MAREK DZIDA, Assoc.Prof., D.Sc., M.E.
Faculty of Ocean Engineering
and Ship Technology
Gdańsk University of Technology

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

Part 1.
The dynamic model of propulsion system

SUMMARY

The paper presents a dynamic model of ship propulsion system, elaborated with the use of the stiff finite element method. The ship propulsion system consisted of two gas turbines driving - through toothed gear - controllable pitch propeller, was used to analysis. In the simulation model disturbances both from setting of propeller shaft's angular speed and of propeller pitch during the system's operation in rough sea conditions, were accounted for.

INTRODUCTION

In marine applications the gas turbines are mainly used in the navy. However presently they are often and often used to move fast car-passenger ferries, big passenger liners and special ships.

The gas turbines in ship propulsion systems have rotational speed in the range of 3000 ÷ 8000 rpm. In ships of the types when disturbances occur, especially in extreme conditions, the dynamic processes appear which require rapid reactions of control systems to be made to protect the power propulsion system against any exceedance of admissible values of its operational parameters.

On one hand the designing of the control system of a gas turbine used as ship's main engine is governed by the general principles of operation of ship propulsion system. On the other hand the gas turbine control system has its specific features. These are: transient processes of gas temperature before gas turbine, their influence on power and efficiency of gas turbine, 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.

Power and efficiency of gas turbine are very sensitive to changes of ambient parameters (temperature and pressure).

The ship propulsion system with gas turbines driving controllable pitch propeller is affected not only by the excitations from settings of angular speed of propeller shaft and of propeller pitch, but also a strong influence is exerted by sea waves (sea state) on operation of the ship propulsion system.

MODELLING SHIP'S GAS TURBINE PROPULSION SYSTEM

In the presented investigations the ship propulsion system is considered as a controllable object which includes such elements as : a gas turbine, transmission gear, couplings, driving shafts, propeller, and ship propulsion control system (Fig.1).

The gas turbine as a controllable object is composed of a rotary compressor, combustion chamber, and turbine which - for ship applications - is split into the compressor driving turbine (compressor turbines) and ship propeller driving turbine (power turbine).

In the gas turbine control system, the control signal is either a set angular speed value (when gas turbine solely drives ship propeller) or gas turbine power demand (when gas turbine drives ship propeller in cooperation with other engines) [4]. Large and fast changes of the control signals cause large changes of other signals, e.g. gas temperature at combustion chamber outlet. The maximum value of this temperature has to be limited.

The disturbance signals in the gas turbine control system are: variable effects of sea waves acting on ship's hull (sea state), and also parameters of the air delivered to the compressor (ambient temperature and pressure).

MODELLING DYNAMIC BEHAVIOUR OF PARTICULAR ELEMENTS OF SHIP'S GAS TURBINE PROPULSION SYSTEM

For the investigations in question the ship propulsion system fitted with gas turbines which drive - through toothed gear -ship's controllable pitch propeller, was selected (Fig.1).

The method of stiff finite elements (SFE) was used to describe rotatary elements of the propulsion system [1, 3, 5]. The method applied for description of behaviour of a ship propulsion system with diesel engines gave correct results [2].

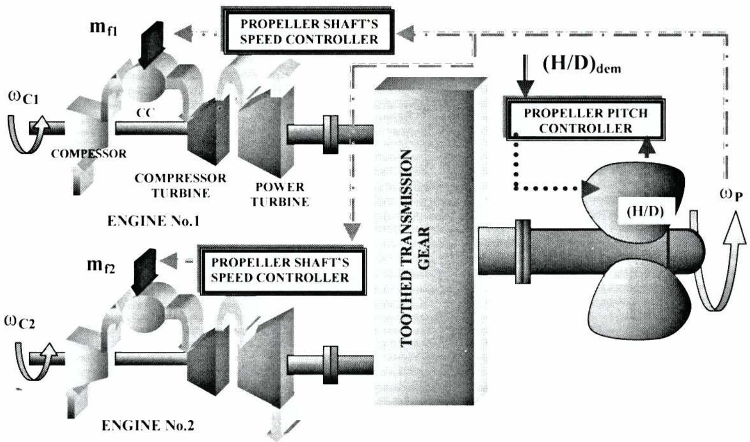

Fig.1. Schematic diagram of ship propulsion system with gas turbines applied as main engines

In order to model the dynamic behaviour of the ship propulsion system considered as an object of control it was divided into some subsystems to which the SFE method was applied.

Fig.2 shows the structural diagram of the considered ship propulsion system in accordance with the system's schematic diagram given in Fig.1.

