ENHANCING SHIP NAVIGATION SAFETY BY IMPROVING STEERING SYSTEM RELIABILITY

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ABSTRACT

Recent years ships navigation was intensively increased. Thus enhancing safety in maritime transport becomes a more difficult task which requires improvement of navigator skills from one side and technical means reliability from the other side. With technical point of view safe navigation depends on ship controllability which is provided by reliable steering system operation.

In some cases steering gear control systems give only common alarm without showing the exact source of failure. This problem can be solved by providing steering gear control system by fault detection and fault isolation algorithms.

This paper proposes fault detection and fault isolation algorithms for such faults in the steering gear system as: rudder stuck due to hydraulic lock when two pumps in operation; backlash in rudder position feedback circuit.

Keywords: *Steering gear, fault-tolerant control, control algorithm, reconfiguration, compensation.*

1. INTRODUCTION

A number of ships navigation accidents are known due to faults in steering gears [1]. One of the first steps on steering system reliability improvement was made by the 1981 Amendments to International Convention SOLAS-74 which requires that the main steering gear is arranged so that after a single failure in its piping system or in one of the power units the defect can be isolated so that steering capability can be maintained or speedily regained. In modern steering systems this requirement is fulfilled by making redundant each power and control component of the system [1]. In spite of redundancy in steering system fault finding and isolation process is manual and still takes a lot of time thus increasing risks of ships navigation safety and even becoming a reason of incidents and accidents.

2. RESEARCH ACTUALITY

Steering system reliability and efficiency problems were considered in papers [2; 3]. According to [2] steering system reliability enhancing problem could be solved by implementing fault detection and fault isolation algorithms into steering gear control system.

Such algorithms could be used either for automatic fault isolation by control system or for operator advice in decision-making system. For the achievement of this goal it is reasonable to use an emerging area in automatic ship control – Fault-tolerant control (FTC) [4], where several disciplines and techniques are combined to obtain a unique functionality. In paper [5] FTC was applied for ship course changing/keeping system.

FTC provides a mechanism to monitor behaviour of components and function blocks and to take appropriate remedial action in order to keep the manoeuvre capability of the ship and prevent the loss of the control performance. The strict requirements for navigation safety, the complexity of ships function tasks define the actuality of applying FTC methods as for whole ships control systems or particular steering gear control system.

3. FINDINGS OF THE RESEARCH

Two typical faults in hydraulic steering gear [1] are considered in this paper: backlash in rudder position feedback circuit; rudder stuck due to hydraulic lock when two pumps in operation.

For research authors used mathematical model of hydraulic steering gear given in [6]:

$$y(s) = \frac{B \cdot Q_s}{\left(I \cdot s^2 + B \cdot A \cdot s\right)} \cdot \left(\frac{1}{\tau \cdot s + 1}\right) \cdot X(s) - \frac{1}{I \cdot s^2 + B \cdot A \cdot s} \cdot \left(\sum M_{ext}(s)\right) \tag{1}$$

where $B = \frac{A \cdot \rho/2 \cdot Q_s}{\left(2 \cdot \pi \cdot r \cdot U \cdot C_d\right)}$,

Q_s – hydraulic oil volumetric flow rate through the pump; A – piston's area; ρ – hydraulic oil density; C_d – discharge coefficient, equal to $\pi/(\pi+2)$ for turbulent flow; r – piston radius; I – moment of inertia; U – oil volume elasticity value; $x \in [-1,1]$ – rated position of valve; y – piston velocity; $\Sigma\ M_{ext}$ – external resistance moment. Hydraulic steering gear block diagram is presented in figure 1. This steering gear is a “follow up” system with PD controller, where command rudder angle δ_c is generated by steering wheel or autopilot.

