Influence of gas turbine controller adjustment on ship propulsion system behavior in rough sea conditions

Part 2. The simulation investigations

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ABSTRACT

The paper presents simulation investigations of influence of gas turbine controller adjustment on ship propulsion system operating in heavy sea conditions, based on the model presented in Part I of the paper. The ship propulsion system with two gas turbines driving – through mechanical gear – ship controllable pitch propeller, described in Part I, was used to analysis. The harmonic disturbances due to sea waves with selected frequencies were used as input function in computing the system's amplitude characteristics at different settings of P and PD controllers.

Key words : ship propulsion systems, gas turbines, automatic control, sea waving

INTRODUCTION

The designing process of the control system of the gas turbine used as ship's prime mover is governed by the general principles of ship power plant designing. However the gas turbine control system has its specific features. These are : transient processes of gas temperature before gas turbine, their influence on gas turbine power and efficiency, and on its mechanical and thermal stresses. In order to limit maximum temperature values it is necessary to use some limitations which influence transient processes in the entire control system. The ship propulsion system with gas turbines driving controllable pitch propeller is affected not only by the excitations due to settings of propeller shaft's angular speed, and of propeller pitch, but also a strong influence on operation of the ship propulsion system is exerted by sea waves (sea state). The description of the problem, the elaborated simulation model together with made assumptions, was presented in Part I of the paper. In this part (Part II) the simulation investigations, carried out by means of the model, and their results are presented and thoroughly discussed.

STRUCTURE OF THE INVESTIGATED SHIP PROPULSION SYSTEM WITH GAS TURBINES

The ship propulsion system with two gas turbines driving – – through toothed transmission gear – ship controllable pitch propeller (see Fig.1, Part I) was used to analysis.

In the propulsion system the propeller shaft's angular speed controller and the propeller pitch ratio controller was used. For each of the engines the separate control loop was applied. In the speed controller two additional limiters were applied : that of combustion chamber outlet temperature, which is actuated when a given threshold temperature is exceeded, and that of maximum fuel flow to combustion chamber. The controller structure was presented in Part I of the paper.

The gas turbine in the propulsion system in question is a two-shaft turbine with separated power turbine, operating in simple open cycle. The parameters of the analyzed ship propulsion system are given in Tab.1 [1].

Tab.1. *Parameters of the ship propulsion system in question*

Engines	Number 2		
Rated power of ship propulsion system	$(\mathbf{N_E})_r$	kW	462.4
Rated angular and rotating speed of power turbine (PT) shaft	$(\omega_{PT})_r$ $(\mathbf{n_{PT}})_r$	rad/s rpm	2513 24000
Rated torque of power turbine	$(\mathbf{M_{PT}})_r$	Nm	92
Rated power of power turbine	$(\mathbf{N_{PT}})_r$	kW	231.2
Propeller	Number 1		
Reduction gear ratio	**g**	ω_{PT}/ω_P	60.00
Wake fraction	**w**	-	0.218
Propeller diameter	**D**	m	1.5
Rated propeller pitch ratio	**H/D**	-	0.7
Rated torque of propeller	$(\mathbf{M_P})_r$	Nm	10818
Rated angular and rotating speed of propeller shaft	$(\omega_P)_r$ $(\mathbf{n_P})_r$	rad/s rps	41.89 6.667
Rated power of propeller	$(\mathbf{N_P})_r$	kW	453.2

For the simulation investigations used was the proportional controller (P) or – alternatively – the proportional-derivative controller (PD), having the following adjustment coefficients:

k_P - gain (amplification) coefficient of controller (for P and PD controllers)
T_D - differential time constant (for PD controller)

The harmonic disturbances due to sea waves were applied to determine – for assumed disturbance frequencies – the amplitude characteristics at different settings of the P and PD controllers.

HARMONIC DISTURBANCES DUE TO SEA WAVES AFFECTING SHIP PROPULSION SYSTEM

The disturbances from the side of sea waves lead to disturbances of resistance torque of rotary system elements. The loads were determined as the quantities of the determinate amplitudes dependent on the disturbance amplitude [2].

Such disturbance was introduced to the system as a change of the propeller advance speed V_p . The speed V_p is calculated in accordance with the relevant formula given in Part I, in which the speed change due to sea waves has been accounted for.

The mean water speed of advance onto propeller, c_m , with accounted for sea wave action, can be determined from the relevant relationship given in Part I. From the continuous sea wave spectrum only some its definite frequencies ω_m were selected.

In Tab.2 given are the main wave parameters in different sea states, on the basis of which values of c_m and ω_m have been determined.

In order to investigate the influence of sea conditions on the operation of the ship propulsion system with gas turbines the amplitude characteristics of the system for a harmonic disturbance from the side of the propeller (sea wave influence) were determined. In the calculations the mean ship's speed V_o was assumed constant, and the characteristics were determined for two values of the mean advance speed of water flow onto propeller, affected by sea waves :

Tab. 2. Main wave parameters in different sea states [2]

Wind velocity	[°B]	5	6	7	8-9	10	11
Sea state	[°B]	3	4	5	6	7	8
Mean wave period	T_w^m [s]	3.7	4.5	6.0	7.6	8.7	9.5
Wave height	H [m]	1.25	2.0	3.5	6.0	8.5	11.0
Wave length	L [m]	21.4	31.6	56.2	90.2	118	141
Wave velocity	c [m/s]	5.8	7.0	9.4	11.9	13.6	14.8
Water speed on wave surface	c_o [m/s]	1.06	1.40	1.83	2.48	3.06	3.64

- the speed amplitude c_m which corresponds to 3°B sea state (H = 1.25 m ; L = 21.4 m) and h_p = 0.9 m
- the speed amplitude c_m which corresponds to 8°B sea state (H = 11 m ; L = 141 m) and h_p = 0.9 m

In both cases the characteristics were determined in function of the disturbance frequency ω_m (wave period T_w).

