THE INFLUENCE OF THE SHIP'S STEERING MACHINE OVER YAW AND ROLL MOTIONS

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Abstract: The steering machine is a nonlinear system, with two important limitations: the maximum rudder angle and rudder rate. Therefore, the commands from yaw and rudder-roll control systems are modified and the expected effect is not always the optimum one. It is important to know the influence of the steering machine, trying to avoid the limitations or to include them into the control law. The goal of this paper is to analyze the steering machine limitations and their influence over yaw and roll motions of the ship. Also, some expert rules are generated, which can be used to implement more efficient control laws.

Keywords: steering machine, autopilot commands, rudder-roll damping system

1. INTRODUCTION

The principal function of a ship steering machine is to move the rudder to a desired angle when demanded by the yaw control system or by the helmsman. The rudder can also be used to reduce the roll motion of the ship, being commanded by a rudder-roll damping system.

Using the rudder for simultaneous heading control and roll reduction have been analyzed by numerous authors (Kallstrom, 1987; Van Amerongen, *et al.*, 1990; Laudval, and Fossen, 1997; Hearns, and Blanke, 1998; Perez, *et al.*, 2000). It is a single input-multiple output problem, since there is only one actuator to achieve two objectives, which can not be optimally at the same time.

Based on frequency characteristics of the rudder influence on yaw and roll motions, the two objectives can be separated in the frequency domain. Small frequencies are used for heading control and high frequencies, for roll reduction. Thus, the problem is divided into two mono-variable control systems, taking into account only one motion of the ship: the autopilot and rudder-roll controller.

In general, the steering machine is a hydraulic mechanism commanded by an on-off hysteretic controller. It is a highly nonlinear system, with two dominating nonlinearities: rudder magnitude and rate saturations (Van Amerongen, 1982; Fossen, 1994).

For most commercial ships, the maximum rudder angle ($\delta_{\max}$) and rate ($\dot{\delta}_{\max}$) will typically satisfy:

$$(1)\quad \delta_{\max} \in \left[25, 35\right](\text{deg}), \quad \dot{\delta}_{\max} \in \left[2, 7\right](\text{deg/s})$$

The influence of the steering machine is more visible for roll motion. Therefore, the linear rudder-roll control systems try to avoid these limitations by gain scheduling techniques (Van der Klugt, 1987; Laudval, and Murray, 1997). On the other hand, the yaw motion is less affected and thus, most linear autopilots ignore the negative effect induced by the steering machine.

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The goal of this paper is to analyze the steering machine limitations and their influence over yaw and roll motions. These limitations can not be avoided, especially for nonlinear multivariable systems. Also, some expert rules are generated, which can be used to implement more efficient control laws.
The paper is organized as follows. Section2 provides mathematical models used in simulations. In section 3, the limitations of steering machine are analyzed. In section 4 the steering machine influence on yaw and roll movements is studied and some expert rules are generated. Section 5 describes some simulation results based on steering machine model. Conclusions are presented in section 6.

2. MATHEMATICAL MODELS

As a requisite for the simulation results, models for yaw and roll ship dynamics, steering machine and disturbances had to be generated. Combining these models, nonlinear extended model results, as shown in figure below.

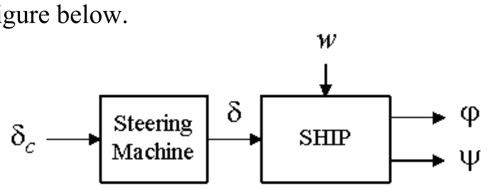

Fig. 1. Nonlinear model of a ship

2.1 Ship dynamics

The equations describing the horizontal motion of a ship can be derived by using Newton's laws expressing conservation of hydrodynamic forces and moments. A three degree-of-freedom linear model is obtained with coupled sway-yaw-roll equations, which can be identified (Van der Klugt, 1987).

Using the Laplace transform and eliminating the sway speed (v), two transfer functions result ($H_{\delta\psi}$ and $H_{\delta\varphi}$) which describe the transfer from rudder angle (δ) to yaw angle (ψ) and to roll angle (φ) respectively. Also, wave disturbances (w) are considered. The Laplace equations are:

$$(2)\quad \begin{cases} \psi(s) = H_{\delta\psi}(s)\cdot\delta(s) + H_{w\psi}(s)\cdot w(s) \\ \varphi(s) = H_{\delta\varphi}(s)\cdot\delta(s) + H_{w\varphi}(s)\cdot w(s) \end{cases}$$

The transfer functions have parameters depending on the speed of the ship (u) and the incidence angle (γ). The frequency characteristics of the resulting ship model are shown below.

