \omega_n^2 k_{vp} & 0 & 0 \\ 0 & 0 & -1/\tau_v & 0 & 0 \\ 0 & 0 & k_{vr}/\tau_r & -1/\tau_r & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ \omega_n^2 k_{dp} \\ k_{dv}/\tau_v \\ k_{dr}/\tau_r \\ 0 \end{bmatrix} \tag{3.2}$$

and

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

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

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

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 more into 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 figure 3 is considered.
The non-linear model of the steering machine has been given in figure 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.
2. Introduction of automatic gain control.
3. Introduction of an adaptive criterion.

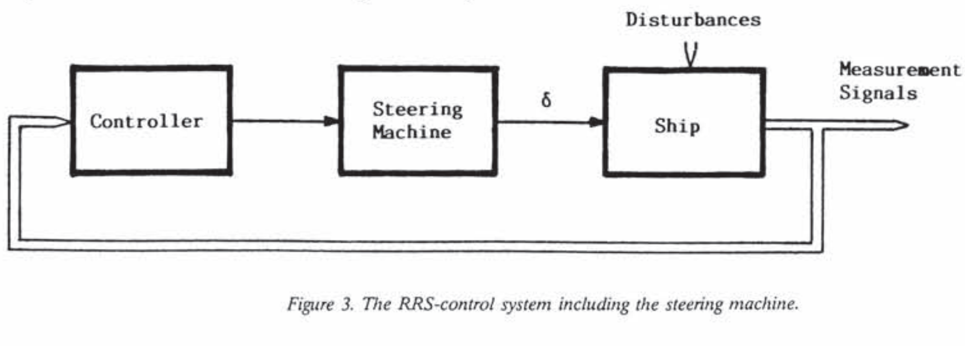

Figure 3. The RRS-control system including the steering machine.

3.2.1 Optimization of the controller gains by means of hillclimbing

The system given in figure 3 has been simulated, using the simulation package PSI (Van den Bosch, 1981). This package enables optimization of a system by means of an hillclimbing procedure. It's use is not restricted to linear systems nor to quadratic criteria. This makes it possible to use more appropriate criteria (Van Amerongen, Van der Klugt and Pieffers, 1984) and to take into account the non-linear steering machine 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 program 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. The problem which remains is to measure or estimate the amplitude and frequency of the disturbances during normal operation, because these quantities form the base for the gain scheduling.

This method has also been used to determine values of the maximum rudder speed, necessary for realizing the required roll reduction with a rudder roll stabilization system.

Simulations

The controller described, has been tested during extensive computer simulations. Besides simulations with the model according to figure 1, a series of simulations has been carried out with a more extensive model available at the computer of the Maritime Reasearch 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 a realistic situation as much as possible. 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 would be appropriate (Van Amerongen, Van der Klugt and Pieffers, 1984).

Scale-model experiments

After the simulation experiments a series of trials with an 8 meter long scale model has been carried out at the Haringvliet, a former sea arm in the South West of the Netherlands (Van Amerongen, Van der Klugt and Pieffers, 1984).

The main benefit of these trials was that several realistic situations were encountered which were not foreseen during the simulations. One of these was the constant roll angle, as a result of the wind force. It also became clear that even with a fast steering machine, saturation cannot be completely prevented. The steering problems related to these situations were recognized and had to be solved by modifications or extensions of the controller algorithms. The problem of the saturation of the steering machine will be further discussed in the next section.

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 however, that it necessitates a lot of computations for each particular situation and that it doesnot guarantee that saturation of the rudder speed be prevented. A better solution is offered by a mechanism which 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. When there is no further risk for saturation the gain is gradually increased until the 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 not able anymore to deteriorate the performance of the system. A patent is pending for such a mechanism (the "Automatic Gain Controller" (AGC)) which has proven to be a robust and simple algorithm.

The controller, extended with the AGC has been tested in several series of full-scale trials. These trials have been described extensively in Van Amerongen, Van der Klugt and Pieffers (1984). From the results it may be concluded that the roll reduction with a rudder of 15 degrees per second will be at least as good as the reduction which can be obtained with the present fin-stabilizer system.

3.2.3. Introduction of an adaptive criterion

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. Therefore, the idea of an "Adaptive Criterion" combined with the LQG approach is 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:

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

Without loss of generality for the method mentioned below it is assumed that $\underline{w}$ 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):

$$\underline{u} = -K\underline{x} \tag{3.5}$$

where

$$\begin{aligned} K &= R^{-1}B^{T}P \\ 0 &= A^{T}P + PA + C^{T}QC - PBK \end{aligned} \tag{3.6}$$

Van Amerongen, Van der Klugt and Van Nauta Lemke (1986) propose a robust real-time method to calculate the optimal controller. It is based on the translation of Eqs. (3.6) to the non-linear "innovation process" (3.7) which has as inputs u_m the weighting factors of criterion (3.4). The equations can be used to compute the controller gains when the process parameters vary slowly.

$$\begin{aligned} \dot{\underline{x}}_m &= A_m\underline{x}_m + B_m\underline{u}_m \\ \underline{y}_m &= C_m\underline{x}_m \end{aligned} \tag{3.7}$$

On-line simulation by means of numerical integration yields, as outputs ($\underline{y}_m$) of the innovation process, the optimal controller gains, K. Therefore, on-line changing the weighting factors of the criterion, for instance if the steering machine is saturating, will result in another "optimal" controller. By multiplying each element of $d\underline{x}_m/dt$ with a scaling factor l_i, the rate of convergence of this innovation process can be controlled.

