

## ANALYSIS OF THE PERFORMANCE OF THE SHIP STEAM BOILER USING SIMULATION

by

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*The aim of this paper is to demonstrate the successful application of system dynamics simulation modelling at investigating performance dynamics of the ship steam boiler. Ship steam boiler is a complex non-linear system which needs to be systematically investigated as a unit consisting of a number of subsystems and elements, which are linked by cause-effect feedback loops, both within the system and with the relevant surrounding. In this paper the authors will present the efficient application of scientific methods for the research of complex dynamic systems called qualitative and quantitative simulation system dynamics methodology, which will allow for production and use of higher number and kinds of simulation models of the observed elements, and finally allow for the continuous computer simulation, which will contribute to acquisition of new information about the non-linear character of performance dynamics of ship steam boilers in the process of designing and education. Ship steam boiler will be presented in POWERSIM simulation language in mental-verbal, structural, and mathematical computer models.*

**Key words:** *ship steam boiler, simulation modelling, system dynamics, continuous and discrete simulation*

### Introduction

The purpose of this paper is to present the efficiency of application of the system dynamics simulation modelling [1] to the research of performance dynamics of complex non-linear marine propulsion systems. The ship boiler system is a complex non-linear system which needs to be systematically investigated as a whole, consisting of a number of subsystems and elements, which are linked by cause-effect (UPV) feedback loops (KPD), both within the propulsion system and with the relevant surroundings.

The essential hypothesis of this paper is the authors' conviction that the ship steam boiler is a non-linear and very complex technical system with pronounced multiple, inter-causal connections and feedback loops dominating the performance of the relevant variables.

Furthermore, the additional assumption is that these pronounced manifestations are so complex that only the application of the relatively newer scientific methodology of the system dynamics simulation modelling will eventually result in a higher level of insights into dynamic phenomena of transitional manifestations of the observed system, which will be confirmed, in both theoretical and practical ways, by the scientific comparison of simulation results with empirical measurements.

Indirect methodologies, which have been used so far, do not meet present-day needs for insights into behaviour dynamics of non-linear ship systems. They have been based on using

classical, mainly linearised methods such as Laplace's transformation, transient functions, and stability criteria.

Although System dynamics, as a scientific discipline, has been around for several decades, it was the high performance speed of modern digital computers, which increased the accuracy of simulation modelling, that has now allowed practical and simple application of the computer simulation of non-linear dynamic systems of higher level (whose models comprise thousands of differential equations), *i. e.* extremely complex systems. Over the last few years the dynamic simulation system has been used to a great extent during research of behaviour dynamics of all sorts of complex systems.

The authors believe that System dynamics is an excellent scientific tool for investigating behaviour dynamics of complex engine systems, sub-systems, and elements. System dynamics as a scientific discipline is actually a mathematical-computer-simulation methodological tool that serves as the basis of the general system theory and management theory.

Given the high complexity of ship systems, this paper has presented the efficiency of application of a scientific method of investigating complex dynamic systems called: Qualitative and quantitative simulation methodology of System dynamics (System Dynamics Modelling Approach – MIT), which has enabled designing and using a number of types of simulation models for an observed reality, and has finally enabled a continued computer simulation using fast and accurate digital computers. This has considerably contributed to acquiring new insights into the non-linear nature of performance dynamics of the boiler system in the process of designing and education.

Simulation modelling, supported by System dynamics and intensive use of modern digital computers, is one of the most appropriate and successful scientific methods of investigating performance dynamics of non-linear natural, technical and organisational systems. In the educational and design practice so far, the methodology of system dynamics, as a relatively newer scientific discipline, proved to have been an efficient tool in the scientific research of the problems of management, behaviour, sensitivity, and flexibility of numerous systems and processes.

