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DESIGN OF THE SHIP COURSE CONTROL SYSTEM

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1. Introduction

Control engineering plays a fundamental role in modern technological systems. The benefits of improved control in industry can be immense. Thus in design of control systems, the knowledge of control theory is most significant but its practical application is also as important as the benefits it can bring. Like many other aspects of creative activity of a human being, the process of design of a control system cannot be easily formalized. Nevertheless, it is possible to divide it into certain separate autonomous phases (stages). One of possible variants of such a division, along with the order of consecutive actions, is shown in Fig. 1 [Szymkat 1993].

Consecutive stages in the design of the control systems are the following:

- Conceptual phase (formulating the target of control, defining requirements),
- Modeling (developing a mathematical model, carrying out measurements and processing measurement data, on-line and off-line identification),
- Analysis of the model developed in the previous phase (its visual and controlling abilities, static and dynamic properties),
- Synthesis of the control system (defining its structure and selecting parameters),
- Validation of the control system characteristics (stability, susceptibility, reliability, modeling, computer simulation),
- Implementation of the control system (algorithms for measurement data processing, filtration, estimation of those process variables which are not measured, calculating control parameters in real time, testing, physical execution).

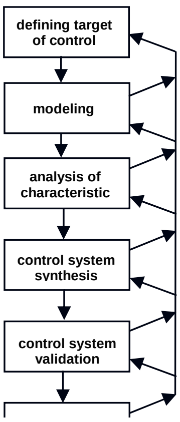

Figure1. Stages of control system design process

It is not always that all those stages can be clearly separated. Unsatisfactory results in one phase often happen to require repetition and correction of actions taken in the previous design phases. The design cycle of the control system will be discussed on the case of the design of a non-linear course control system for a physical model of the VLCC Blue Lady tanker (Fig. 2). Matlab-Simulink was used as complementary software (Computer aid control system design CACSD) at all design stages. The following toolboxes were used: control system, identification system, signal processing, and - during implementation - real time workshop RTW and xPC-target toolbox.

2. Conceptual phase

The requirements for the tanker course control system can be formulated in the following way: the designed control system should reveal ability to stabilize the desired course with the assumed control accuracy (yawing amplitude); as well as to secure the automatic course change with the stabilization of the set angular speed of the turn, and set overshot and rise or settling time. These requirements can be easily and clearly determined by the ship services with no qualifications in automation.

3. Model of the control plant, measurements, model identification, modeling

Large tankers are unstable on a course within the range of small rudder angles. Therefore a linear model of the control object in the control synthesis is not recommended. The known non-linear Norrbin model based on the linear first-order Nomoto model can be described by the following equation [Norrbin 1970]:

$$T \cdot \ddot{r} + a_3 \cdot r^3 + a_2 \cdot r^2 + a_1 \cdot r + a_0 = k\delta \tag{1}$$

where: δ - rudder angle, r - angular velocity of hull, T, k, a_i, - parameters of ship dynamics,
The 3rd-order polynomial:

$$H_N(r) = a_3 r^3 + a_2 r^2 + a_1 r + a_0 \tag{2}$$

describe the non-linear manoeuvring characteristic produced by Bech's reverse spiral manoeuvre. For course-unstable vessels $a_1 = -1$ and for those course-stable $a_1 = 1$.
Identification data were collected on the Silm Lake, at the Ship Handling Research and Training Centre of Foundation for Safety of Navigation and Environment Protection in Ilawa, Poland. Isomorphic VLCC tanker model built in the 1:24 scale was used as an object of identification. This model is originally used at ship handling training for deck officers. Principal parameters of the model in relation to those of the real tanker are given in Table 1, and its sketch is shown in Fig. 2 [Kobyliński 1999].

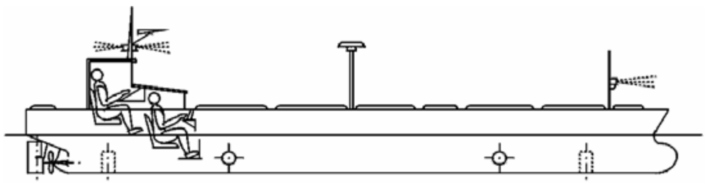

Figure 2. Sketch of VLCC tanker model - "Blue Lady"

Table 1. "Blue Lady"; Model of a VLCC Tanker

Item	Ship	Model
Length overall	330.65 [m]	13.78 [m]
Beam	47.00 [m]	2.38 [m]
Draft – full load	20.60 [m]	0.86 [m]
Displacement – full load	323 660 [t]	22.83 [t]
Draft – ballast	12 [m]	0.5 [m]
Displacement – ballast	176 000 [t]	12.46 [t]
Speed	15.2 [kn.]	3.1 [kn.]