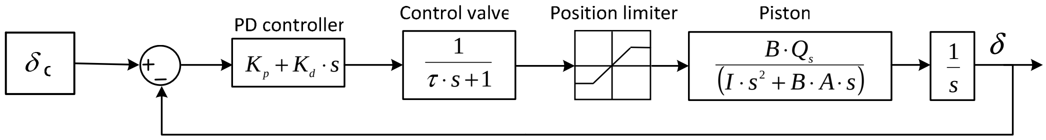

Figure 1 Hydraulic steering gear block diagram

The first fault can be modelled by including the backlash block in the feedback circuit of the hydraulic steering gear block diagram (fig.3).

The steering gear control process was modelled with different command angles and proper for practice backlashes (1-3˚) due to equipment wear.

The following model numeric values were used for modelling [6]: $B{\cdot}Q_s$=37564.44; I=25; $B{\cdot}A$=6629.02; τ=0.4.

Modeling results are presented in figure 2.

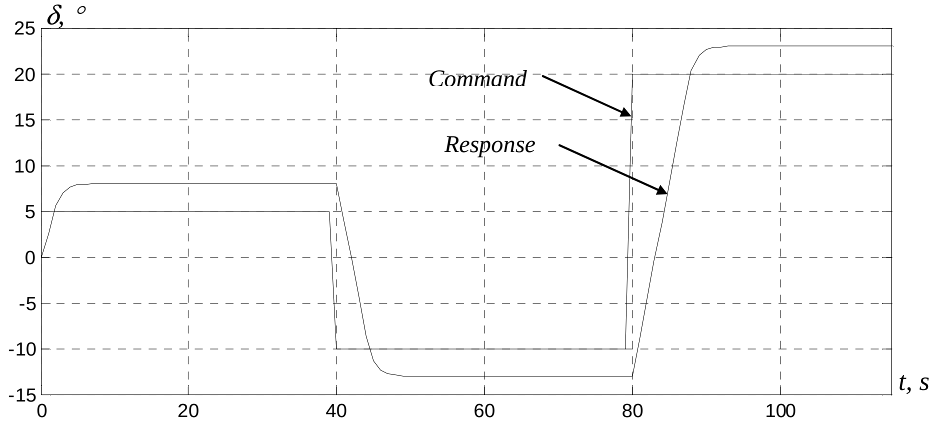

Figure 2 Steering gear response with backlash in feedback

As shown in figure 2, in case of 3˚ feedback backlash, rudder response will exceed command signal by the same value. According to FTC methods such problem can be solved either by system reconfiguration or fault compensation. Authors use second method and for this goal upgrade system presented in figure 1 adding reference model and compensator (fig. 3).

It is expected that reference model (fig. 3) precisely describes steering gear response. In this case difference signal d between model output δ^* and steering system output δ could be used for compensation of backlash influence. For compensation authors consider the signal, described by formula:

$$c(t) = c(t-1) + k \cdot d(t) \tag{2}$$

where c – compensating signal; k – gain; d – difference signal between model output and steering system output.

Modeling results of steering system with compensator are presented in figure 4. As seen from the diagrams (fig. 4), application of such FTC method like compensation in steering gear control system can reduce rudder position control error from 3˚ to 0,5˚ in case of backlash in rudder position feedback circuit.

Taking into account that modern control systems are based on microprocessors, FTC methods can be implemented in control system software.