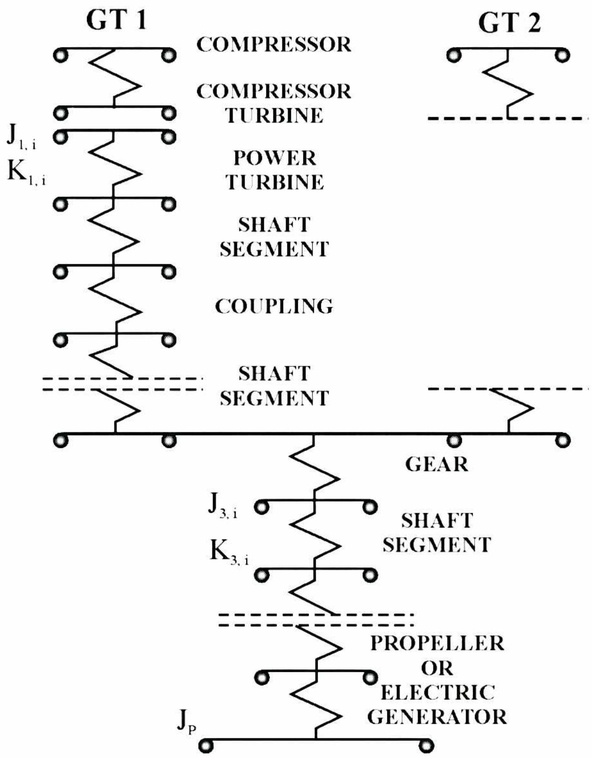

Fig.2. Structural diagram of the considered ship's gas turbine propulsion system : J – moment of inertia, K – coefficient of torsional stiffness, indices 1,2,3, denote : 1 – GT1, 2 – GT2, 3 – propeller shaft

In the considerations of dynamic behaviour of each of the shaft elements its torsional stiffness as well as material and viscous damping was taken into account.

The dynamic equation of a rotating propulsion shaft element was determined by using the second-order Lagrange equation in which element's mass (undeformable disc) and also shaft's segment flexibility was accounted for (Fig.3).

$$J_i \frac{d^2\varphi_i}{dt^2} + B_i \frac{d\varphi_i}{dt} + d_{i-1}\left(\frac{d\varphi_i}{dt} - \frac{d\varphi_{i-1}}{dt}\right) + d_i\left(\frac{d\varphi_i}{dt} - \frac{d\varphi_{i+1}}{dt}\right) + K_{i-1}\left[\varphi_i(t) - \varphi_{i-1}(t)\right] + K_i\left[\varphi_i(t) - \varphi_{i+1}(t)\right] = M_i(t)$$

where :

- φ – angle of torsion
- J – shaft segment's moment of inertia
- d – material damping coefficient
- B – viscous damping coefficient
- K – torsional stiffness coefficient.

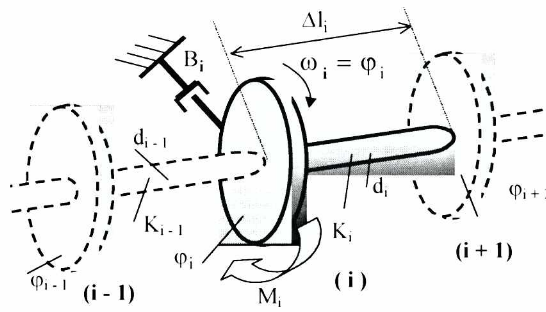

Fig.3. Schematic diagram of i-th element of rotating propulsion shaft

The moment $M_i(t)$ in this equation is an external moment (driving or propeller torque) acting onto an element.

The gas turbine is a dynamic object which is complex both structurally and due to non-linear character of its static characteristics. The dynamic model of the gas turbine was divided into the basic elements which were mathematically described in detail in [1 , 3].

Dynamics of controllable pitch propeller with accounting for disturbances due to sea waves

The dynamics of the controllable pitch (CP) propeller was determined in the same way as of a fixed pitch propeller [1, 3, 5]. Effects of the propeller resistance torque and the propeller damping torque due to water were calculated. Fig.4 shows the schematic diagram of the propulsion shaft element with CP propeller. The quantities were determined in function of the propeller movement parameters and its geometry.

The propeller torque M_P was determined by means of the following relationship used in ship hydromechanics :

$$M_P = k_Q \cdot \rho \cdot D^5 \cdot n_P^2 + B_P \cdot \Delta\omega_P$$

where :

- k_Q – propeller torque coefficient [-]
- ρ – water density [kg/m^3]
- D – propeller diameter [m]
- n_P – propeller rotating speed [rps]
- B_P – coefficient of propeller viscous damping [Nms/rad]
- $\Delta\omega_P$ – increment of propeller speed [rad/s].