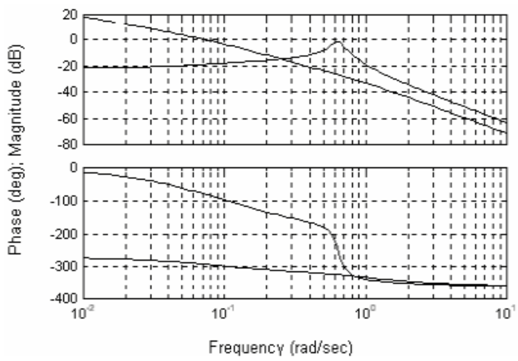

Fig. 2. Frequency characteristics of ship model

2.2 Steering machine model

Steering machine is based on two-loop electro-hydraulic steering subsystem common on many ships (Omerdiae, *et al.*, 1997). The model is nonlinear and is represented in Figure 3.

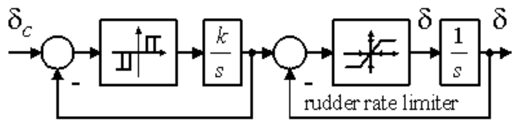

Fig. 3. Nonlinear model of steering machine

Also, the model includes the rudder limiter which is not represented in the figure to preserve the clearness of illustration. Moreover, the rudder angle is small enough and it is not limited, for all simulations.
A maximum rudder deflection of ±35 (deg) and a maximum rudder rate of ±2.5 (deg/s) are considered.

The nonlinearity of the first loop is important because it introduces a rudder positioning error and affects the efficiency of the control laws. Considering only yaw angle and mono-variable autopilots, the first loop can be disregarded. The resulting model has two nonlinearities generated by rudder limiter and rudder rate limiter (Van Amerongen, 1982).

For roll movements, the first loop increases the phase lag and decreases the rudder force moment on roll angle, as illustrated in the next section. This can affect the simulation results, when different moments of time are studied. Therefore, the first loop can not be disregarded.

2.3 Wave model

In this paper, wave disturbances are considered. The wave can be regarded as an ergodic random process with elevation $\zeta(t)$ and zero mean. Knowing the mean square spectral density function $\phi_{\zeta\zeta}(\omega)$ of the wave elevation $\zeta(t)$, shortly called wave spectrum, the statistical parameters of the wave can be computed. Then, the wave model can be generated.

Based on wave spectrum, the wave disturbance can be modeled as the sum of a limited number of sinusoidal waves (Lyon, 1970):

$$(3)\ \ w(t) = \sum_{i=1}^{N} A_i \cdot \sin(\omega_i \cdot t + \varphi_i)$$

where A_i and ω_i are the amplitude and angular frequency of the *i*-th component. φ_i is the phase angle drawn randomly from a uniform density distribution.

The relative frequency between the wave and the ship modifies the wave spectrum and this transformation must be taken into account for wave model generation (Nicolau, and Ceanga, 2001).

3. THE STEERING MACHINE LIMITATIONS

The steering machine must fulfill some performance conditions:
- the response time to a rudder command imposes a minimum rudder rate. Due to hydraulic mechanism, this is a small value and represents the principal limitation of the steering machine;
- the rudder positioning must be made within a minimum accuracy value of 1 (deg). The rudder positioning error affects the yaw motion.

Also, the rudder deflection magnitude is another supplementary constraint, but this limitation is less important because the maximum rudder angle is not reached very often in typical heading or rudder-roll control problems. For simulations, a slow steering machine is considered, with:

$$\delta_{\max} = 35\ (\text{deg}) \text{ and } \dot{\delta}_{\max} = 2.5\ (\text{deg/s}) \quad (4)$$

3.1 The rudder rate limitation

Because the rudder rate is small, the steering machine can not track rudder commands with big amplitude and high frequencies. An important phase lag appears and the steering machine is acting nonlinearly.

To illustrate the effect of the limited rudder rate, a sinus input signal is considered:

$$(5)\ \ \delta_C = A \cdot \sin(\omega t)$$

The signal has the maximum rate value:

$$(6)\ \ \dot{\delta}_{C\max} = A \cdot \omega$$

If the rudder rate is smaller than the maximum input signal rate, then the rudder movement can not follow the input command, as illustrated in the next figure.

