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Correction of steam superheater mathematical model

SUMMARY

The article presents a model of the steam superheater installed in the main propulsion boilers on board t/t GIEWONT. The model structure is non-linear with time-lags. The correction of model static and dynamic properties was carried out in view of adapting it to optimal control synthesis. The correction includes the compensation of measurable and non-measurable disturbances. The compensation of measurable disturbances was based on the condition of total invariance, while the compensation of non-measurable disturbances was done on the basis of a formulated principle of an internal model for SISO linear stationary time-lag systems.

INTRODUCTION

The efficiency of the steam turbine power plant can be increased by raising the superheated steam temperature at the superheater outlet. The superheater, a very expensive element of the boiler equipment, is usually chosen so that investment costs can be possibly low. That is why it often works at the limits of its strength parameters. A major threat for superheater is the exceeding of a working temperature above which its durability rapidly drops. To increase the superheater working temperature it was necessary to work out a control system that would maintain the working temperature within a narrow range with high accuracy. To this end a steam superheater model was developed which accounts for both sea passage states and manoeuvring states.

MODEL OF TURBINE POWER PLANT STEAM SUPERHEATER

On board t/t GIEWONT and many other similar ships main propulsion boilers are fitted with two-stage superheaters which increase steam temperature to 788 K (515°C). The steam temperature control is effected by changing the position of a three-way mixing valve. Basic factors affecting the steam temperature at the superheater outlet are changes of fuel and air quantities fed into the boiler. These changes are well correlated with boiler load fluctuations [3].

Gathered data on the static and dynamic properties of steam superheaters [1], [2], [3] with parameters similar to those of the superheater installed on the t/t GIEWONT allow to draw several conclusions concerning the superheater model structure.

1. The steam superheater is a plant that at its steady state can be described by a nonlinear equation:

$$T = f(\alpha)_{Q=const}$$

where T, α and Q are, respectively, steam temperature at the superheater outlet, position of three-way mixing valve and boiler load.

2. Critical factors affecting the steam temperature, of the disturbing character, are changes of fuel and air quantities delivered to the boiler.

3. Changes of fuel and air quantities delivered to the boiler are well correlated with boiler load.

4. Dynamic properties of the main line are well described by the differential second order equation with delayed argument, the coefficients of which are functions of the boiler load.

5. Dynamic properties of the disturbance line are well described by the transfer function of time-lag second order unit.

The superheater model structure eventually adopted is shown in Fig. 1.

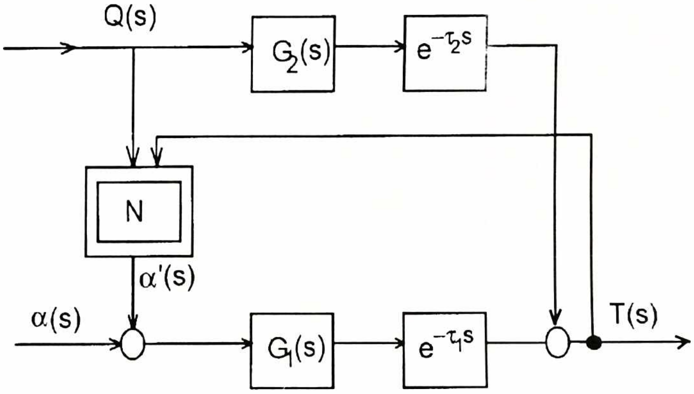

Fig. 1. Diagram of steam superheater model structure:
Q – boiler load, α – position of three-way mixing valve, T – steam temperature at superheater outlet, N – nonlinear static unit, and G, G_2, α':

$$G_2(s) = \frac{T_{3C}s+1}{(T_{1C}s+1)^2} \qquad G_1(s) = \frac{T_{2C}s+1}{(T_C s+1)^2}$$

$$\alpha' = N(Q,T)$$

A universal model-tuning method was used for parameter identification. Model parameter values were chosen as mean values from the analyzed functions. The conducted verification proved the correctness of the model at the significance level 0.05 [3],[4].

The accepted model well reflects dynamic properties of the steam superheater both in sea passage conditions (steady states) and at sudden changes of load that occur during manoeuvres. This is demonstrated in Tab. 1 which includes examples of superheated steam temperature changes at the outlets of the real plant and the model. The values of boiler load Q, position of three-way mixing valve a and temperature T are the values measured on board.

The investigation based on measurement results from other ships with an equivalent type of superheater has confirmed the correctness of the model.