INVESTIGATIONS OF CONTROLLER ADJUSTMENT INFLUENCE ON SHIP PROPULSION SYSTEM OPERATION IN HEAVY SEAS

The simulation model (Fig.7) elaborated by means of the MATLAB (and SIMULINK package), presented in Part I and [1], was used for the investigations in question.

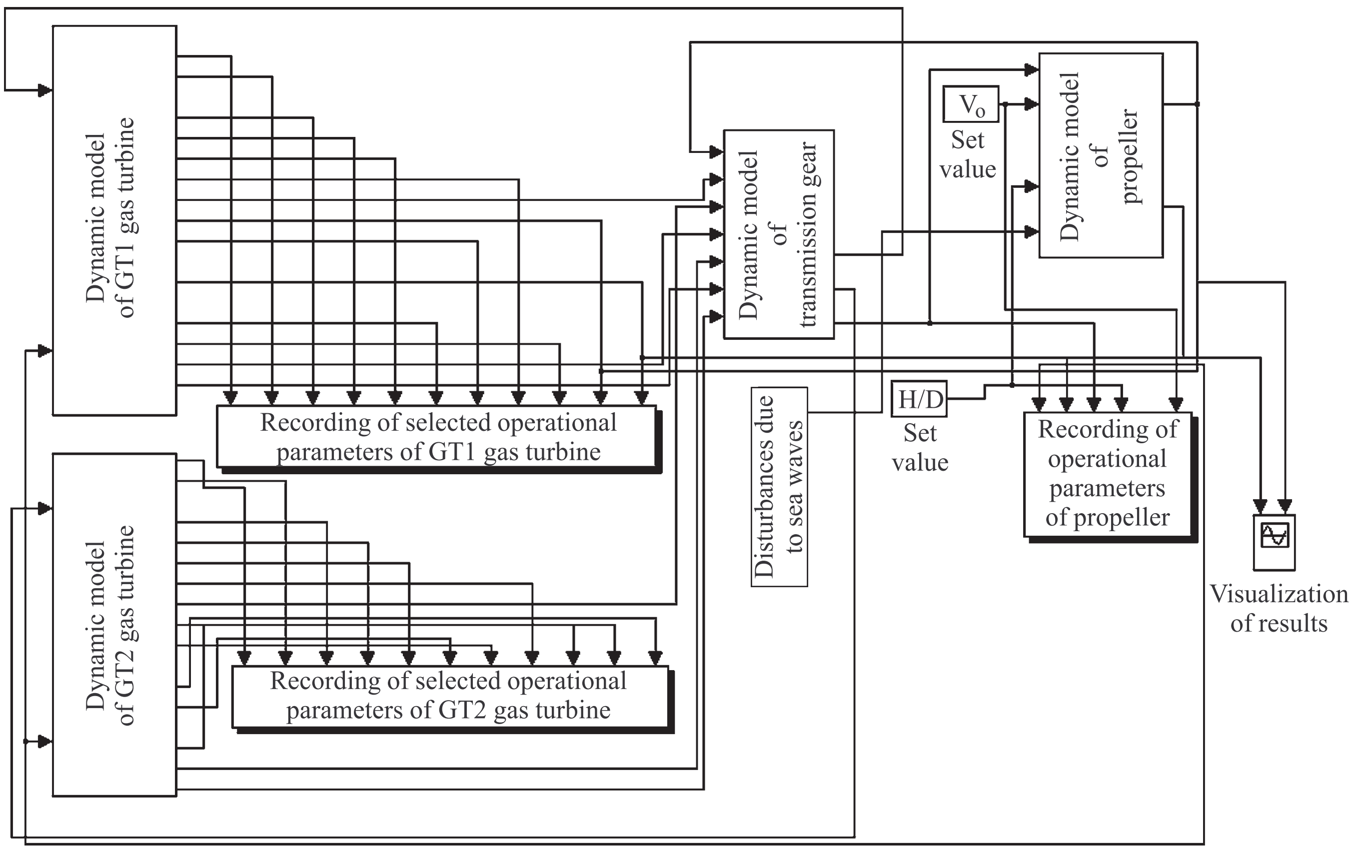


Fig. 7. Simulation model of ship propulsion system with gas turbines and controllable pitch propeller

The amplitude characteristics of the propulsion system were determined for two types of gas turbine speed controllers, P and PD, controlling the propeller angular speed. The characteristics were calculated for different controller settings and different disturbance amplitudes corresponding to the sea wave amplitude at 3°B and 8°B sea state. The calculations were performed for the constant value of the propeller pitch ratio :

H/D = 0.7 and the constant linear speed of ship : V_o = idem.

The increments of any variable of the propulsion system, X, were defined as follows :

$$\Delta X = \frac{X - X_o}{X_o}$$

where :
X_o - initial value of a parameter of propulsion system
X - instantaneous value of the parameter

The ship propulsion system's amplitude characteristics accounting for disturbances due to sea waves

In the calculations of the system's amplitude characteristics in question, the following settings were assumed :

for the proportional controller (P): k_P = 5; 10; 15; (20)

for the proportional-derivative controller (PD) :
k_P = 5 T_D = 0.1 s ; 1 s ; 3 s.