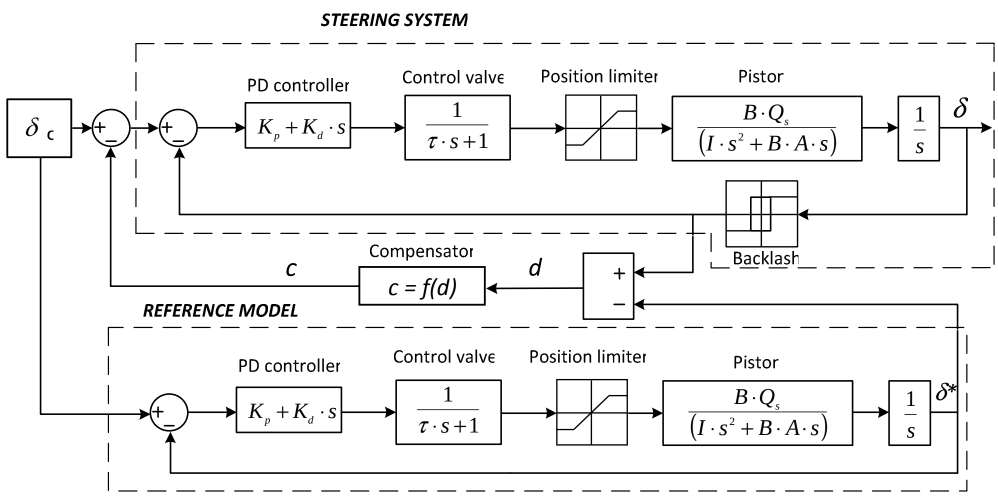

Figure 3 Block diagram of steering gear control system with compensator

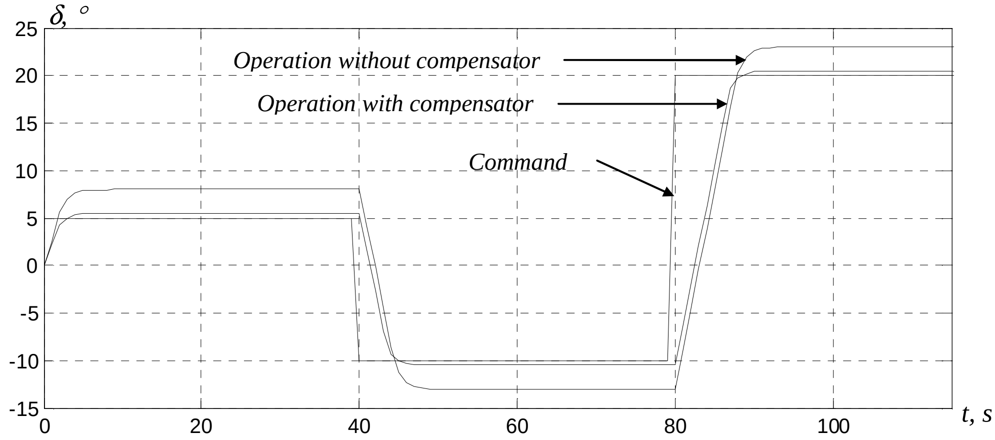

Figure 4 Steering gear response with/without compensator

Thus backlash compensation can be expressed by next algorithm:

$$Start.INPUT(\delta_c, \delta, \delta^*).(\delta = \delta^*)\overset{1}{\uparrow}\omega\overset{3}{\uparrow}$$

$$\overset{1}{\downarrow}(\delta > \delta^*)\overset{3}{\uparrow}CVP = RCVP\overset{2}{\uparrow}OUTPUT.$$

$$(\delta_c = \delta_c(t-1) - k(\delta - \delta^*))\omega\overset{3}{\uparrow}$$

$$\overset{2}{\downarrow}OUTPUT.MCVF.DOP\overset{3}{\downarrow}End$$

where δ – rudder position; δ_c – rudder command; δ^* – reference model rudder position; *CVP* – control valve position; *RCVP* – reference model control valve position; *MCVF* – message: control valve failure; *DOP* – decision of operator request.

As mentioned above, such fault as rudder stuck due to hydraulic lock when two pumps in operation is dangerous and can lead to loss of ship controllability.

Such fault can be modeled by inputting to steering gear model of maximum amplitude rudder command signal (-35˚) as presented in figure 5.

As seen in diagram "Failure without reconfiguration" in figure 6 rudder stuck in hard to port (-30˚) position at the moment of 90 sec.