## **Simulation modelling of the ship steam boiler**

### *Mathematical model of ship steam boiler*

Studying thermodynamic behaviour of ship steam boiler may be, performed in such way that the steam boiler is observed as a heating capacity unit consisting of the following heating capacity elements, according to [2-6]:

- metal parts of the boiler,
- economisers,
- quantity of water in the boiler and pipes,
- quantity of dry saturated and overheated steam, and
- steam super heater.

The boiler may be considered as a homogenous device, a thermal accumulator, *i. e.* a homogenous thermal capacity. The equations of thermal balance of such thermal accumulator (capacity) suggest determining the equation for the level of the water in the boiler.

In order to create equations of performance dynamics of the boiler it is necessary to observe only the steam piping part of the boiler (fig. 1).

The following are brought to the steam piping:

- thermal power of the fuel which is brought to the burner of the boiler  $Q_G$  [kJh<sup>-1</sup>],

- thermal power of the feed water which is brought to the boiler  $Q_{PV}$  [kJh<sup>-1</sup>], and
- thermal power of the steam which is discharged from the boiler  $Q_P$  [kJh<sup>-1</sup>].

System dynamics mathematical model of the ship steam boiler is defined by explicit form of differential equations, according to [2]:

(1) Equation of the boiler dynamics for the steam pressure:

$$\frac{d\varphi_K}{dt} = \frac{1}{T_{a1}} (\mu_G - a_1\mu_V - a_2\mu_P - a_3 \frac{d\mu_P}{dt} - k\varphi_K) \quad (1)$$

(2) Equation of the boiler dynamics for the water level:

$$\frac{d\varphi_Y}{dt} = \frac{1}{T_{a2}} (\mu_V - b_1\varphi_K - b_2 \frac{d\varphi_K}{dt} - b_3\mu_P - b_4 \frac{d\mu_P}{dt}) \quad (2)$$

where  $\varphi_K$  is the relative state of the steam pressure in the boiler,  $\varphi_Y$  – the relative state of the water level in the boiler,  $T_{a1}$  [s] – the time constant of the steam boiler for the steam pressure,  $T_{a2}$  [s] – the time constant of the steam boiler for the water level,  $k$  – the coefficient of self-regulation of the steam boiler,  $\mu_G$  – the relative change of the position of the fuel valve,  $\mu_V$  – the relative change of the valve of the feed water,  $\mu_P$  – the relative change of the position of the steam discharge valve,  $d\varphi_K/dt$  – the speed of the change of the relative increment of the boiler steam pressure,  $d\mu_P/dt$  – the speed of the relative change of the position of the steam discharge valve,  $a_{1,2,3}$  – are the coefficients of the steam boiler for the steam pressure, and  $b_{1,2,3,4}$  – the coefficients of the steam boiler for the water level.

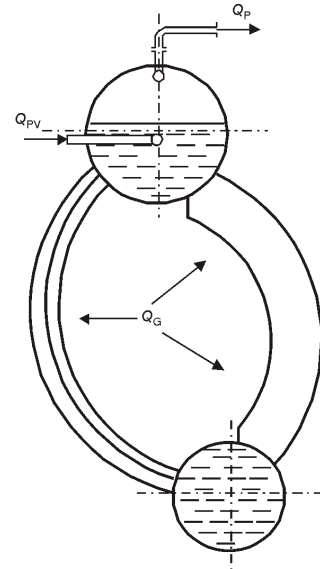


Figure 1. Presentation of the steam boiler with natural circulation [7]

*System dynamics mental-verbal of the ship steam boiler*

On the basis of a mathematical model, or the explicit form of the mode equation of the ship steam boiler (1) it is possible to determine the mental-verbal model of the ship steam boiler:

- if the relative increment of the steam pressure in the boiler  $\varphi_K$  increases, the speed of the change of the relative pressure in the boiler  $d\varphi_K/dt$  will decrease, which gives a negative cause-effect link (-), and
- if the speed of the change of the relative increment of the steam pressure  $d\varphi_K/dt$  increases, the state of the relative increment of the steam pressure in the boiler  $\varphi_K$  will increase, which is the integral or sum of all changes of the state, which gives a positive cause-effect link (+).