The disturbance period T_w was assumed in the range from 0.1 s to 30 s. The disturbance amplitudes (i.e. the mean propeller speed of advance c_m) were chosen as follows :

c_m = 0.745 m/s - corresponding to the wave of

L = 21.4 m, and H = 1.25 m, (3°B sea state)

and :

c_m = 3.450 m/s - corresponding to the wave of

L = 141 m, and H = 11 m, (8°B sea state).

In Fig.8 presented are the gas turbine power amplitude characteristics for the disturbance due to sea waves corresponding to 3°B sea state, at three settings of the P controller of the propulsion system.

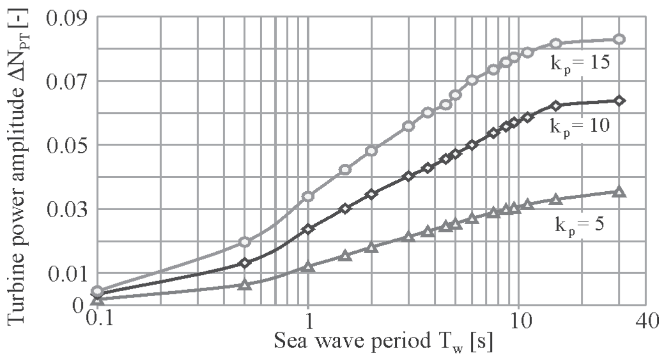


Fig. 8. The gas turbine power amplitude characteristics for 3°B sea state conditions, at different settings of the P controller with limiters

With increasing the mean sea wave period T_w and the controller amplification coefficient k_P the gas turbine power amplitudes ΔN_{PT} also increase. In Fig.9 presented are the relative amplitude characteristics obtained by relating the power amplitude increment ΔN_{PT} to the disturbance amplitude c_m , for the same settings of the P controller and two disturbance amplitudes due to sea waves. From the presented diagrams it appears that the courses of the relative power pulsations are close to each other, hence in further considerations only the frequency characteristics for the disturbance amplitude due to sea waves corresponding to 8°B sea state (c_m = 3.450 m/s) are taken into account.

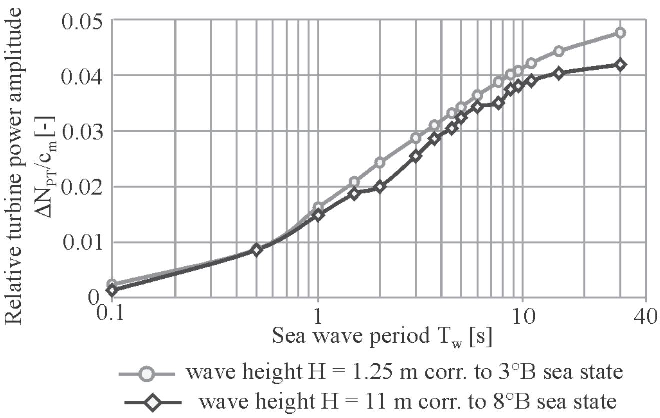


Fig. 9. *The relative amplitude characteristics of gas turbine power, $\Delta N_{PT}/c_m$, in function of the sea wave period T_w , at the constant setting k_P = 5 of the P controller with limiters*

In Fig.10 the ship propulsion system amplitude characteristics accounting for wave-induced disturbances, are presented for typical parameters of the propulsion system. Fig.10a shows the amplitude characteristics for the P controller, and Fig.10b – for the PD controller. In both controllers the limiters described in Part I (i.e. the maximum fuel flow limiter and the combustion chamber outlet temperature limiter) were applied.

Results for the ship propulsion system with P controller (Fig.10a)

For all quantities characterizing the propulsion system the increase of the controller's amplification coefficient k_P causes the increase of amplitude of the relevant quantity. The amplitudes of the gas turbine power N_{PT} and the fuel flow m_f increase along with increasing the sea wave period T_w. The maximum amplitudes of the combustion chamber outlet gas temperature θ_3 move towards higher values of the mean wave periods along with increasing the controller's amplification coefficient k_P; e.g. for the amplification coefficient k_P = 5 the maximum amplitude occurs at T_w = 2.5 s, whereas for k_P = 15 it appears at the wave period T_w = 5 s.

Results for the ship propulsion system with PD controller (Fig.10b)

At the constant value of the controller amplification coefficient k_P the amplitudes of each of the power propulsion system quantities increase along with increasing the differential time constant T_D. For all the analyzed system parameters, except the fuel flow m_f and the propeller speed n_p, their maximum amplitudes occur within the interval between the minimum and maximum period of the considered sea wave. At the values of the controller differential time constant T_D equal to 1s and 3 s, the fuel flow characteristics decrease along with increasing the sea wave period T_w. At T_D = 0,1s the transient characteristics are almost identical with the transient signals of the P controller having the same value of the amplification coefficient k_P. For the propeller speed n_P the amplitude characteristics differ only a little both in function of the sea wave period and of the controller's differential time constant settings.

The influence of controller limiters on the ship propulsion system's operation in heavy seas

Fig.11 shows the transient signals of the selected quantities of the considered propulsion system in the case of the use of the P and PD controllers both with and without limiters during operation of the system in heavy sea conditions (8°B sea state).

