SYSTEM DYNAMICS SIMULATION MODELLING OF THE VESSELS SYSTEMS AND PROCESSES

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ABSTRACT

The paper deals with dynamic analysis of automatic ship steering gear systems utilising complex controls that function according to the principle of proportional, integral and derivation regulators. The analysis involves a system dynamic simulation modelling methodology as one of the most suitable and effective means of dynamic modelling of complex non-linear, natural, organisational and technical systems.
The paper discusses system dynamics simulation models being used in qualitative (mental-verbal, structural) and quantitative (mathematical and computer) simulation models on ships equipped with trailing steering systems and PID regulator.
Authors suggest using the presented models for designing and constructing new steering systems, for diagnosing existing constructions and for education in Universities.

Keys words: System Dynamics, continuous model, simulation, ship direction.

Presenting Author's biography

Ante Munitić was born in Omis, Croatia. He received a double BS in 1. Electro-Energy Engineering and 2 Electronic Engineering, and a MS in Electronic-Operating Research at the University of Split, Croatia, and a Ph.D. degree in Organization Science (System Dynamics) at the Belgrade University, Yugoslavia. All degrees were earned while actively engaged in teaching at the university. He is now Full Professor Doctor of the Computer & Informatics Science and is a Maritime-Faculty University Professor of the following courses: 1. Computer science, 2. Marine Systems and Processes Management Modeling (System Dynamics) and 3. Marine Integral Information Systems. His research interests are 1. Researching System Dynamics Methodology, 2. Relative System Dynamics (optimization), 3. System Dynamics Analogizes, and 4. Dynamics of Chaotic System. He is a member of the Society for Computer Simulation and the System Dynamics Society.

1. INTRODUCTION

Integrated transport ships as means of transport have an important place both in transporting cargo and passengers. The ship has to have the ability to follow a given trajectory and to change its course according to given regulations.

The regime of keeping the ship on its given course to ensure its stability, as results of analysis show, requires frequent turning of the rudder blade. Manual steering, needed for 4^o to 6^o degree turns, turns the steering gear engine on and off app. 400 in an hour, while automatic steering raises this up to 1500.

The most important regime of navigation is straight linear movement of the ships along its course. This is achieved by steering gear which compensates for external disturbances and influences which can cause departures from the given course.

Automatic steering gear systems are used for automatic ship control. They can be stabilizational, trailing or programmed steering systems.

To steer the ship along its given course requires acquaintance with the nature and the power of forces affecting the ship, as well as the ship's manoeuvrability.

This paper deals with trailing systems of rudder control with PID-regulator. A mathematical model of the ship is given, in the form of a system of three differential equations, a model of a trailing system of ship rudder control, and a mathematical model of PID-regulator.

The third part discusses a dynamics structural model of automatic ship control with graphic displays of direct and indirect influences that each variable and parameter has on a particular element of the system.

The fourth part deals with a computer simulation model, where various disturbances affecting the ship's course are planned and anticipated, analysing their effect on ship direction, position of rudder and their frequency.

System dynamics is a research methodology for analysis modelling, simulating and optimising complex dynamic systems. This paper has utilised the system dynamics modelling as a relatively new scientific methodology applicable in analysis of technical, natural and social systems.

2. SYSTEM DYNAMICS SIMULATION MODELS OF THE VESSEL'S AUTOMATIC SEA-GOING REGULATION

Real systems are basically non-linear. In solving them, a linearization operation is usually applied, providing good results under certain restricting conditions. But in order to get a full picture of the reality, the system has to be observed as a whole. This approach allows a system dynamics over-view and the solution of problems. System dynamics is one of the most suitable and effective methods for dynamic modelling of complex non-linear natural, technical and organisation systems. It has its own set of strict rules for proper professional procedure and methodology. This means that system dynamics deal with time-dependent behaviour of managed systems for the purpose of describing the system and understanding, through qualitative (mental, verbal and structural) and quantitative (mathematical and computer) simulation models, how information feedback governs its behaviour, and designing robust information feedback structures and control policies through simulation and optimisation.