Identification of a tanker model has been executed basing on the prerecorded histories of the course and rudder deflection angle measured during the Kempf manoeuvre tests. The mathematical model parameters were estimated using algorithms available in the Matlab System Identification Toolbox

[Ljung1997]. Direct estimation of the Dieudonné polynomial parameters by processing course and rudder deflection angles recorded during normal model operation has not occurred successful.

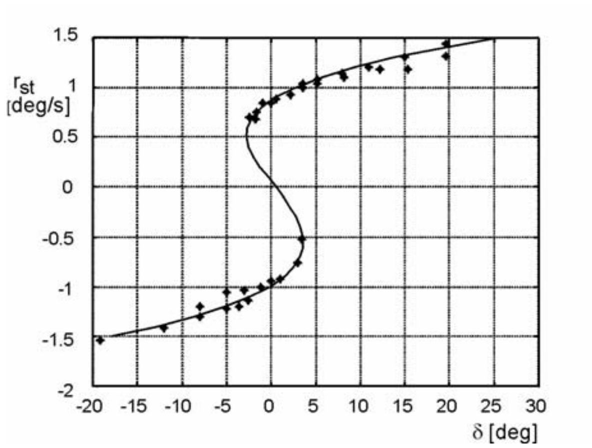

Figure 3. Measurement results and Dieudonné spiral for the Blue Lady model (full load, half-ahead) approximated by polynomial with the parameters indicated in Table 2.

The model build with this method revealed good conformity with measured course- and angular velocity histories. However, the simulated turning circle test trajectories differed substantially from the measurements.

Estimates of the polynomial parameters were also different for successive measurements carried out in similar conditions. The suitable Dieudonné polynomial parameters can be determined with sufficient accuracy from the turning circle tests. Such tests were executed with the model on lake and the sample results are shown in Fig. 3.

Figure indicates measured values of the angular velocity in a function of various rudder angles together with approximated Dieudonné spiral. The presented results were performed at the linear velocity of 0.87 m/s (half-ahead) of the model. Parameters of that curve were determined using regression method (see Table 2).

Table 2. Approximation Polynomial Parameters for the Dieudonné Spiral of Blue Lady Model at the Half-Ahead Velocity and Under Full Load

a3	a2	a1	a0	k
1.2322	0.0665	-1	0.07536	0.1256

The time constant T of the Norrbin model - Eq. (1) was separately estimated, on the basis of the course- and rudder deflection histories pre-recorded during Kempf Zig-Zag manoeuvre. The model angular velocity r was not directly measured during manoeuvre tests. Therefore it was estimated by means of the stationary Kalman filter using signal model.

Sample of recorded histories of the rudder deflection angle and the course measured during Zig-Zag manoeuvre test are shown in Fig. 4. In the same figure respective graphs obtained in the identification process are indicated. Respective estimated value of time constant is equal to T = 48.5 s.

4. Synthesis of the control system

Linear algorithms, which are usually used in ship’s autopilots, can keep the stability of a course control system on a direction unstable ship. However, a global stability requirement for controlling such a ship needs strong derivative action of the controller. High value of the derivative gain coefficient compensates the unstable pole of the object within the range of small rudder angles. It is, however, unfavourable for large rudder angles and large course deviations as it limits the turn rate, and therefore extends the settling time. These difficulties can be avoided by using a controller, which parameters are a function of the course deviation. Error deviation thresholds, which determine changes of controller parameters, are usually selected heuristically.

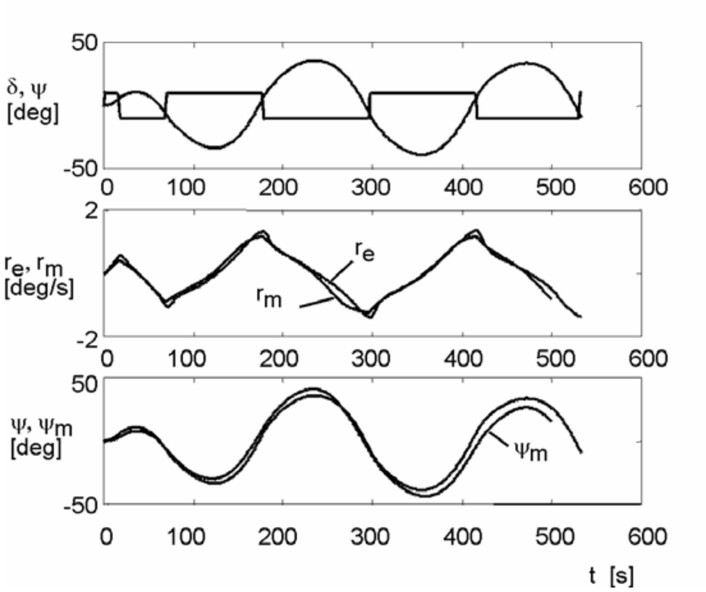

Figure 4. Histories of course ψ, rudder deflection angle δ, estimated angular velocity re of the isomorphic tanker model Blue Lady recorded during the Kempf Zig-Zag test and the respective histories ψ_m and r_m of identified Norrbin model.