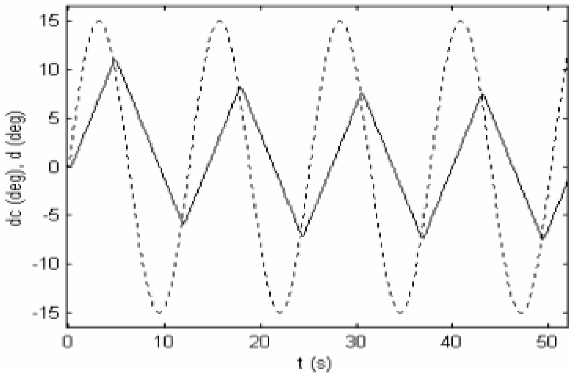

Fig. 4. Response of the steering machine when the rudder rate is smaller than command rate

In the figure, the rudder command is illustrated with dotted line and rudder angle is represented with continuous line. The values are:

$$(7)\ \ \dot{\delta}_{C\max} = 3 \cdot \dot{\delta}_{\max}$$

where $A = 15$ *(deg)* and $\omega = 0.5$ *(rad/s)*.
In order for steering machine to act like a following system, the amplitude and the frequency of the input signal must be related:

$$(8)\ \dot{\delta}_{C\max} = A \cdot \omega \ \le \ \dot{\delta}_{\max}$$

Also, a small low frequency component appears which converges asymptotically to zero.
Due to positioning error, the maximum frequency of the rudder command is $\omega_{max} = 2.5$ *(rad/s)*, being reached for minimum amplitude of $A = 1$ *(deg)*, as shown in figure below.

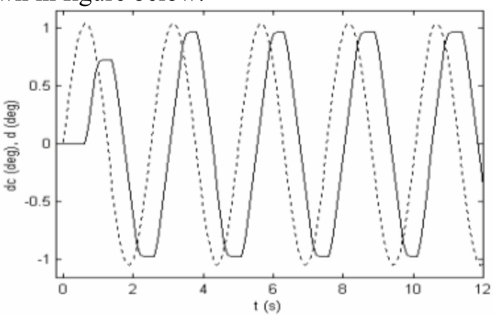

Fig. 5. Maximum frequency of the input signal

It can be observed that the maximum frequency induces an important phase lag, so the real frequency value must be smaller than ω_{max} . The spectral analysis of the rudder command and rudder angle shows that the steering machine is acting like a low-pass filter. This is obviously for a rectangular rudder command, when the rudder angle contains fewer spectral components. In figure below, the signals and their FFTs are illustrated.

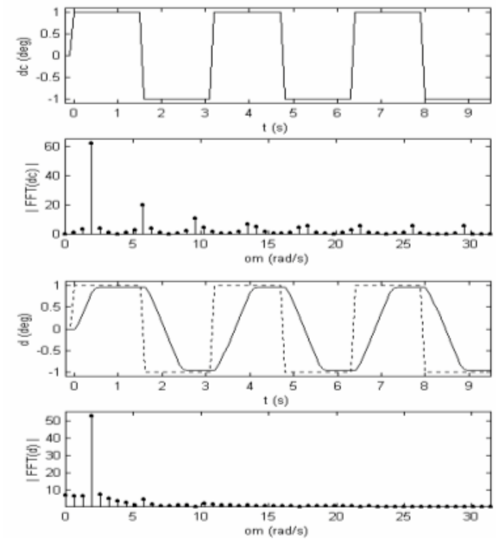

Fig. 6. Spectral components of the rudder command and rudder angle

3.2 The rudder angle limitation

The maximum value of rudder deflection is imposed by constructive constraints. If the input amplitude is bigger than this value, the rudder angle is saturated, even for a very small frequency. Supposing a big amplitude *A = 50 (deg)* of the rudder command and a small frequency $\omega = 0.055$ *(rad/s)*, the steering machine response is shown in the next figure.

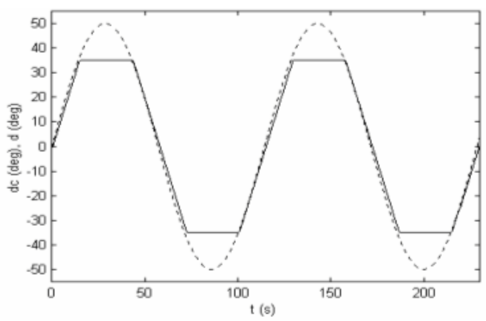

Fig. 7. Rudder angle limitation

The rudder command is illustrated with dotted line and the rudder angle, with continuous line. It can be observed that the steering machine can not track the input signal. The limitation can be avoided if the heading and rudder-roll control systems generate only rudder commands with relative small amplitude.