Ship navigation conditions are not permanent. They are subject to continuous change because of changes in the sea and atmospheric conditions, navigational routes and areas, work assignments and regimes. When building a mathematical model of a ship, it is necessary to assume one is dealing with a solid body that has six degrees of freedom of movement. The movement of the ship, as it engages rudder control for disturbances affecting the ship and causing torque on a horizontal plane, can be observed at small values of angle of inclination, differential values, insignificant vertical movements, and movements with small values for the angle of roll. Today, different variants of non-linear differential equations systems are used which, each with a different basic manner of writing.

In order to get equations of the state of automatic control of steering systems it is necessary to break down the whole system into functional blocks as shown in the picture 1. The picture shows a block diagram of an automatic navigation control system for navigation along a given course, with basic units clearly marked: the ship (B), as the object of regulation, the trailing system of rudder control (SSUKB) and the PID-regulator with proportional, integral and derivational functions (PID-R).

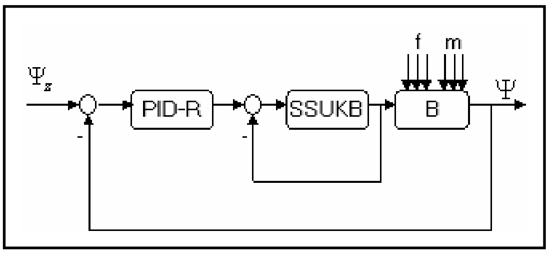

Figure 1. Block diagram representing an automatic ship navigation control system

2.1. SYSTEM DYNAMICS SIMULATION MODELS OF THE VESSEL

The dynamic mathematical ship navigation model gives a principle according to which ship parameters change during navigation on a horizontal plane and under influence of various disturbances (8).

$$\frac{d\psi}{dt} = \omega \qquad (1)$$

$$\frac{d\beta}{dt} = f - k_1\alpha - k_2\beta - k_3\beta|\beta| - k_7\omega \qquad (2)$$

$$\frac{d\omega}{dt} = m - k_4\alpha - k_5\beta - k_6\omega \qquad (3)$$

ψ - relative value for the change of the course angle;
α - relative value for the change in the rudder angle;
m - coefficient of disturbance depending on the influence of the wind, sea currents and waves, length of the ship, the moment of inertia of ship, ship speed and added water mass which is being moved by ship movement;
ω - relative value for the change of angular velocity;
β - relative value of angle of roll;
f - coefficient of disturbance depending on the forces on the wind, waves, currents, length of the ship, water mass being moved by ship movement and ship speed influences;
k_1 - k_7 - corresponding coefficient of reinforcements.

In accordance with system dynamics quantitative or mathematical model (equations from 1-3) it would be possible to work out the structural and mental-verbal system dynamics simulation model of the vessel's navigation process (Figure 2.).

It is possible to see that the structural model has a lot of the cause-consequences links (CCL), as well as four feedback loops (FBL).

The System Dynamics Mental-verbal model of the vessel's navigation system or process is:

"If the constants K_1, K_2, K_3, K_7- coefficients of reinforcements grow, then the rate variable DBETADT-rate or speed of the relative value of angle of roll will drop. This means that the CCLs have a negative (-) dynamics character."

Furthermore:
"If the coefficients F and M grow, then the rate variable DBETADT will grow also". This means that both of the CCLs have a positive (+) dynamics character."