3.3 Adaptation of the criterion.

The word "optimal" in relation with the LQG method is more an indication for the method than a guarantee for 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, Van der Klugt and Van Nauta Lemke (1986) 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 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 measurements) 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

$$J = \lambda(q_\varphi J_\varphi + J_\psi) \tag{3.8}$$

where

$$J_\varphi = \sum_{i=k}^{3} q_k E[y_k \cdot y_k] \tag{3.9}$$

describes the influence of the roll motions on the criterion while J is selected to be similar to the course-keeping criterion, given by Van Amerongen (1984). Further simplification is obtained by choosing fixed values for the weighting parameters q_k. Therefore, it remains only necessary to choose the weighting parameter q_φ depending on the weather conditions.

The above-mentioned demands can easily be translated into a rate of change Δ_q of the weighting parameter q_φ (Van Amerongen, Van der Klugt and Van Nauta Lemke, 1986a). Therefore, the parameter q_φ will be adjusted according to:

$$q_\varphi = q_0 + a\int \Delta_q dt \tag{3.11}$$

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

The weighting parameters q_φ and q_k 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 proposed method of translating operational requirements into a criterion function is related to the theory of fuzzy sets (see for instance Van Amerongen, Van Nauta Lemke and Van der Veen, 1977). This theory might offer some better tools for such a translation.

Simulations with the adaptive criterion were carried out with the simulation package PSI. 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:

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

where

λ = 0.5
ω = the natural roll frequency of the ship

- the maximum rudder speed = 15 deg/s
  the maximum rudder angle = 22 deg/s
  the ship's speed = 20 knots

Figure 4 shows a comparison of a ship with roll stabilization (solid lines) and the same ship without roll stabilization. Figure 5 shows the fluctuations of the controller parameters during this simulation. After approximately 20 s the controller gains K_3, K_4 and K_5 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.

After 200 s the maximum rudder speed is changed to 7 deg/s, again resulting in a change of the controller gains.

Figure 4 clearly demonstrates the roll reduction. The course deviations remain small. Even at low rudder speeds roll reduction is possible, although with lower controller gains and of course with less reduction, especially for large roll angles. Without adaptation of the controller gains the system with a 7 deg/s. rudder would show no roll reduction at all.

The method appears to be robust and it is not very sensitive for variations in the parameters of the the mathematical model. However, it is still being investigated whether the performance can be improved by on-line estimation of the process parameters.

4. 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 are known. Large variations in these parameters were made in order to determine the sensitivity for these variations. Although no serious problems were encountered, the addition of an on-line parameter estimator may improve the performance. This will be subject of further research.

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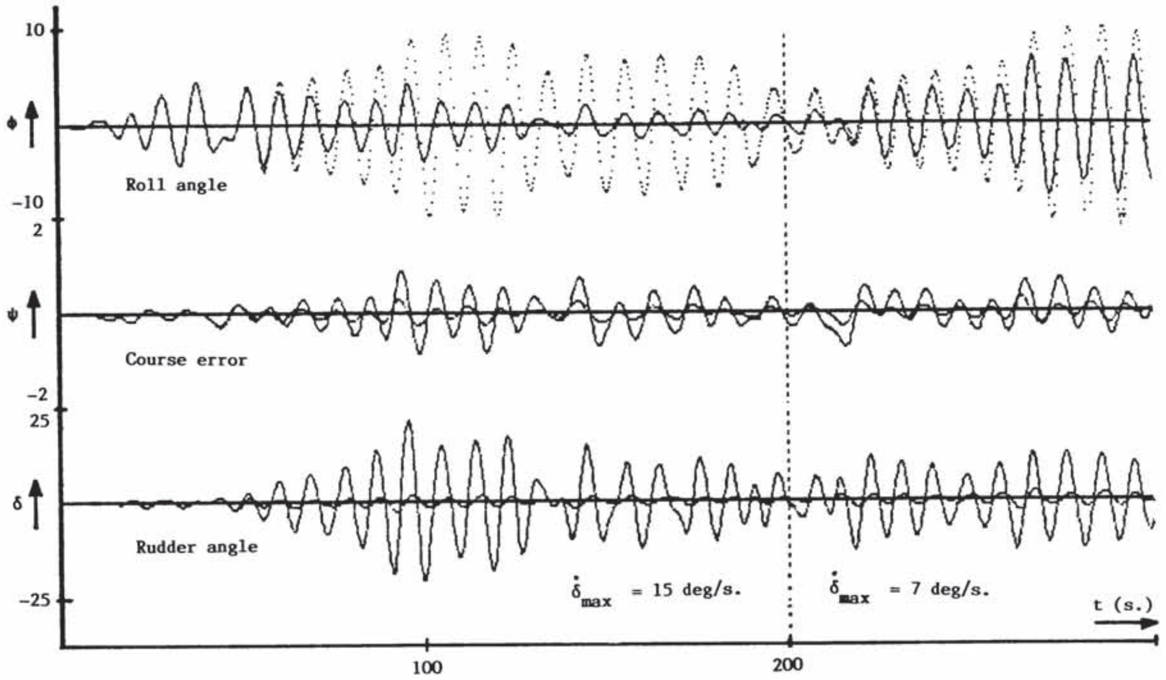