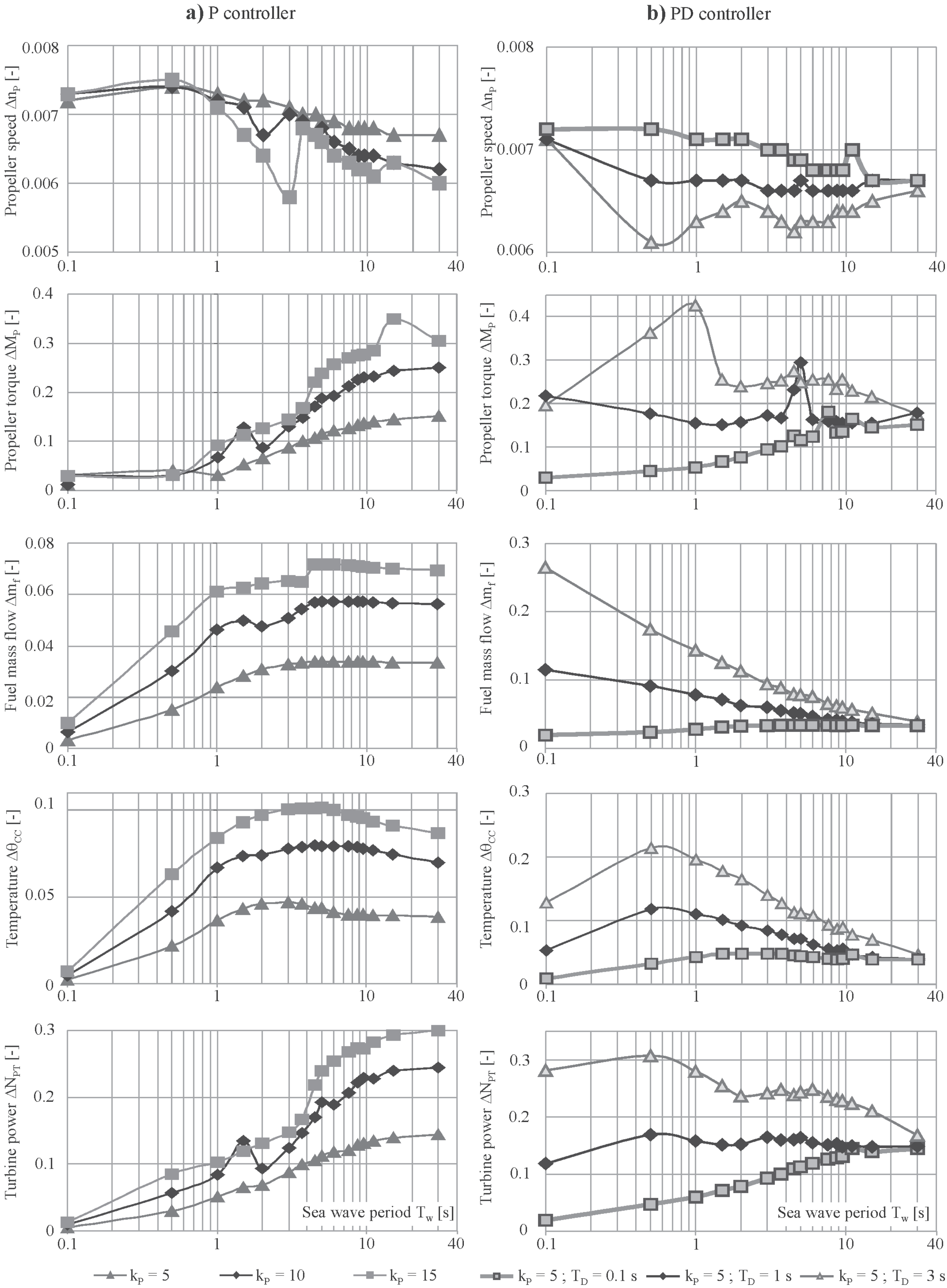


Fig. 10*. The amplitude characteristics of the ship propulsion system affected by sea wave disturbances of the amplitude corresponding to 3°B sea state;*
a) *for the P controller with limiters* ***b)*** *for the PD controller with limiters*