Tab. 1 Superheated steam temperature changes of the real plant and the model

Time	Q	α	T	Deviation T from real value
s	T/h	% of open.	°C	°C
0	20,60	11,0	503,70	0,00
20	20,94	11,0	503,70	0,00
40	20,60	11,0	503,76	0,02
60	20,39	11,0	503,87	0,07
80	20,47	11,0	503,98	0,13
100	20,34	11,0	504,09	0,19
120	20,17	11,0	504,18	0,25
140	20,34	11,0	504,26	0,31
160	20,17	11,0	504,33	0,37
180	20,47	11,0	504,40	0,48
200	20,90	11,0	504,45	0,53
220	20,21	11,0	504,51	0,60
240	20,39	11,0	504,58	0,67
260	21,46	11,0	504,62	0,72
280	22,97	11,0	504,66	0,74
300	24,26	11,0	504,76	0,73
320	25,55	11,0	505,00	0,67
340	27,82	11,0	505,43	0,55
360	28,17	11,0	506,06	0,35
380	28,43	11,0	507,07	0,15
400	28,56	15,0	508,26	-0,01
420	29,07	15,0	509,48	-0,06
440	28.77	20.0	510.57	-0.19
460	29,11	20,0	511,66	-0,22
480	29,46	20,0	512,48	-0,21
500	29,85	20,0	513,26	-0,11
520	28,77	20,0	514,03	-0,02
540	29,03	20,0	514,77	0,13
560	28,99	20,0	515,39	0,26
580	29,20	20,0	515,95	0,39
600	29,42	30,0	516,46	0,52
620	28,90	30,0	516,96	0,63
640	29,11	30,0	516,93	0,62
660	29,29	30,0	516,70	0,60
680	29,11	30,0	516,41	0,69
700	29,11	30,0	516,07	0,82
720	29,29	30,0	515,68	0,94
740	28,86	30,0	515,26	1,05
760	28,77	30,0	514,85	1,15
780	28,77	30,0	514,43	1,25
800	28,51	25,0	513,97	1,29
820	28,43	25,0	513,53	1,29
840	28,47	25,0	513,30	1,34
860	28,47	25,0	513,14	1,33
880	28,60	25,0	513,03	1,28
900	28,64	25,0	512,94	1,21

CORRECTION OF STATIC AND DYNAMIC PROPERTIES OF STEAM SUPERHEATER AS CONTROLLED PLANT

The nonlinearity compensation was obtained by creating an appropriate closed-loop system consisting of a plant (Fig. 1) and a nonlinear static unit N^*. A block diagram of the closed-loop system is shown in Fig. 2.

The influence of measurable disturbances (changes of fuel and air quantities) was eliminated by making the controlling quantity, i.e. the position of three-way mixing valve, dependent upon boiler load. A block diagram of the system of control through disturbance input is shown in Fig. 3.

However, the determined compensator [3] with transfer function matrix :

$$K(s,z) = -G_1^{-1}(s,z)G_2(s,z),$$

where z^{-1} is time-lag operator, does not ensure total invariance of superheated steam temperature relative to boiler load. This results from the fact that the accuracy of disturbance compensation depends on factors such as the knowledge of mathematical model of the main line, disturbance line, accuracy of disturbance measurement and accuracy of physical realization of the compensator. In addition, nonmeasurable disturbances caused by plant parameter changes affect the controlled plant [1].