In the observed circle of the cause-effect (KPD) there are only two cause-effect (UPV) links, and the sum of their negative values is 1, so the global sign for cause-effect KPD is negative, which means self-regulating, which leads any change of the state towards quiescent state according to [8]:

- if the coefficient of self-regulation of the steam boiler for the steam pressure  $k$  increases, the speed of the change of the relative increment of the steam pressure in the boiler  $d\varphi_K/dt$  will decrease, which gives a negative cause-effect link (-);
- if the time constant of the boiler for the steam pressure  $T_{a1}$  increases, the speed of the change of the state of the relative increment of the boiler steam pressure  $d\varphi_K/dt$  will decrease, which gives a negative cause-effect link (-);

- if the relative change of the position of the fuel supply valve  $\mu_G$  increases, which assumes the increase of fuel supply in the time unit, the speed of the change of state of relative increment of the boiler steam pressure  $d\varphi_K/dt$  will increase, which gives a positive cause-effect link (+);
- if the auxiliary coefficient  $a_1$  increases, the speed of the change of relative increment of the boiler steam pressure  $d\varphi_K/dt$  will increase, which gives a positive cause-effect link (+);
- if the relative change of the position of the feed water valve  $\mu_V$  increases, the speed of the change of the relative state of the increment of the boiler steam pressure  $d\varphi_K/dt$  will increase, which gives a positive cause-effect link (+);
- if the auxiliary coefficient  $a_2$  increases, the speed of the change of the state of the relative increment of the boiler steam pressure  $d\varphi_K/dt$  will decrease, which gives a negative cause-effect link (-);
- if the relative change of the steam discharge valve  $\mu_P$  increases, the speed of the change of the state of the relative increment of the boiler steam pressure  $d\varphi_K/dt$  will decrease, which gives a negative cause-effect link (-);
- if the auxiliary coefficient  $a_3$  increases, the speed of the change of state of the relative increment of the boiler steam pressure  $d\varphi_K/dt$  will decrease, which gives a negative cause-effect link (-);
- if the speed of the relative change of the position of the boiler steam discharge valve  $d\mu_P/dt$  increases, the speed of the change of the state of the relative increment of the boiler steam pressure  $d\varphi_K/dt$  will decrease, which gives a negative cause-effect link (-);
- if the relative change of the position of the boiler steam discharge valve  $\mu_P$  increases, the speed of the change of the relative change of the boiler steam discharge valve position  $d\mu_P/dt$  will increase, which gives a positive cause-effect link (+).

On the basis of the mathematical model, or the explicit form of the equation of the ship steam boiler (2) it is possible to determine the mental-verbal model of ship steam boiler:

- dynamic performance process of the steam boiler with natural circulation for the water level does not have self-regulating property, because there is no internal negative cause-effect link (UPV), which the dynamic process of steam boiler performance with natural circulation for the steam pressure has:
- if the time constant of the steam boiler for the water level  $T_{a2}$  increases, the speed of the change of the state of relative increment of the boiler water level  $d\varphi_Y/dt$  will decrease, which gives a negative cause-effect link (-);
- if the relative change of the feed water valve position  $\mu_V$  increases, the speed of the change of the relative increment of the steam boiler water level  $d\varphi_Y/dt$  will increase, which gives a positive cause-effect link (+);
- if the auxiliary coefficient  $b_1$  increases, the speed of the change of the state of the relative increment of the steam boiler water level  $d\varphi_Y/dt$  will decrease, which gives a negative cause-effect link (-);
- if the relative increment of the boiler steam pressure  $\varphi_K$  increases, the speed of the change of the state of the relative increment of the boiler water level  $d\varphi_Y/dt$  will decrease, which gives a negative cause-effect link (-);
- if the auxiliary coefficient  $b_2$  increases, the speed of the change of the state of the relative increment of the boiler water level  $d\varphi_Y/dt$  will decrease, which gives a negative cause-effect link (-);
- if the speed of the change of the relative increment of the steam pressure  $d\varphi_K/dt$  increases, the speed of the change of the state of the relative increment of the boiler water  $d\varphi_Y/dt$  level will decrease, which gives a negative cause-effect link (-);