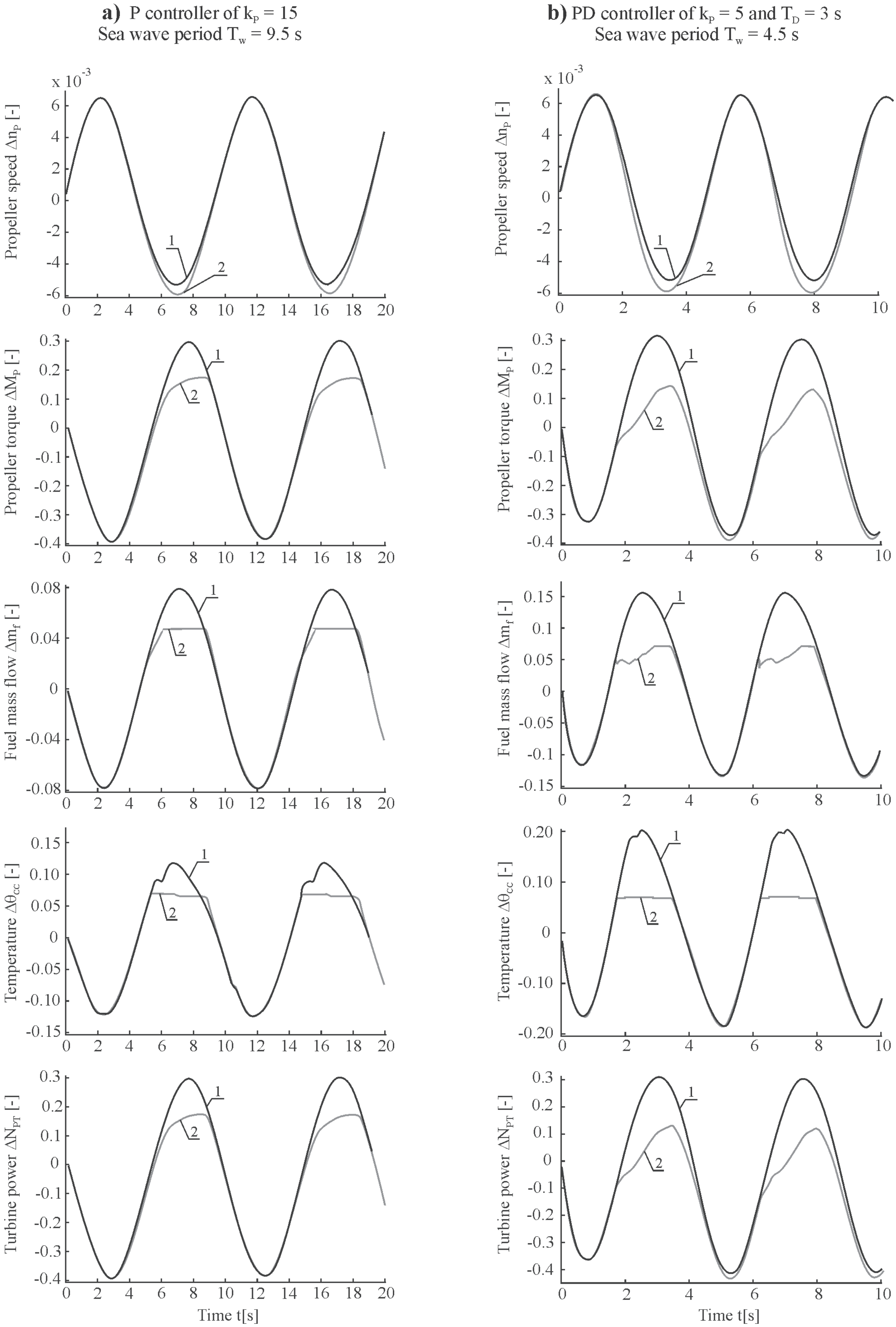


Fig. 11. *Transient signals of selected quantities of the considered ship propulsion system affected by sea wave disturbances of the amplitude corresponding to 8°B sea state*
a) *for the P controller;* ***b)*** *for the PD controller; 1 – without limiters, 2 – with limiters*

The results for the system with the P controller are given in Fig.11a for the sea wave of the mean period $T_W = 9.5$ s, and in Fig.11b - the results for the system with the PD controller and the sea wave of $T_W = 4.5$ s. The controllers with limiters make the correct work of the propulsion system possible, not allowing for exceedance of gas temperature and stresses in the propulsion shaft over the permissible limits both in transient and steady states. The work of the system in heavy seas without the limiters in the control system is inadmissible.

The ship propulsion system's operation in heavy seas at different types and settings of the speed controller

The transient signals of the propulsion system operating in the heavy sea conditions corresponding to 8°B sea state were determined for two mean sea wave periods T_W : 4.5 s and 9.5 s, with taking into account two types of the turbine speed controller: P and PD. The transient signals are presented in Fig.12.

The transients of the propeller shaft speed n_P for all investigated controller settings show similar form and they do not much differ to each other. It results from the fact that it is the control signal.

The transients of the propeller torque M_P for the P controller of $k_P = 5$, and the PD controller of $k_P = 5$ and $T_D = 0,1$ s do not much differ to each other as well. The amplitudes of changes are the smallest at both sea wave periods T_W : 4.5 s and 9.5 s and all considered controller's settings. The largest amplitudes of changes appear for the P controller of $k_P = 15$ and the sea wave period $T_W = 9.5$ s. For the period $T_W = 4.5$ s the largest amplitudes appear for the PD controller of $k_P = 5$ and $T_D = 3$ s.

The amplitudes of fuel flow to gas turbine combustion chamber, m_f, for the P controller of $k_P = 5$ and the PD controller of $k_P = 5$ and $T_D = 0,1$ s, associated with the influence of the sea wave of $T_W = 4.5$ s, are almost identical. For $T_W = 9.5$ s at the same setting of the P controller they are the smallest. For the PD controller the amplitudes increase insignificantly in comparison with the case of the P controller. In both cases the disturbances due to sea waves do not cause any intervention of the limiters to the propulsion system. For the remaining considered settings of the controllers the amplitudes are much greater, and they are the largest at $T_W = 9.5$ s for the P controller of $k_P = 15$, whereas at $T_W = 4.5$ s - for the PD controller of $k_P = 5$ and $T_D = 3$ s.

The transients of the combustion chamber outlet temperature θ_{CC} for the system operating in heavy sea conditions are similar to those for the fuel flow m_f.

The transients of the gas turbine power N_{PT} at the disturbances due to sea waves are almost the same as the transients of the propeller torque M_p. And, for the P controller of $k_P = 5$ and the PD controller of $k_P = 5$ and $T_D = 0.1$s at the wave period $T_W = 4.5$ s they are almost identical, and the power oscillations due to sea waves amont to $\Delta N_{PT} = (N_{PT} - N_{PTo})/N_{PTo} =$ $= 25$ %; whereas at $T_W = 9.5$ s - to $\Delta N_{PT} = 32$ % for the P controller, and to $\Delta N_{PT} = 36$ % for the PD controller. For the P controller of $k_P = 15$ and the sea wave period $T_W = 9.5$ s, the power oscillations amount to $\Delta N_{PT} = 55$ % and are the largest out of the results for all considered controller settings. At the wave period $T_W = 4.5$ s the power changes for the PD controller of $k_P = 5$ and $T_D = 3$ s are the largest (ca 60 %).