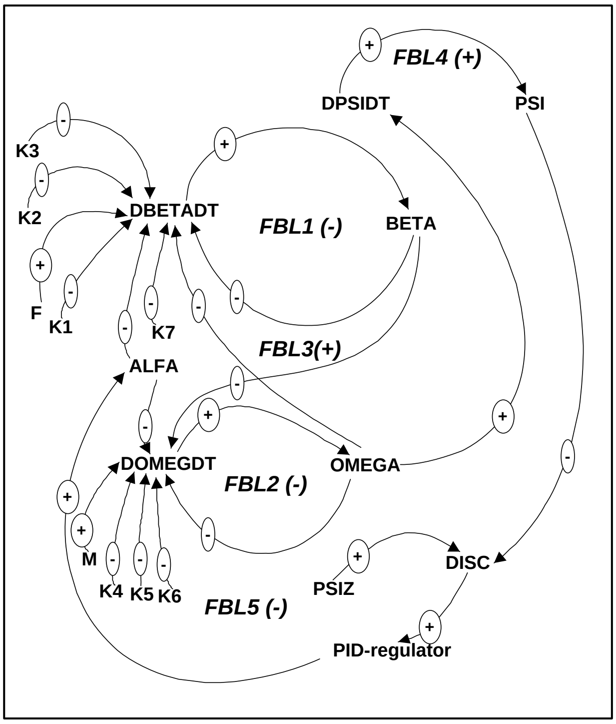

Figure .2. System Dynamics Structural model of the vessel's navigation process

On the same way, we could work out complete mental and verbal models of the all FBLs, but in the abreviated-simbolic way:

FBL1.(-):DBETADT (+) =>BETA (-)=>DBETADT;
FBL2.(-):DOMEGDT(+) =>OMEGA(-)=>DOMEGDT;
FBL3.(+):DOMEGDT(+)=>OMEGA(-) => DBETADT(+) => BETA(-) =>DOMEGDT;
FBL4.(+):DPSIDT(+)=>PSI(-)=>DISC(+)=>PID(+)=>ALFA(-) => DOMEGDT(+)=>OMEGA(+)=>DPSIDT;
FBL5.(-) :DBETADT(+)=> BETA()=>DOMEGDT(+) => OMEGA(+) => DPSIDT(+)=>PSI(-) =>DISC(+)=> PID(+)=> ALFA(-)=>DBETADT;

2.2. SYSTEM DYNAMICS SIMULATION MODEL OF THE VESSEL'S RUDDER CONTROL

The task of the trailing system of automatic regulation is to change the regulated dimensions according to the changes of leading dimensions. In the analysed example SSUBK consists of:

- a semi-conductor amplifier which amplifies the signal of the difference between the given and actual value of the rudder angle,
- a performing engine and reductor which, under the influence of the correct voltage, rotates the engine shaft and reductor,

- a lever transmission, which turns the circular movement of the shaft of the performing engine into steering movement of the distributor rod,
- a selsin sensor working in a transformer regime
- elements of solid feedback; in a local feedback, the selesin sensor and reductor are used,
- elements of feedback of position of rudder sensor
- member of feedback according to the ship's course, which is both a selsin giver and receiver,
- a hydraulic drive.

The following system dynamics mathematical model describes dynamic features of the given SSUBK elements:

$$U_{11} = U_{10} - K_{20}K_{22}\Theta_{12} - K_{23}K_{24}K_{25}\alpha_{12} \quad (4)$$

$$U_{12} = K_{21}U_{11} \quad (5)$$

$$U_{13} = f(U_{12}) \quad (6)$$

$$\frac{d\Theta_{11}}{dt} = K_{26}K_{27}U_{13} \quad (7)$$

$$\Theta_{12} = f(\Theta_{11}) \quad (8)$$

$$h_{11} = K_{28}\Theta_{12} \quad (9)$$

$$\frac{d\alpha_{11}}{dt} = K_{29}h_{11} \quad (10)$$

$$\alpha_{12} = f(\alpha_{11}) \quad (11)$$

U_{10} - relative value of given voltage
U_{11} - relative value of voltage at the exit from summator
U_{12} -relative value of voltage at the exit from semiconductor amplifier
U_{13} - relative value of voltage which id in nonlinear function
Θ_{11}- relative value of theperforming engine shaft's turning angle
α_{11} - relative value of rudder turning angle
h_{11} - relative value of the shift of handle that runs position of distributor piston
K_{20-29} - coefficients of transmission of different mechanisms in SSUBK.