The torque coefficient k_Q is usually determined experimentally [6, 7, 8]. For the CP propeller it depends on the coefficient of advance I_P and the propeller pitch ratio H/D :

$$k_Q = f(I_P, H/D)$$

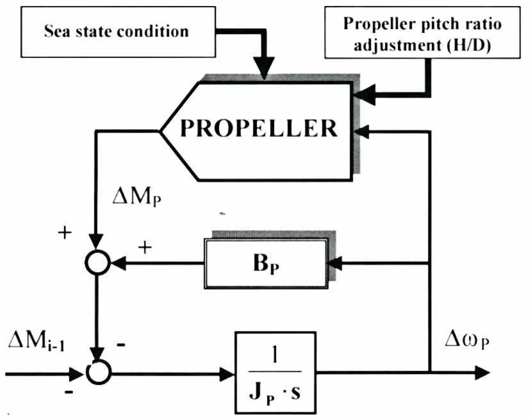

***Fig. 4.** Flow diagram of ship's CP propeller dynamics : B_p – propeller viscous damping coefficient, J_p – propeller mass moment of inertia, ω_p – propeller angular speed, M_{i-1} – propeller torque transmitted by the shaft segment before the propeller*

The advance coefficient is determined by the relationship :

$$I_P = V_P / (n_P \cdot D)$$

where :

V_P – propeller advance speed.

The introduction of the sea-wave-induced disturbances leads to some changes of the propeller torque, which induce dynamic loads onto the rotating system elements. These loads are determined as quantities of a determinate amplitude dependent on excitation amplitude [9].

In ship propulsion dynamic calculations the propeller is considered as an entity (one rotating mass), however in propeller's hydrodynamic characteristics the mean advance speed of water, c_m, is used. This mean speed, constant for the entire propeller, is the amplitude of sinusoidal disturbance of water flow onto propeller. The disturbance (excitation) due to sea waves is introduced to the propeller model through changing the propeller advance speed V_P. This speed was calculated with regard to the change of the speed caused by sea waves, in accordance with the following equation :

$$V_P = V_o \cdot (1 - w) + c_m \cdot \sin(\omega_m \cdot t)$$

where :

V_o – linear speed of ship [m/s]
w – wake fraction [-]
c_m – mean speed of water flow onto propeller, caused by sea waves [m/s]
ω_m – frequency of sea-wave-induced disturbance (excitation) [rad/s].

The mean speed c_m was determined by using the following relationship [8] :

$$c_m = c_o \cdot \exp\left(\frac{-2 \cdot \pi \cdot h_P}{L}\right)$$

where :

c_o – linear speed of water particles on wave surface [m/s]
h_P – depth of immersion of propeller axis [m]
L – sea wave length [m].

The sea wave frequency (excitation frequency) was determined by approximating the real ocean wave by the ideal one [8]. Because the real sea spectrum is wide, a single frequency of the spectrum was assumed as the excitation frequency.

Control system of ship's gas turbine propulsion system

In the modeled ship propulsion system with gas turbines, applied were the controllers of propeller shaft's angular speed (power turbine), separate for each engine, as well as the propeller pitch ratio controller, as shown in Fig.1.

In the control system of propeller shaft's angular speed the PID controller with the gain coefficient k_P, integral time-constant T_i, and differential time-constant T_D, was applied (Fig.5).

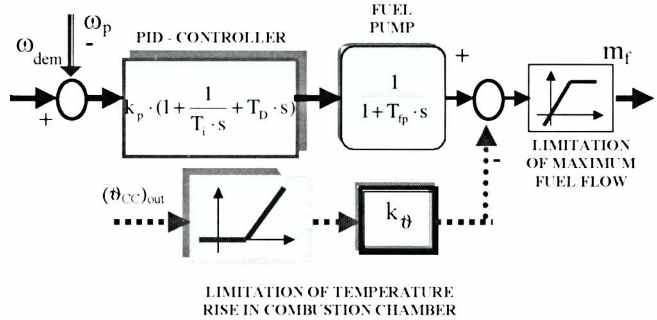

***Fig. 5.** Schematic diagram of the angular speed controller of the propeller shaft (gas turbine) T_{fp} – inertial time constant, k_ϑ – temperature coefficient*

In the gas turbine angular speed controller the two following limiters were applied :

- the limiter of fuel flow
- the limiter of gas temperature at outlet from combustion chamber [$(\vartheta_{CC})_{out}$].