4. THE STEERING MACHINE INFLUENCE ON YAW AND ROLL MOTIONS

4.1 The influence of the steering machine model

The model of the steering machine has different influences on yaw and roll angles. Two situations are considered: with and without the first loop of the model, illustrated in the next figure with solid and dotted lines respectively.

Applying a rudder command (δ_C) of 5 (deg), the rudder angle generated by the steering machine (δ) affects simultaneously the movements of the ship, as illustrated below. A small rudder positioning error appears, generated by the on-off hysteretic controller.

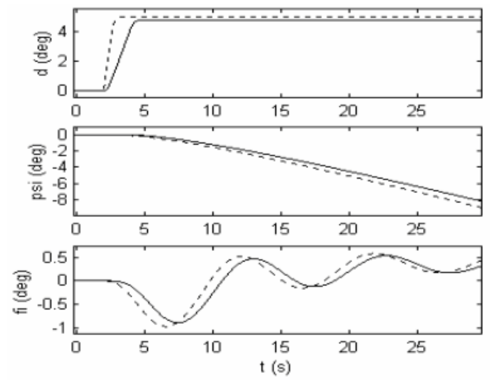

Fig. 8. Yaw and roll movements for two models of steering machine

For yaw movement, only a small difference appears, caused by the positioning error of the rudder when the first loop is considered. The difference is significant after a long period and can be compensated by the control law of yaw angle. Therefore, the first loop can be disregarded when mono-variable autopilot is considered.

Roll oscillations are delayed and amplitudes are smaller if the first loop is included in the model of steering machine. An important phase lag appears from the beginning, which can affect the simulation results, when different moments of time are studied. The acceleration of the roll angle is generated by the rudder force moment on roll motion. The maximum value of the acceleration is obtained for the minimum value of the roll angle, as shown in Figure 9.

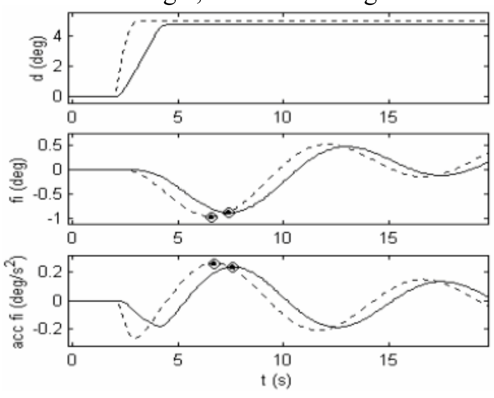

Fig. 9. Roll angle and roll acceleration

It can be observed that the maximum acceleration values are different for the two models of steering machine and the difference increases as the rudder angle increases. Starting from repose point, these values are reached after a time interval, depending of ship characteristics. The points correspond to the maximum value of the rudder force moment.

As a result, the maximum values of rudder moment are different, as illustrated in Figure 10. The linear dependency represented with dotted line corresponds to theoretical rudder moments when steering machine model is ignored.

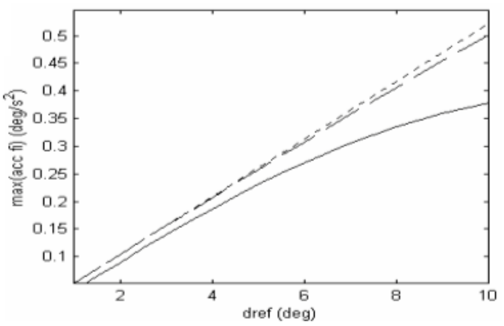

Fig. 10. Maximum rudder moments on roll angle

The maximum rudder moments, generated by steering machine model without the first loop, are represented with dashed line. The values are closed to theoretical moments.

If the first loop is considered, the real maximum value of the rudder moment is smaller and decreases as rudder angle increases, being represented with continuous line.

Consequently, if a rudder-roll damping system is used, the real roll damping effect is smaller than the case when steering machine is approximated without the first loop. Therefore, the efficiency of a control law with rudder-roll damping effect has to be tested considering the two-loop steering machine model.