2.3. SYSTEM DYNAMICS SIMULATION MODEL OF THE PID REGULATOR

PID-regulator incorporates in itself proportional, integral and derivation action. Its dynamic behaviour can be defined with the following mathematical model:

$$\psi_{10} = \psi_z - \psi \quad (12)$$

$$U_{30} = K_{31}\psi_{10} \quad (13)$$

$$\frac{dU_{31}}{dt} = K_{32}U_{30} \quad (14)$$

$$T_{33}\frac{dU_{33}}{dt} = K_{33}\frac{dU_{30}}{dt} - U_{33} \quad (15)$$

$$U_{10} = U_{30} + U_{33} + U_{31} \quad (16)$$

U_{30} - relative value of change in voltage because of ship's change of course
U_{31}- relative value of voltage at the exit from I-member
U_{33} - relative value of voltage at the exit from D-member
K_{31} - coefficient of P-member amplification
K_{32} - coefficient of I-member amplification
K_{33} - coefficient of D-member amplification
T_{33} - time constant of D-member.

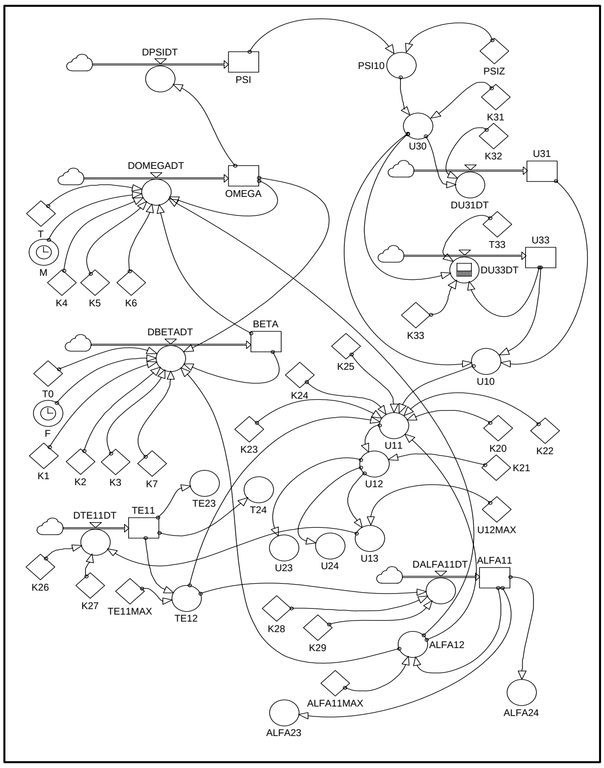

Figure 2.4. System Dynamics structural flows diagram of the ship, following system and PID-regulator in the PowerSim simulation simbols

2.4. SYSTEM DYNAMICS COMPUTER SIMULATION MODEL OF VESSEL'S AUTOMATIC SEA-GOING REGULATION

In accordance with the system dynamics quantitative or mathematical model (equations from 1 to 17), it would be possible to work out the system dynamics structural flows diagram and computer simulation global model of the ship, the trailing system and the PID-regulator (Figure 2.4.). These models are worked out in the POWERSIM-graphical oriented language, which uses special graphical and equation symbols.