- if the relative change of the position of the steam discharge valve  $\mu_p$  increases, the speed of change of the state of the relative increment of boiler water level  $d\phi_Y/dt$  will decrease, which gives a negative cause-effect link (-);
- if the auxiliary coefficient  $b_3$  increases, the speed of the change of the state of the relative increment of the boiler water level  $d\phi_Y/dt$  will decrease, which gives a negative cause-effect link (-);
- if the speed of the change of the relative position of the boiler steam discharge valve  $d\mu_p/dt$  increases, the speed of the change of the state of the relative increment of the boiler water level  $d\phi_Y/dt$  will decrease, which gives a negative cause-effect link (-);
- if the auxiliary coefficient  $b_4$  increases, the speed of the change of the state of the relative increment of the boiler water level  $d\phi_Y/dt$  will decrease, which gives a negative cause-effect link (-).

*System dynamics structural models of the ship steam boiler*

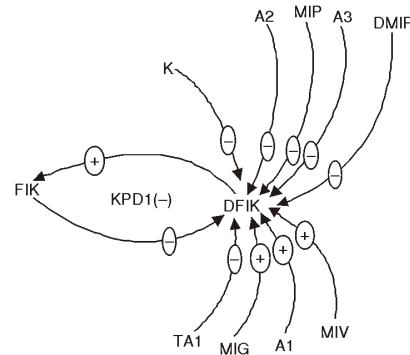
On the basis of the stated metal-verbal models it is possible to produce structural diagrams of the ship steam boiler, as shown in figs. 2, 3, and 4, according to [9-13].

In the observed system there is the feedback loop (KPD1).

KPD1(-):FIK=>(-)DFIK=>(+)DFIK=>(+)FIK; which has self-regulating dynamic character (-), because the sum of negative signs is an odd number.

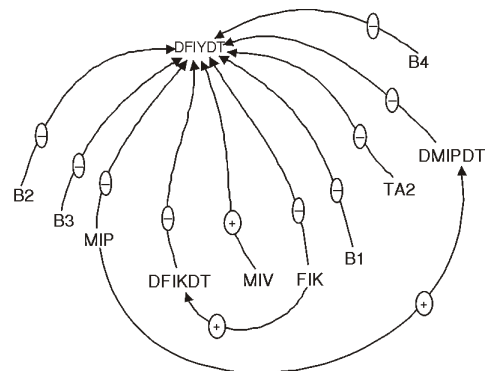
**Figure 2. Structural model of the ship steam boiler – for steam pressure**

*FIK* ( $\phi_K$ ) – relative state of the steam pressure in the boiler, *TA1* ( $T_{a1}$ ) – time constant of the steam boiler for the steam pressure, *K* ( $k$ ) – coefficient of self-regulation of the steam boiler, *MIG* ( $\mu_G$ ) – relative change of the position of the fuel valve, *MIV* ( $\mu_V$ ) – relative change of the valve of the feed water, *MIP* ( $\mu_P$ ) – relative change of the position of the steam discharge valve, *DFIK* ( $d\mu_K/dt$ ) – speed of the change of the relative increment of the boiler steam pressure, *DMIP* ( $d\mu_P/dt$ ) – speed of the relative change of the position of the steam discharge valve, and *A1-3* ( $a_{1, 2, 3}$ ) – coefficients of the steam boiler for the steam pressure