One of the possible solutions of this problem according to good practice [1] can be alternate switching off/on steering gear pumps till the rudder will start move to command position.

Nowadays operators do this procedure themselves, which takes time and can lead to accident.

Taking this into account the reconfiguration algorithm for steering gear control system creation will be preferable.

For this purpose authors add to steering gear control system reconfiguration unit, which inputs are: *ε(t)* – difference between steering gear command and response signal; steering gears conditions (on/off) as illustrated in reconfiguration unit in figure 5.

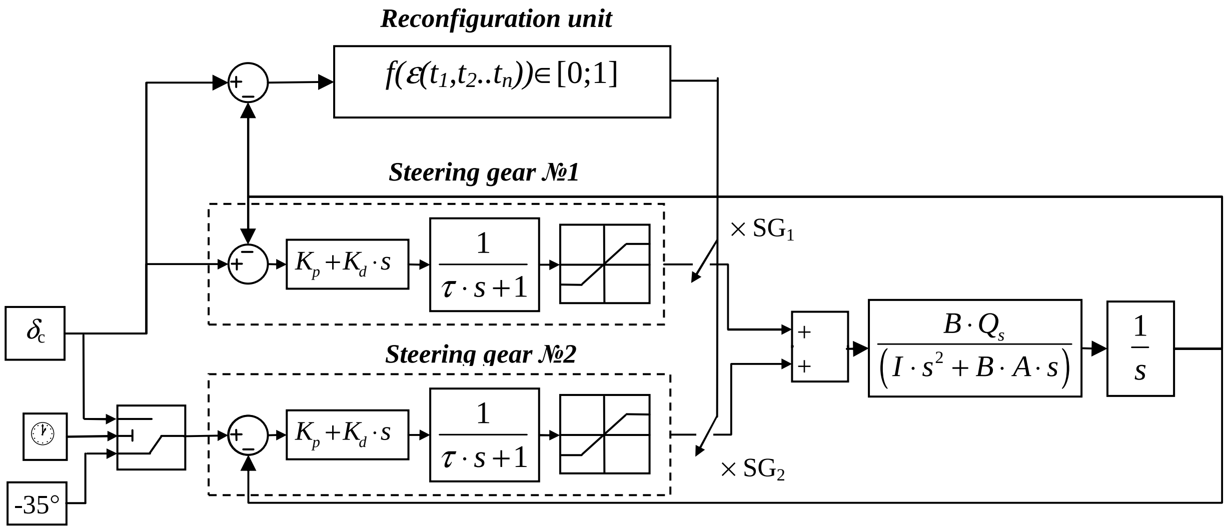

Figure 5 Block diagram of steering gear control system with reconfiguration unit

Authors propose following algorithm for reconfiguration unit:

$$Start.INPUT(\delta_c, \delta, \varepsilon(t) = \delta_c - \delta, SG_1,$$

$$SG_2).\varepsilon(t) = \varepsilon(t - T_1) \neq 0 \,\&\, \varepsilon(t) > \varepsilon(t - T_2) \overset{1}{\uparrow}$$

$$\omega \overset{4}{\uparrow} \overset{1}{\downarrow} SG_1(t-1) = 0 \,\&\, \varepsilon(t) < \varepsilon(t - T_2) \overset{2}{\uparrow} \omega \overset{4}{\uparrow}$$

$$\overset{2}{\downarrow} SG_1(t-1) = 0 \,\&\, \varepsilon(t) = 0 \overset{5}{\uparrow} \overset{3}{\downarrow} SG_1(t-1) = 0;$$

$$SG_2(t-1) = 1 \overset{4}{\uparrow} \omega \overset{5}{\uparrow} \overset{4}{\downarrow} OUTPUT.$$

$$MSG_1(t) = 0; MSG_2(t) = 1.PR.WAIT.$$

$$\varepsilon(t) < \varepsilon(t - T_1) \overset{5}{\uparrow} \omega \overset{10}{\uparrow} \overset{5}{\downarrow} \varepsilon(t) = \varepsilon(t - T_1) \neq 0 \,\&$$