The System Dynamics Computer Simulation Model of the Ship, the Trailing System and PID-regulator in the PowerSim language package is:

```
init     ALFA11 = 0
flow     ALFA11 = +dt*DALFA11DT
init     BETA = 0
flow     BETA = +dt*DBETADT
init     OMEGA = 0
flow     OMEGA = +dt*DOMEGADT
init     PSI = 0
flow     PSI = +dt*DPSIDT
init     TE11 = 0
flow     TE11 = +dt*DTE11DT
init     U31 = 0
flow     U31 = +dt*DU31DT
init     U33 = 0
flow     U33 = +dt*DU33DT
aux      DALFA11DT = K28*K29*TE12
aux      DBETADT = (1/T0)*(F-K1*ALFA12-K2*BETA-
K3*BETA*ABS(BETA)-K7*OMEGA)
aux      DOMEGADT = (1/T)*(M-K4*ALFA12-K5*BETA-
K6*OMEGA)
aux      DPSIDT = OMEGA
aux      DTE11DT = K26*K27*U13
aux      DU31DT = K32*U30
aux      DU33DT = (1/T33)*(K33*DERIVN(U30,1)-U33)
aux      ALFA12  =3*IF(ABS(ALFA11)>= ALFA11MAX,
ALFA11MAX* SIGN(ALFA11),ALFA11)
aux      ALFA23 = ABS(ALFA11)
aux      ALFA24 = SIGN(ALFA11)
aux      F = STEP(.1,20)+-STEP(.1,40)
aux      M = STEP(.1,10)-STEP(.2,20)+STEP(.1,25)+
PULSE
(.3,60,160)+.05*SIN(6.28*TIME/2)*IF(TIME>=80,1,0)+STEP(.
1,120)
aux      PSI10 = PSIZ-PSI
aux      T24 = SIGN(TE11)
aux      TE12 = IF(ABS(TE11)>=TE11MAX,TE11MAX*
SIGN(TE11),TE11)
aux      TE23 = ABS(TE11)
aux      U10 = U30+U31+U33
aux      U11 = U10-K20*K22*TE12-
K23*K24*K25*ALFA12
aux      U12 = K21*U11
aux      U13 =
IF(ABS(U12)>=U12MAX,U12MAX*SIGN(U12),U12)
aux      U23 = ABS(U12)
aux      U24 = SIGN(U12)
aux      U30 = K31*PSI10
const    ALFA11MAX = 1
const    K1 = .05921136
const    K2 = .05
const    K20 = 15
const    K21 = 2
const    K22 = 50
const    K23 = 15
const    K24 = 8
const    K25 = 8
const    K26 = .5
const    K27 = .5
const    K28 = 5
const    K29 = 5
const    K3 = .05
const    K31 = .5
const    K32 = .5
const    K33 = .1
const    K4 = .08
const    K5 = .10435
const    K6 = .03
const    K7 = .09
const    PSIZ = 0
const    T = 200
const    T0 = 5
const    T33 = 1
const    TE11MAX = 1
const    U12MAX = 1
```

3. SIMULATION SCENARIO

The simulation of automatic navigation of a ship has the following scenario:
The horizontal axis represents the time variable.
The load on the ship under automatic navigation is as follows:

- In the 10^{th} second, it changes 10% according to the bounce function,
- In the 20^{th} second, it changes 20% according to the bounce function in the opposite direction,
- In the 25^{th} second, the load decreases 10% according to the rebounce function,
- In the 60^{th} second, an impulse load functions with 20%,
- In the 80^{th} second there is a deviation in accordance with the sinus function with the amplitude of 10%.

4. SIMULATION RESULTS

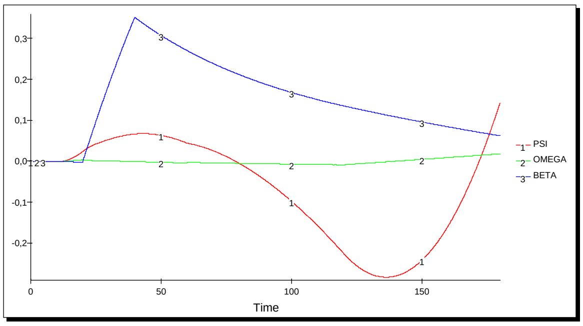

Figure. 4.1. Graphic results of simulation

5. CONCLUSION

The paper utilises one of the most contemporary methods of presenting and analysing dynamic behaviours of a system for automatic navigation and rudder control.
The structural dynamic model enables a visual presentation of very complex systems such as the one used for automatic rudder control for keeping a ship on course. On basis of mathematics and computer models, as well as a structural diagram, it is possible to determine the dynamic behaviour of a system as a whole in accordance to scenarios of one's own choice. It is also possible to make a choice and conduct an analysis of influences with numerous parameters that affect the behaviour of the system.

The authors suggest the use of presented models for designing new constructions of rudder systems, for diagnosing existing devices, and for conducting training processes which provide active and creative participation of students in the process.

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