Isidori [Isidori 1998] has proposed simple algorithm of non-linear control. Let the object (controlled ship) be modelled by a Norrbin model defined by Eq. (1), and let the control be executed by the system shown in Fig 5.

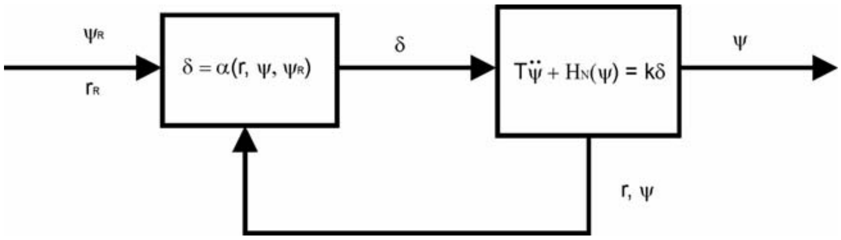

Figure 5. Schematic diagram of non-linear control system

The course and turn rate determine the actual state of the ship. Here, a static-state feedback control mode is applied. The control is defined by a non-linear function of state variables. The dynamics of the steering gear is omitted during control synthesis. This simplifying assumption is fully acceptable, as it does not create significant errors when the time-constant of the ship dynamics is much larger than the equivalent time-constant of the steering gear [Van Amerongen 1982]. The transient component of the course control error:

$$e = \psi_R - \psi \tag{3}$$

where ψ_R – denotes ship desired course, is assumed to satisfy the following differential equation in the transient state:

$$\ddot{e} + \beta_1 \dot{e} + \beta_2 e = 0 \tag{4}$$

Parameters β_1 and β_2 can be determined using the closed system natural frequency ω_n, and the relative damping factor ξ, which equal $\beta_1 = 2\xi\omega$, and $\beta_2 = \omega_n^2$. Placing the error definition from Eq. (3) into Eq. (4), and then into dynamics model defined by Eq. (1), and setting $d\psi/dt=r$ gives:

$$\delta_\psi = \frac{T}{k}\left[\beta_2(\psi_R - \psi) - \beta_1 r\right] + \frac{1}{k} H_N(r) \tag{5}$$

assuming that $d^2\psi_R/dt^2 = 0$ and set value of turn $r_R=0$.
This equation defines the structure of the non-linear ship course controller. The advantage of the controller is possible variation of the derivative action, which is adjusted according to non-linear characteristics of the unstable object. Moreover, the control law described by Eq. (4) allows to define the characteristics of a closed loop control system in a direct way using the natural frequency of the system and the relative damping factor.
For large course changes, reference rudder angles generated by the controller are larger than the maximum rudder angle. Then the rudder angle has to be limited, and changes of error in the control system are not defined by Eq. (4).
It is desirable for large course changes that the course-change is performed at constant turn rate. The transient component of the turn rate error $e_r = r_R - r$ is assumed to satisfy the equation:

$$\alpha_1 \cdot \dot{e}_r + e_r = 0 \tag{6}$$

where r_R is the required turn rate and α_1 is a time-constant. Placing the Norrbin model defined by Eq. (1) into Eq. (6) gives the formula that determines the rudder angles during the turn rate stabilisation period:

$$\delta_r = \frac{T}{k \cdot \alpha_1}(r_R - r) + \frac{1}{k} H_N(r) \tag{7}$$

For continuous operation of ship control system conditions for switching between course-keeping and rate of turn controllers have to be defined. In the course-keeping modus the values of course deviation angle and turn rate are small. Therefore in those situations switching the rate of turn controller on gives no benefit. At large reference course changes, the turn rate that is reached when the course-keeping controller is switched on corresponds to maximum rudder angle and is usually larger then rudder angle corresponding to the required turn rate. Therefore, in those cases the rate of turn controller is to be switched on as it generates smaller rudder angle than the course controller. Generally, the object is to be controlled by that controller in the control system, which calculates the smaller commanded rudder angle. The condition for using a rudder angle generated by one of the two controllers is the following:

$$\delta = \begin{cases} \delta_r & \text{if } \delta_r \le \delta_\psi \quad \text{turning controller} \\ \delta_\psi & \text{if } \delta_\psi < \delta_r \quad \text{course controller} \end{cases} \tag{8}$$