**Figure 3. Structural model of the ship steam boiler – for the water level**

*FIK* ( $\phi_K$ ) – relative state of the steam pressure in the boiler, *TA2* ( $T_{a2}$ ) – time constant of the steam boiler for the water level, *MIV* ( $\mu_V$ ) – relative change of the valve of the feed water, *MIP* ( $\mu_P$ ) – relative change of the position of the steam discharge valve, *DFIYDT* ( $d\mu_Y/dt$ ) – speed of the change of the state of relative increment of the boiler water level, *DFIK* ( $d\mu_K/dt$ ) – speed of the change of the relative increment of the boiler steam pressure, *DMIP* ( $d\mu_P/dt$ ) – speed of the relative change of the position of the steam discharge valve, and *B1-4* ( $b_{1, 2, 3, 4}$ ) – coefficients of the steam boiler for the water level







After the engineer, designer or a student have conducted a sufficient number of experiments, or scenarios, and an insight has been obtained about the performance dynamics of the system using the method of heuristic optimisation, optimisation of any parameters in the system may be performed, provided that the model is valid.

In the presented scenario the simulation model of the ship steam boiler for the steam pressure and the water level with two built-in PID governors will be presented [16-18].

- (1) Consumption of the steam is determined by the impulse function of 50 seconds duration, which means from 200-250 seconds, and  $MIP = 0$ ,  $FIK = 0$ ,  $FIY = 0.9999$  at the initial  $TIME = 0$ .
- (2) Fuel supply MIG is determined as an outlet of PID governor, at which inlet there is the discrepancy of the steam pressure ( $1-FIK$ ), and correspondingly, the water supply MIV is outlet of the other PID governor, to which the inlet is discrepancy ( $1-FIY$ ).
- (3) Other parameters of the ship steam boiler equal nominal values.

Graphic results of the simulation are shown in figs. 6-9.

From the results of the simulation it may be observed that the model shows real performance dynamics and that by applying PID governors and adequate values of coefficients better levelling and attenuation of the transition occurrence of the variables  $FIK$  and  $FIY$  will be achieved.

## Conclusions

System dynamics is a scientific method which allows simulation of the most complex systems. The method used in the presented example demonstrates a high quality of simulations of complex dynamic systems, and provides an opportunity to all interested students or engineers to apply the same method for modelling, optimising and simulating any scenario of the existing elements.