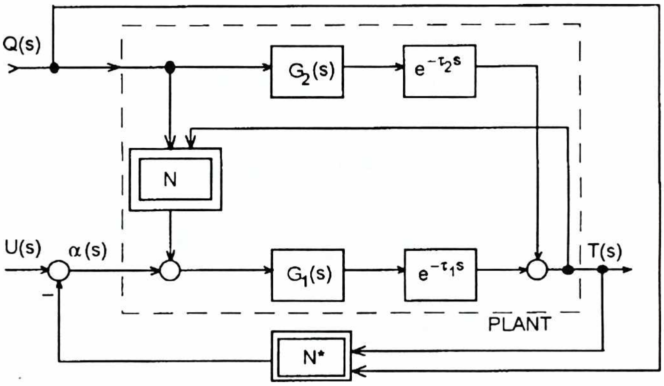

Fig. 2. Block diagram of the closed-loop system

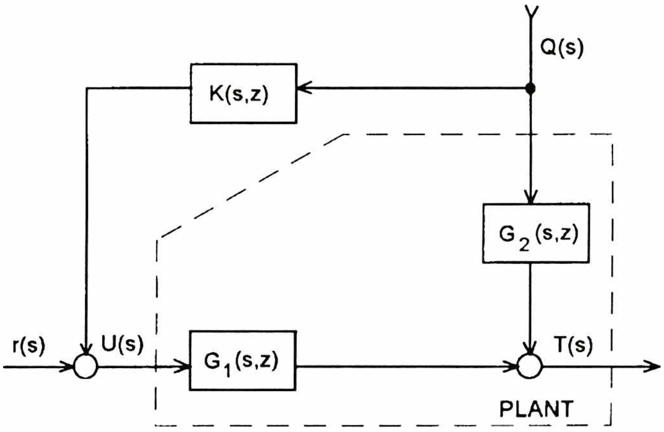

Fig. 3. System of control through disturbance input

The compensation of nonmeasurable disturbances was based on the principle of internal model generalized in relation to linear stationary systems with time-lags [3].

The system of control through disturbance input, shown in Fig.3, can be transformed to the form presented in Fig. 4.

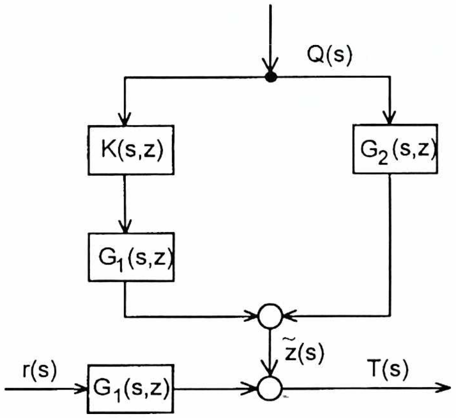

Fig. 4. Equivalent system of control through disturbance input

On the basis of considerations found in [3] it may be said that the signal $\tilde{z}(s)$ practically will not be equal to zero and makes up nonmeasurable disturbance affecting the plant. The analysis of recorded changes of boiler load Q during manoeuvres and sea passages has allowed to claim that nonmeasurable disturbances can be approximated by line segments with sufficient accuracy. Therefore, the state equations describing function Q in a specific time interval may have the form:

$$\begin{bmatrix} \dot{\tilde{V}}_1(t) \\ \dot{\tilde{V}}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \tilde{V}_1(t) \\ \tilde{V}_2(t) \end{bmatrix},$$

$$Q(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \tilde{V}_1(t) \\ \tilde{V}_2(t) \end{bmatrix}$$

where: V_1, V_2 are state variables responsible for the constant value and slope of boiler load Q changes.

Hence the Laplace transform of disturbance $\tilde{z}(s)$ (according to Fig.4) is equal to:

$$\tilde{z}(s) = \overline{G}_2(s,z)\tilde{V}_0$$

whereas the transfer function:

$$\overline{G}_2(s,z) = \{K(s,z)G_1(s,z) + G_2(s,z)\} \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} s & -1 \\ 0 & s \end{bmatrix}^{-1} =$$

$$= \frac{1}{s^2}\{K(s,z)G_1(s,z) + G_2(s,z)\} \begin{bmatrix} s & 1 \end{bmatrix}$$

and the initial state vector :

$$\tilde{V}_o = \begin{bmatrix} \tilde{V}_{o1}(0) \\ \tilde{V}_{o2}(0) \end{bmatrix}$$

Transfer functions $K(s,z)$, $G_1(s,z)$, $G_2(s,z)$ are those of stable units [3]. Therefore, to compensate nonmeasurable disturbances, the unit with transfer function s^{-2} is to be included, according to the internal model principle, in the feedback loop. The block diagram of the system with disturbance compensator is shown in Fig. 5.

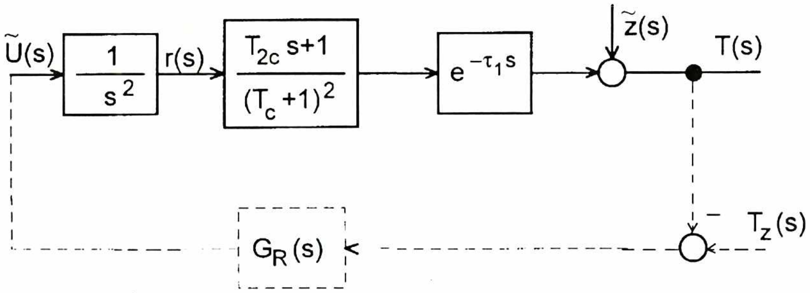

Fig. 5. Closed-loop system with nonmeasurable disturbance compensation (and stabilizing unit with transfer function G(s); T_Z(s) – *Laplace transform of the steam temperature set at superheater outlet)*