5. Computer simulation and performance view of the control system

The presented control algorithms were used for computer simulation tests, performed in Matlab-Simulink environment. The Simulink simulation diagram is shown in figure 6.
Model of the rudder dynamics ($\delta_{max}=\pm35$ deg, $(d\delta/dt)_{max}=10$ deg/s) were introduced into the tanker's model. Two control units, namely: course controller and turn controller are installed in the feedback loop. The decision which unit is in charge of rudder angle is determined by a sub-system comparing

the two control signals. Control simulation tests were performed for various sailing conditions: at different sailing speeds and different loads of the tanker. The figure 7 shows sample time-histories of the course, turn rate, and rudder angle within the time period including the course-change manoeuvre.

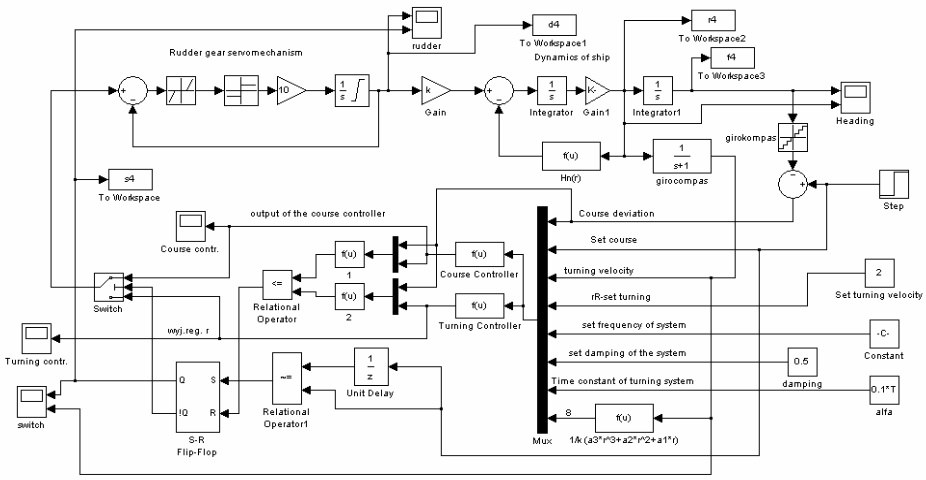

Figure 6. Simulation diagram of the ship course control system (Matlab-Simulink)

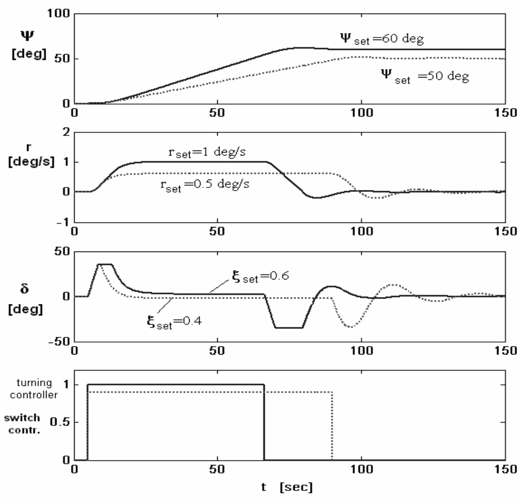

Figure 7. Time-histories of the course, turn rate, and rudder angle for physical model tanker Blue Lady

6. Implementation and verification of the control system on physical model of ship

The presented control algorithms were used to steering of the Blue Lady model. The tests were performed on the Silm Lake. Two PC-type computers were installed on the model and used as a hardware platform for control system. They were connected with gyrocompass Anschütz Standard 20 and steering gear via serial links RS 232 and RS 422. Real-time control system was built using Matlab-Simulink environment supported by Real Time Workshop and xPC-Target toolboxes.

Control tests were performed for various weather conditions: at different forward speed values and different load conditions of the model.

Figure 9 shows sample time-histories of the course, turn rate, and rudder angle within the time period including the course-changing manoeuvres with the turn controller switched on and off, as well as course-keeping sections.