Figure 4 Roll reduction with the adaptive criterion

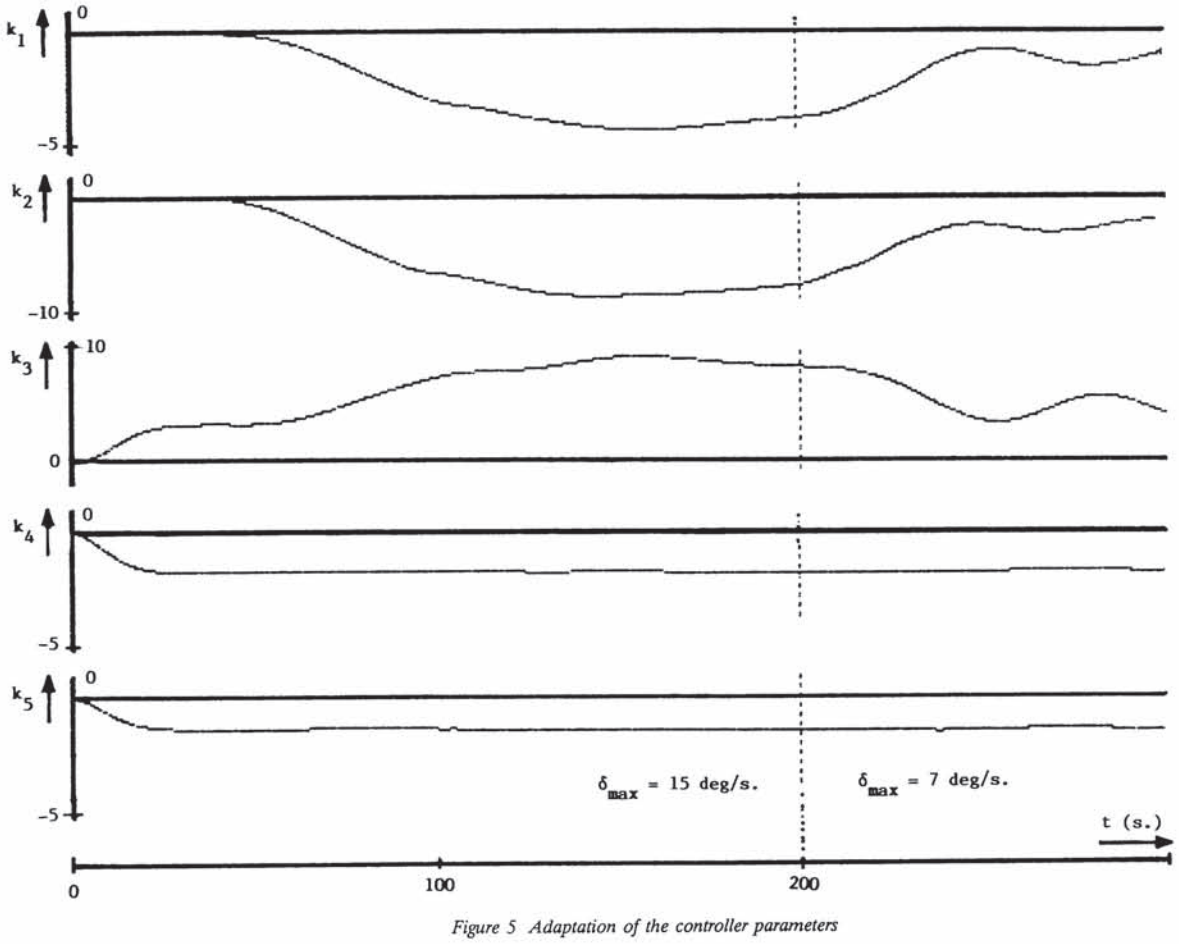

Figure 5 Adaptation of the controller parameters