The performed analysis of the ship gas turbine propulsion system operating in heavy seas shows that in the considered system :

- for the P controller $k_P = 5$ should be set; and
- for the PD controller $k_P = 5$ and $T_D = 0.1$ s
- however, for the PD controller at the constant value of its amplification coefficient and the increasing differential time constant the oscillations of the propulsion system parameters around their steady values set for operation in heavy seas, increase
- for higher sea state the amplitudes of the considered propulsion system parameters increase along with increasing the amplification coefficient k_P of the P controller
- for the PD controller the amplitudes increase with sea state increasing, however at a given sea state the maximum amplitudes do not occur at the maximum sea wave period as it is the case for the P controller.

INFLUENCE OF CONTROLLER TYPE AND SETTINGS ON OPERATION OF THE SHIP PROPULSION SYSTEM AT STEP CHANGES OF THE PROPELLER PITCH RATIO H/D

The influence of controller's type and settings on operation of the ship propulsion system in question at step changes of the propeller pitch ratio H/D was investigated for the case of calm sea. The same propulsion system simulation model as that presented in Part I, was used for the investigation.

Fig.13 shows the transient responses of the ship propulsion system on step changes of the propeller pitch ratio H/D within the range from 0.7 to 1. The controllers of two types, P and PD with limiters and different settings were applied.

The following control performance criteria were applied for the analysis of the influence of the controller's type and settings :

the minimum control time :

$$t_c = \min$$

and the integral performance criteria :

$$J_1 = \int_0^\infty \left| e(t) - e_{so} \right| dt$$

$$J_2 = \int_0^\infty \left(e(t) - e_{so} \right)^2 dt$$

Fig.14 shows the performance criteria in function of controller settings determined for the selected parameters of the ship propulsion system : n_p, N_{PT}, θ_{CC}.

From the presented diagrams it results that for the investigated propulsion system at step changes of the ship propeller pitch ratio H/D :

on the basis of the integral performance criterion J_1 :
the P controller of $k_P \approx 11$ should be taken as the optimum one,
on the basis of the criterion J_2 :
also the P controller of the same k_P value;
however no distinct minimum of this integral appears.

From the criterion of the minimum control time t_c of the propeller speed n_P it results that for the P controller a change of the controller amplification coefficient k_P does not much influence the control time. For the PD controller the same criterion reveals that the minimum of the control time occurs within the interval of the differential time constant T_D from 0.1 to 1s.