4.2 Different moments of time for rudder command generation

Usually, the rudder commands are generated by the autopilot control law. The rudder command in one way acts simultaneously on the yaw and roll movements of the ship.

A rudder command with positive effect on yaw angle can generate a negative effect on roll angle. Hence, it is important to generate only rudder commands with damping or non-increasing effects over roll movements.

For simplicity, a pulse type rudder command is generated for simulations. The positive edge is used as a previous command, starting the roll oscillations. The negative edge represents the command that has to be analyzed.

Depending on the moment of time when the command is generated (negative edge), the effect on roll movement can be of increasing or decreasing the roll angle, as illustrated below. The command represented with dotted line generates a bigger roll angle as the one illustrated with continuous line.

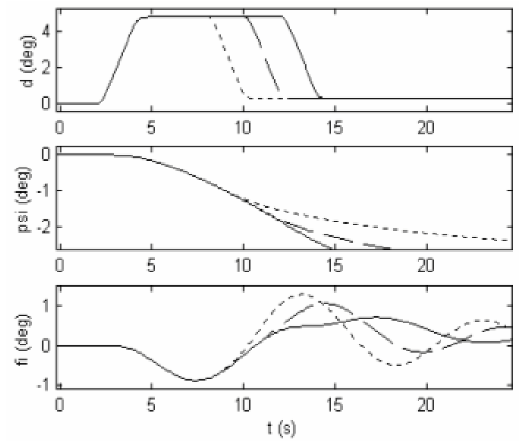

Fig. 11. Different time moments for rudder command

To identify specific time moments or time intervals when the rudder has positive influence on roll movements, the roll angle, rate and acceleration has to be analyzed.

The negative edge of the rudder command is generated at four different moments of time: the minimum and maximum values of roll angle and roll rate respectively.

If the rudder angle is decreased during the minimum value of roll angle or roll rate then the roll amplitude and the roll acceleration increase, as shown below.
At these time moments, it is better for roll motion if the rudder command is delayed as illustrated with dotted lines, instead of decreasing its value.

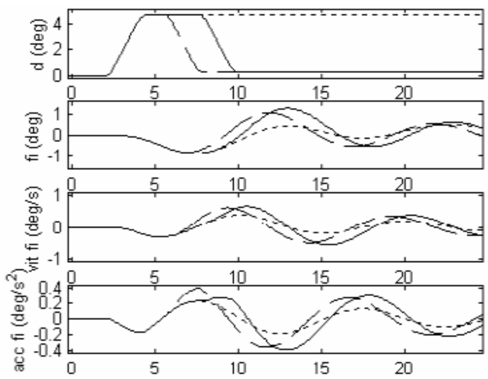

Fig. 12. Decreasing the rudder command during the minimum values of roll angle and roll rate

Rule no. 1 : During the time moments around the minimum values of roll angle and roll rate, the rudder command must be increased or delayed.

If the rudder angle is decreased during the maximum value of roll angle or roll rate then the roll amplitude and the roll acceleration remain comparable with those of damping oscillation, as illustrated below. The damping effect is not so visible, because one single moment of time was analyzed.

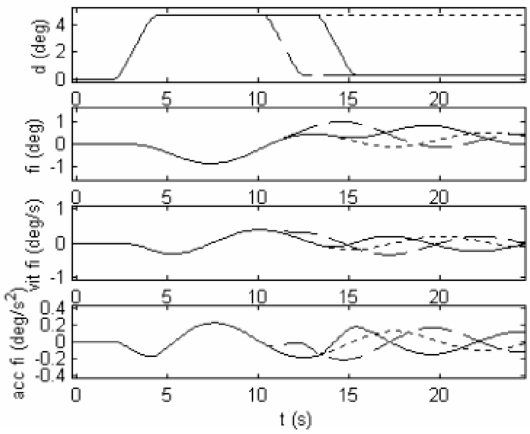

Fig. 13. Decreasing the rudder command during the maximum values of roll angle and roll rate

Rule no. 2 : During the time moments around the maximum values of roll angle and roll rate, the rudder command can be decreased or delayed.

The best time moment to decrease the rudder command depends of ship dynamics. It is somewhere between the time moments corresponding to maximum values of roll angle and roll rate, as shown in Figure 14. The right time moment is closed to maximum roll angle values.

Rule no. 3 : The optimum time interval to decrease rudder command is placed between maximum values of roll rate and roll angle.