$$\&\, |\varepsilon(t)| > |\varepsilon(t - T_1)| \overset{6}{\uparrow} \omega \overset{9}{\uparrow} \overset{6}{\downarrow} SG_2(t-1) = 0 \,\&$$

$$\&\, \varepsilon(t) < \varepsilon(t - T_2) \overset{7}{\uparrow} \omega \overset{9}{\uparrow} \overset{7}{\downarrow} SG_2(t-1) = 0 \,\&$$

$$\varepsilon(t) = 0 \overset{8}{\uparrow} \omega \overset{9}{\uparrow} \overset{8}{\downarrow} WR : DOP; MEM \overset{9}{\downarrow}$$

$$OUTPUT.MSG_1(t) = 1; MSG_2(t) = 2.$$

$$PR.WAIT.\varepsilon(t) < \varepsilon(t - T_1) \overset{8}{\uparrow} \overset{10}{\downarrow} End$$

where $SG_{1,2}$ – steering gears condition Boolean functions (on/off – 1/0); $T_{1,2}$ – fault evaluation time constants (T_1=3 sec, T_2=6 sec, with discretization step Δt=1 sec).

The modeling results of the system reconfiguration when rudder stuck are presented by “Failure of SG №1”, “Failure of SG №2” diagrams in figure 6.

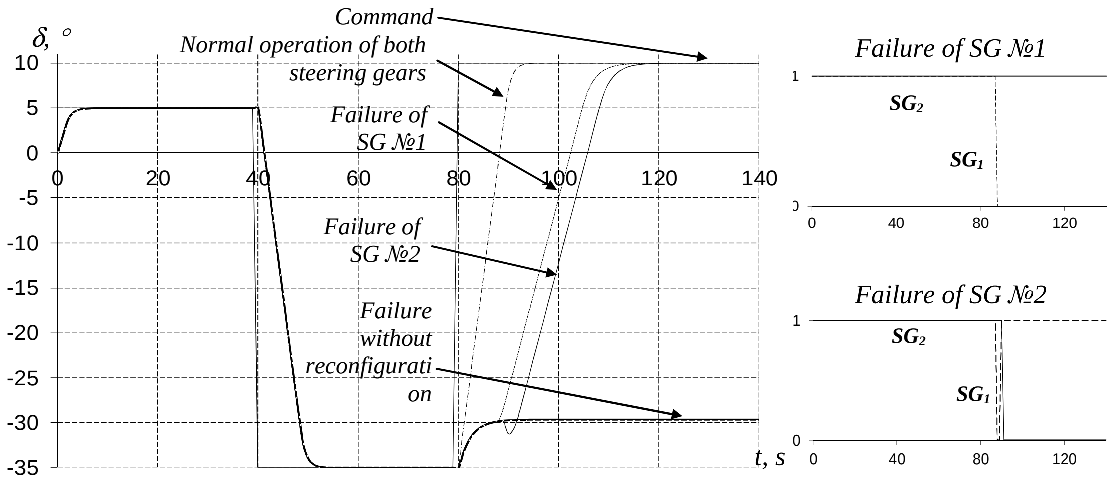

Figure 6 Steering gear response diagrams with/without reconfiguration

As seen from the diagrams (fig. 6) reconfiguration can be quickly isolated using the proposed above algorithm.

The proposed algorithm can be implemented in software form in steering gear control system.

4. CONCLUSIONS

The steering system compositions were found to be tolerant for such faults as: rudder stuck due to hydraulic lock when two pumps in operation; backlash in rudder position feedback circuit. Reconfiguration and compensation algorithms were developed using FTC methods.

Simulation results in MATLAB have shown that FTC methods are effective applicable to the steering systems and are desirable to use in future researches for improving steering system reliability.

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