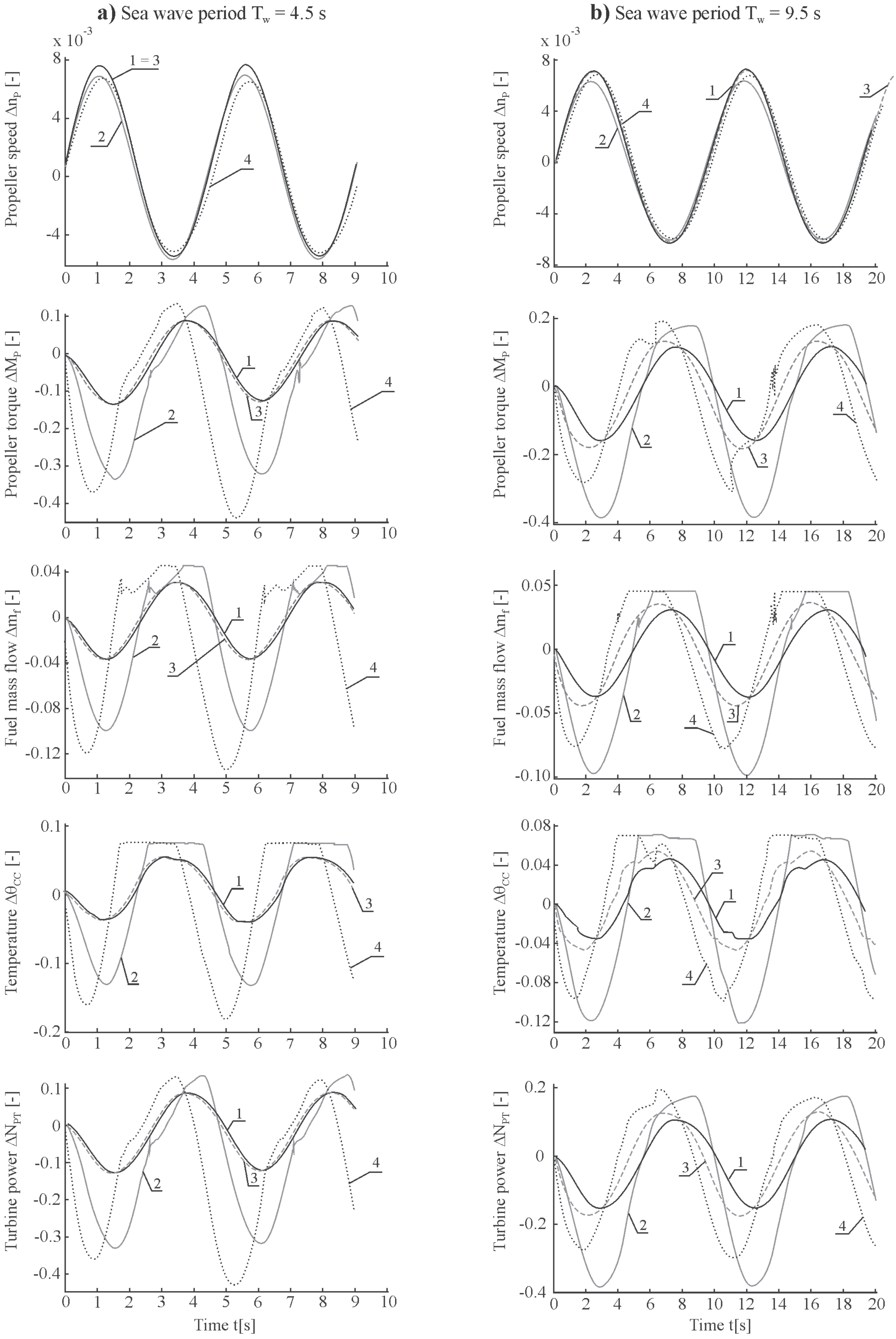


Fig. 12. *Transient signals of the considered ship propulsion system affected by sea wave disturbances of the amplitude corresponding to 8°B sea state:* ***1*** *– P controller of $k_P = 5$;* ***2*** *– P controller of $k_P = 15$;* ***3*** *– PD controller of $k_P = 5$ and $T_D = 0.1$ s;* ***4*** *– PD controller of $k_P = 5$ and $T_D = 3$ s   Both controllers fitted with the limiters*

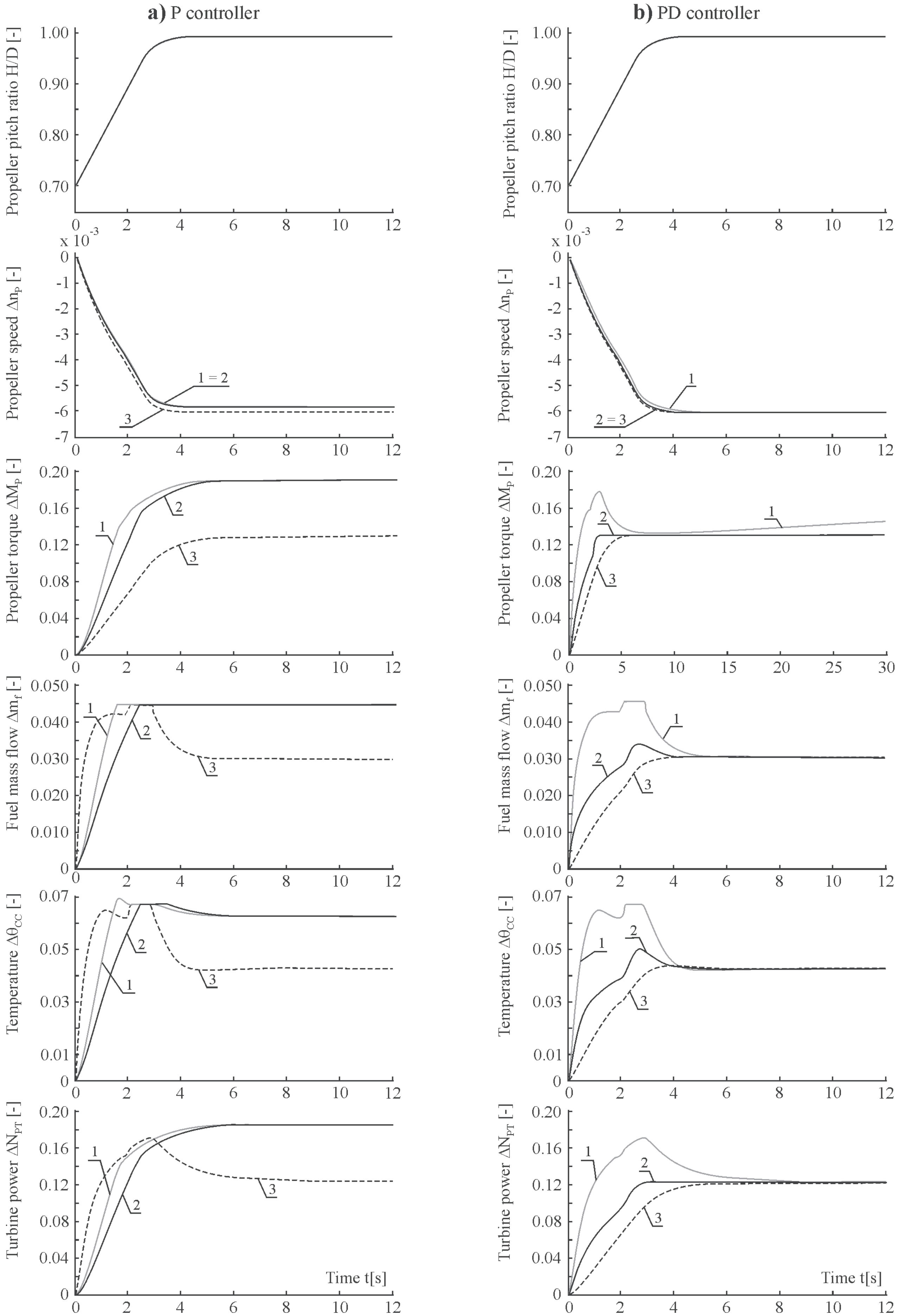
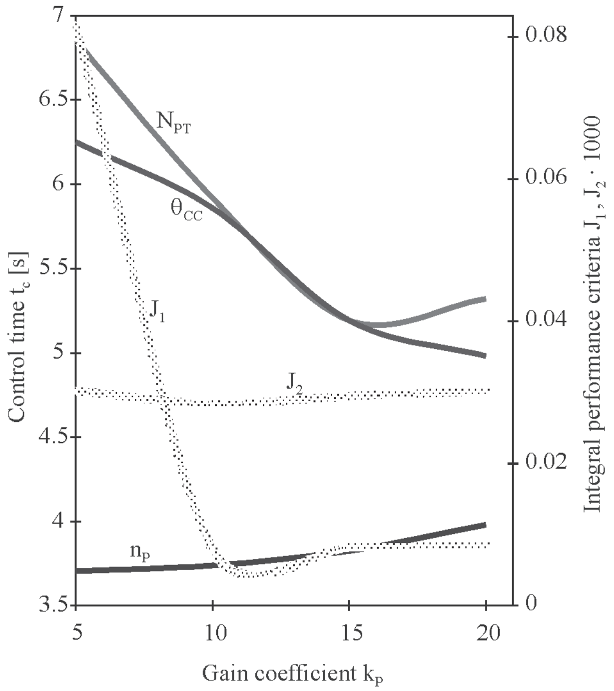