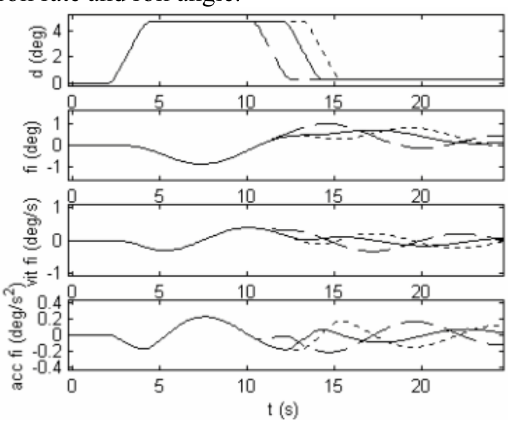

Fig. 14. Rudder command at a time moment between the maximum values of roll angle and roll rate

Similar rules are generated for time moments of increasing rudder command. Knowing the nonlinear model of the steering machine, more precise moments of time can be obtained.

5. SIMULATION RESULTS

5.1 The yaw error compensation

Modifying the rudder command to generate a positive effect on roll angle can affect the yaw angle. The yaw error can be compensated by changing the control law. An example is illustrated below.

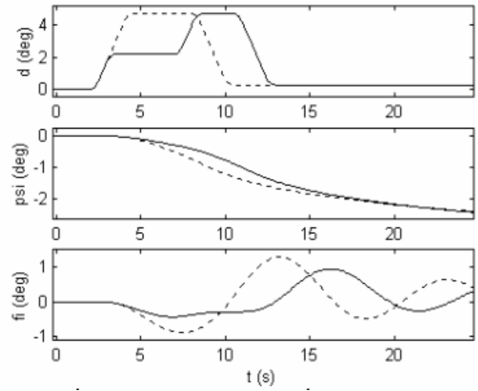

Fig. 15. The yaw error compensation

Modifying the control law, the negative edge of the rudder command is delayed to reduce the roll oscillations. The time delay increases the yaw angle. Hence, the amplitude of the command must be reduced in the first part to compensate the yaw error. Also, the second positive edge is generated at a certain moment of time to have a positive influence on roll angle.

5.2 Rudder command analysis generated by a classical autopilot

A conventional PID course keeping autopilot is considered with nonlinear steering machine model. Wave disturbances (*w*), rudder angle (*d*), yaw angle (ψ) and roll angle (φ) are illustrated in Figure 16.

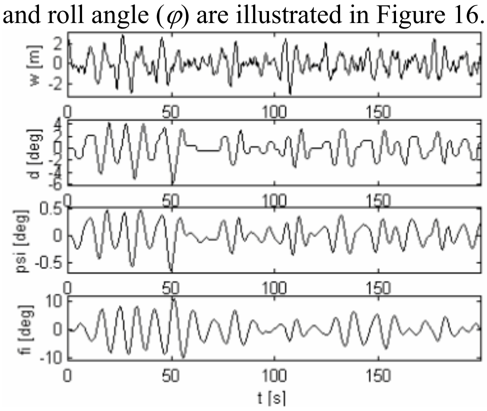

Fig. 16. Ship's motion with course keeping system

Analyzing the rudder commands generated by the autopilot for all discrete moments of time, a new discrete function $F(\delta_C)$ is computed:

$$(9)\quad F(\delta_C) = \begin{cases} -1 & \text{if the roll effect is negative} \\ 0 & \text{if the effect is not important} \\ 1 & \text{if the roll effect is positive} \end{cases}$$

For the rudder command sequence generated by autopilot in the example above, the resulting function *F* is illustrated below.

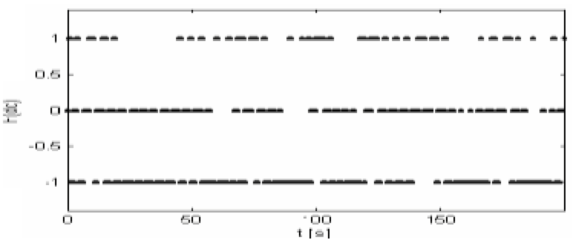

Fig. 17. The effect function of the rudder commands

There are many moments of time when the rudder command, generated by autopilot to have positive effect on yaw angle, has negative effect on roll angle.

6. CONCLUSIONS

The model of the steering machine is nonlinear. Knowing its limitations and influence over yaw and roll motions is important for generating new control laws, with expert rules included.

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