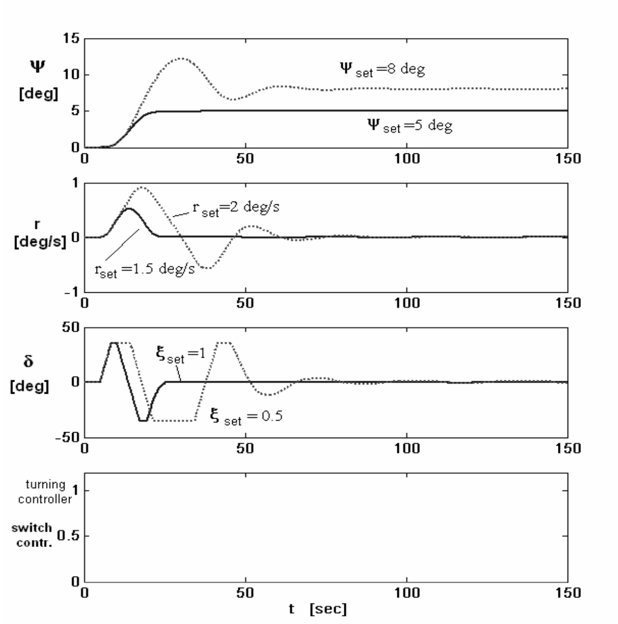

Figure 8. Time-histories of the course, turn rate, and rudder – turning controller not switch on

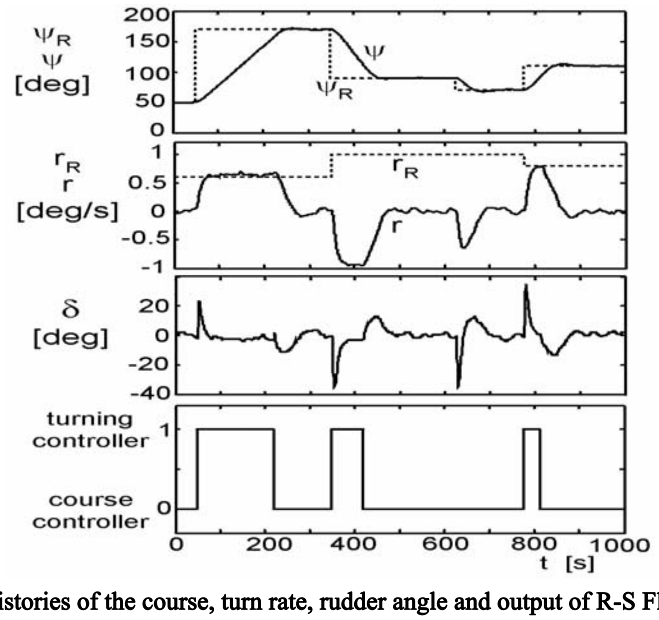

Figure 9. Time histories of the course, turn rate, rudder angle and output of R-S Flip Flop recorded during control system tests

7. Conclusions

On the basis of the performed identification and control tests the following conclusions can be formulated:

- The designed ship course control system meets all above defined requirements, reveals the ability to set up the control accuracy, over-shot value at course change, control time, and angular speed of the turn.
- The presented control system reveals good dynamical characteristics;
- The characteristics of the control system can be conveniently defined using direct transient indices, for instance control system natural frequency and relative damping factor, which can be easily transposed into other required quantities, like transient rise time or overshoot;
- The proposed method of controller switching is relatively simple, providing smooth transition of the control signal – the value of the commanded rudder angle. In cases when the reference course change is small, the controlled ship, generally, does not reach the required turn rate fast, therefore the rate of turn controller is switched on for a short time, or does not start at all.
- Designed control system has a good accuracy and very well properties. During investigation on the lake, when the wind speed exceeded 30kn for the real tanker, the model was controlled very reliable and with a fine accuracy within the limits of ±1.5 deg at the straight course. In the calm, the model yawed within the ±0.5 deg. Simultaneously the rudder motion was small and "soft".

References

Szymkat M., Komputerowe wspomaganie w projektowaniu układów regulacji, WNT Warszawa 1993

Isidori A., Nonlinear Control Systems, Springer Verlag, Berlin-New York, 1989.

Kobylinski L., (ed.) Manned Model Course on Handling of Large Ships and Ships with Unusual Manoeuvring Characteristics: Course File, Ship Handling Research and Training Centre, Ilawa, 1999

Ljung L. Matlab Identification Toolbox User's Guide, The MathWorks Inc., Natick, MA, 1997

Norrbin N. H., Theory and observation on the use of a mathematical model for ship maneuvering in deep and confined waters. Proceedings of the 8th Symposium on Naval Hydrodynamics, Pasadena CA,1970, pp.451-460

Van Amerongen, Adaptive Steering of Ships – A Model Reference Approach to Improved Manoeuvring and Economical Course Keeping, PhD Thesis, Technische Hogeschool, Delft 1982

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