***Fig. 13.** Transient responses of the considered ship propulsion system on step changes of the propeller pitch ratio H/D :*
***a)** P controller : **1** – of k_P =15; **2** – of k_P=10; **3** – of k_P = 5; **b)** PD controller : **1** – of k_P = 5 and T_D = 3 s;*
***2** – of k_P = 5 and T_D = 1 s; **3** – of k_P = 5 and T_D = 0.1 s Controllers with limiters; calm sea conditions*

For such quantities as the gas turbine power N_{PT} and the combustion chamber outlet temperature θ_{CC}, the minimum stabilization time in response to step changes of the propeller pitch ratio H/D is achieved:

in the case of the P controller
for k_P value within the interval from 15 to 20
in the case of the PD controller
for its optimum settings : $k_P = 5$ and $T_D = 1$s.

a) P controller



b) PD controller of $k_P = 5$

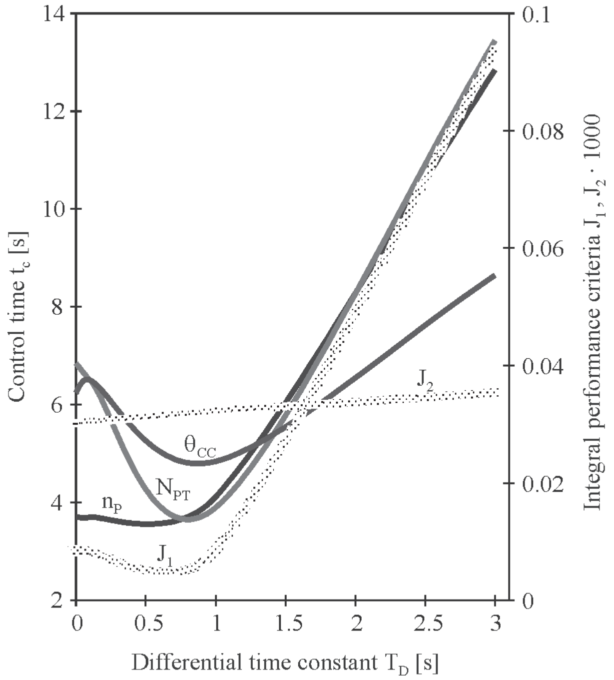


Fig. 14. *The integral control performance criteria J_1 and J_2 and the ship propulsion system control time t_c in function of the controller settings k_P and T_D at step changes of the propeller pitch ratio H/D, determined for the following parameters of the ship propulsion system: n_P , N_{PT} , θ_{cc} . Controllers with limiters; calm sea conditions*

FINAL REMARKS

The presented analysis demonstrated that :

- For the investigated ship propulsion system with gas turbines driving - through mechanical gear – controllable pitch propeller the optimum controller settings for calm sea conditions are not optimum ones for the system working in heavy sea conditions.
- In the control loop of the propulsion system the maximum fuel flow limiter and that saveguarding against increase of combustion chamber outlet temperature should be applied.
- The optimum setting values for the P and PD controllers in regard to sea wave disturbances are lower than the optimum ones regarding to change of ship propeller pitch. It seems reasonable to adjust the controller to the lower setting values, i.e. those obligatory for the propulsion system working in heavy sea conditions. In this case the oscillation amplitudes of its particular quantities are much smaller than those for the controller adjusted to the optimum settings in regard to change of pitch of CP propeller.

NOMENCLATURE

c_m - mean speed of water flow onto propeller, caused by sea waves
e - error
e_{so} - error in steady state
h_P - mean depth of immersion of propeller axis
k_p - controller amplification coefficient
m_f - fuel mass flow
t - time
T_D - differential time constant
T_w - sea wave period
V_o - linear speed of ship
V_P - propeller advance speed
θ_{CC} - combustion chamber outlet gas temperature
ω_m - frequency of sea - wave - induced disturbance (excitation)

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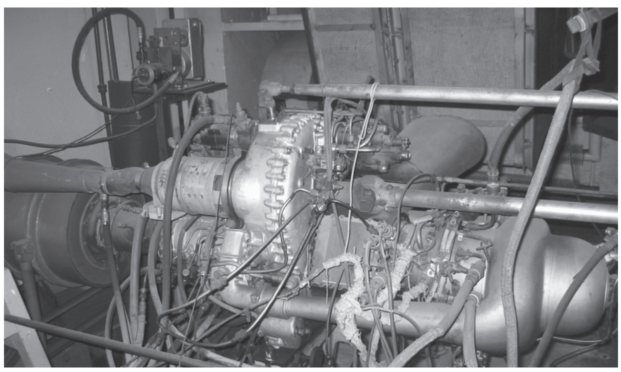

Laboratory test stand of an aircraft gas turbine