A modified mathematical model of the plant obtained through the nonlinearity compensation, the compensation of changing boiler load influence on superheated steam temperature and incorporating the nonmeasurable disturbances compensation is described by the following equations:

$$\dot{x}(t) = Ax(t) + B\tilde{u}(t - \tau_1)$$
$$T(t) = Cx(t),$$

where $u,v \in R$, $x \in R^4$.
Individual matrices assume the following values:

$$A = \begin{bmatrix} -9{,}38967 \cdot 10^{-3} & 0{,}7652582 & 25{,}0 & 0{,}0 \\ 0{,}0 & -9.38967 \cdot 10^{-3} & 1{,}0 & 0{,}0 \\ 0{,}0 & 0{,}0 & 0{,}0 & 1{,}0 \\ 0{,}0 & 0{,}0 & 0{,}0 & 0{,}0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0{,}0 \\ 0{,}0 \\ 0{,}0 \\ 8{,}81659 \cdot 10^{-5} \end{bmatrix}, \qquad C = \begin{bmatrix} 1{,}0 & 0{,}0 & 0{,}0 & 0{,}0 \end{bmatrix}$$

and the time-lag t_1 = 31,0 s.
Fig. 6 presents a diagram of the modified plant state variables.

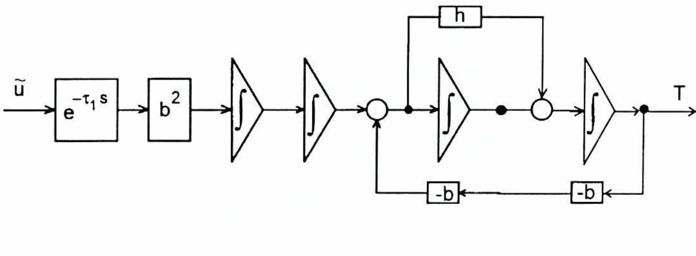

Fig. 6. Diagram of the modified plant state variables
(b = *9,38967 ×* 10^{-3}, h = *25,0)*

CONCLUSIONS

The assumed method of compensating the nonlinearity of measurable and nonmeasurable disturbances has allowed to obtain a mathematical model of time-lag control. This essentially facilitates the synthesis of optimal control that ensures increased efficiency of the marine power plant resulting in reduced fuel consumption [3].

The conducted simulation research has confirmed the significantly better temperature stability $(\Delta T_{\max} \cong 1^\circ C)$ in comparison with the temperature change recorded on board the ship.

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NOMENCLATURE

Q – boiler load,
α – position of three-way mixing valve,
T – steam temperature at superheater outlet,
N, N^* – nonlinear static units,
G_1, G_2 – transfer function matrix of the plant,
K – compensator transfer function matrix,
$T_c, T_{1c}, T_{2c}, T_{3c}$ – time-constants,
U – control signal ,
r – control signal after compensation,
$\tilde{U}$ – final control signal,
$\tilde{z}$ – final disturbance signal,
$\tilde{V}_1, \tilde{V}_2$ – state variables responsible for the changes of intercept and slope values of boiler load .

Appraised by Andrzej Piegat, Assist. Prof., D.Sc.

Current *reports*

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SHIPSTAB Computer Software Package

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The SHIPSTAB package is an itegrated system of computer programs for ship - in - service stability evaluation consisting of the six main modules:

1 - ship form representation
2 - ship hull compartmentation
3 - hydrostatics
4 - ship form stability
5 - loading calculations
6 - ship stability evaluation

Ship shape is described by means of an appropriately defined, independent system of waterlines and frames, generated on the basis of ship's body lines. It is possible to describe shape discontinuities of ship's hull with use of a form editor. Ship's hull surface is represented during calculations by a mesh of cubic splines.

On this basis Bonjean's scale and hydrostatic curves for an arbitrary waterline are calculated. Ship form stability in a form of the so called stability cross-curves may be calculated also for an arbitrary waterline. The package makes it possible to carry out also basic load calculations to determine position of the centre of gravity as well as shearing force and bending moment calculations for ship's hull strength assessment. The SHIPSTAB package is provided with multiple graphic interfaces and is elaborated with application of the state-of- the- art numerical techniques. The package may be installed on IBM/PC/PS computers, working under MS-DOS operating system control, and equipped with RAM memory of not less than 640 kB capacity, and a hard disk unit of not less than 20 MB capacity.

Photo: TECHNICAL UNIVERSITY of Gdańsk