Propeller pitch ratio control system

In the case of the propeller pitch control, magnitude of input function is influenced by construction of propeller pitch changing system and its control algorithm. Fig.6 shows the schematic diagram of the pitch ratio control system of CP propeller.

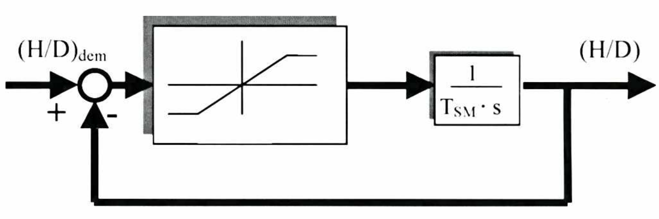

Fig. 6. Schematic diagram of the pitch ratio control system of CP propeller T_{SM} – servo-motor time-constant

SIMULATION MODEL OF SHIP PROPULSION SYSTEM WITH TWO GAS TURBINES DRIVING - THROUGH MECHANICAL GEAR - ONE CONTROLLABLE PITCH PROPELLER

For the simulation investigations the ship propulsion system presented in Fig.1, was assumed. In the system applied was the controller of propeller shaft's angular speed, separate for each turbine, having the structure shown in Fig.5.

Two identical gas turbines working in the simple open cycle consisting of two shaft turbines : the high-pressure turbine, i.e. compressor turbine (CT) and the low-pressure turbine i.e.power turbine (PT). This model was programmed by using MATLAB software together with SIMULINK overlay.

The described mathematical model of the ship propulsion system in question makes it possible to simulate both transient and steady--state characteristics of the propulsion system in the following cases :

- change of the propeller pitch ratio H/D in calm water and heavy seas
- ship propulsion system's operation (load) in heavy seas
- changes of setting of propeller shaft's angular speed.

In all above specified cases it is possible – by using the presented simulation model – to choose a structure and settings of the aplied controller.

Simulation investigations of the influence of the controller's setting on operation of the described ship propulsion system in heavy seas will be presented in the next part of this paper.

Appraised by Zygfryd Domachowski, Prof.,D.Sc.

NOMENCLATURE

B - viscous damping coefficient
CC - combustion chamber
D - propeller diameter
H - propeller pitch
H/D - propeller pitch ratio
i - number of rotary element of propulsion system
J - moment of inertia
K - coefficient of torsional stiffness
m - mass flow
M - torque, moment
n - rotating speed
S - Laplace operator
t - time
T - time constant
ϑ - temperature
ω - angular speed

Indices

dem - demanded value
f - fuel
p - propeller
C - compressor
CC - combustion chamber
GT - gas turbine

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FOREIGN conferences

A jubilee conference

In 2003 Harbin Engineering University, China, has celebrated 50th anniversary of its activity and on this occasion it organized :

the International Workshop on Maritime Safety, Efficiency and Low Environmental Impact

held on 4 and 5 September.

A co-organizer of the event was Department of Naval Architecture and Marine Engineering, Universities of Glasgow and Strathclyde, which have cooperated with the Chinese university.

Also some Polish scientists were among 31 authors of the papers prepared for the Conference. They presented the following topics :

- *Challenges in marine engineering – scientific research and education* – by M.H. Ghaemi, K. Kosowski and J. Szantyr (Gdańsk University of Technology)
- *Advanced intelligent integrated ship monitoring and control system for supporting the decision-making process* by J. Kruszewski (Gdynia Maritime University) and M.H. Ghaemi (Gdańsk University of Technology).

STAB 2003

On 15÷19 September 2003 the 8th International Conference on :

Stability of Ships and Ocean Vehicles

was organized by Escuela Tecnica Superior de Ingenieros Navales, Universidad Politecnica de Madrid.

Its aim was to contribute to development of knowledge and activities leading to improvment of safety at sea by building safer ships and their more safe operation. To this end devoted were 58 papers presented in 19 topical groups and 4 workshops of 8 topics.

In the realization of the Conference's program two representatives of Polish scientific institutions took also part :

- during a session of the „Design and Safety" topical group the paper on : *A risk-based method for ship safety assessment at the preliminary design stage* was presented by Mirosław Gerigk, D.Sc. (Gdańsk University of Technology)
- during the workshop on „Risk based approaches" Prof. Lech Kobyliński (Polish Academy of Sciences, and Foundation for Safety of Navigation and Environment Protection) presented the issue : *Capsizing scenarios and hazard identification.*

The STAB Conferences have always received a great interest and recognition from the side of Polish scientific workers, the evidence of that is the Conference of 1986 organized by Gdańsk University of Technology.