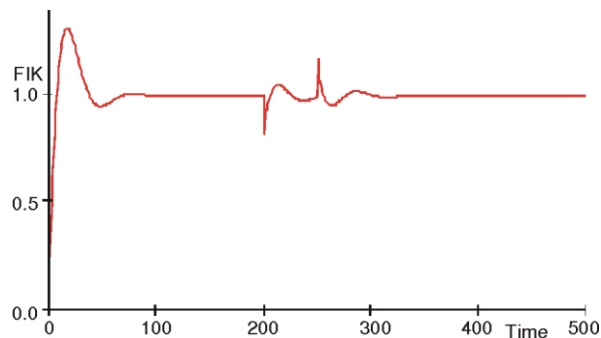


Figure 6. Relative state of the steam pressure in the steam boiler

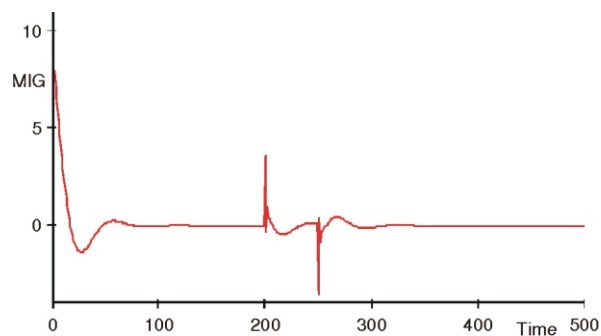


Figure 7. Relative change of the position of the fuel valve

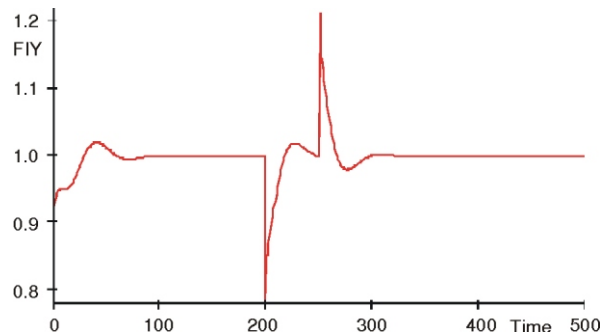
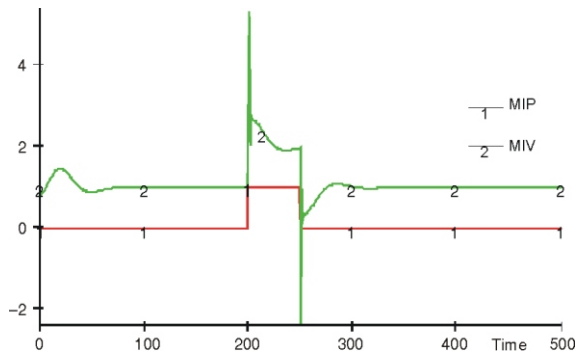


Figure 8. Relative state of the water level in the steam boiler



**Figure 9. Relative change of the position of the feed water valve and relative change of the position of the steam discharge valve (color image see on our web site)**

Furthermore, the users of this method of simulating continuous models in digital computers have an opportunity to acquire new information in dynamic systems performance. The method is also important because it does not only refer to computer modelling, but also clearly determines mental, structural, and mathematical modelling of the elements of the system.

This paper's contribution is as follows.

New insights have been made into performance dynamics of a complex ship boiler system. All relevant causal connections have been defined as well as relevant feedback loops dominating within a ship steam boiler.

- The design of the dynamic simulation model of a ship steam boiler enables diagnosis, condition forecasting, and higher quality of decision making, aiming at the safe managing of the operation of the ship as a whole,.

In the process of education of present and future university marine and electrotechnical engineers in the field of simulation modelling of complex organizational, natural, and technical systems.

Enables students, technicians, and engineers to “feel” the performance dynamics of the ship steam boiler as a whole at any moment.

Enables designers of new ship propulsion systems and processes to get necessary information in the stage of designing by using computer in applying the systematically dynamic scientific method of simulation modelling, and to avoid waiting for the results of experimental testing.

Forming basis for further scientific research of the performance dynamics of ship propulsion systems as a whole, and of ship handling systems in view of the long-term development project of the “intelligent” ship handling.

In this paper we have presented an efficient application of the system-dynamic methodology of simulation modelling while investigating the performance dynamics of technical systems with non-linear characteristics, aiming at a more thorough research of performance during transient phenomena occurring when working conditions and exploitation loads are changed.

This paper deals with the ship steam boiler, *i. e.* we have made qualitative and quantitative simulation models based on the mathematical model which is partly taken from [2] (pages 26-31). Eventually the model has been shown with a set of differential equations, which indeed makes it one of exceptionally complex technical systems with dominating set of relevant causal connections and feedback loops that we have defined. The simulation has been carried out with regard to the performance dynamics of the observed systems.

Based on our long term experience in the application of dynamics methodology of simulating and in this short presentation we provide to each expert who needs it, the possibility



to acquire additional knowledge about the same system in a brief scientifically based method of exploring the complex systems [19-21]. It means:

“Do not simulate behavior dynamics of complex system using so called *black box* approach, because practice of education and designing of complex system confirmed that is better to simulate using the so called *white box* approach, e. g. *System dynamics methodology!*”

Finally, we may quote the Chinese proverb saying:

*“When I hear I forget. When I see I remember. When I work I understand.”*

This wisdom can be rephrased into the System dynamics notions as a summarization of our conclusion:

*“When I hear mental and verbal model of dynamic process,  
I forget”.*

*“When I see structural model and reality of dynamic process,  
I remember.”*

*“When I make mathematical or computing simulation model of  
dynamic process, I learn”.*

*“When I make simulation or exercise either on System dynamic model or dynamic process, I refresh my technical knowledge with gained theoretical and practical knowledge on dynamic process”.*

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