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Application of bond graph methods to starting air installation modelling

SUMMARY

Notions of the generalized effort and flow rate related to the compressor by using the bond graph theory were introduced in the paper. A model of starting air installation is presented. The complete installation working in steady-state and changeable conditions is described by means of the bond graph method.

Relationships between the installation working parameters in selected points of its structure were elaborated with the use of acceptable simplifications. A calculation example of the pressure changes in the tank at changeable air consumption during successive engine start-ups is attached.

INTRODUCTION

For many years the modelling and simulation based on the bond graph method (BG) and state equations (SE) have been developed in the Department of Combustion Engines and Compressors, Mechanical Faculty, Technical University of Gdańsk.

Background of the method was first presented by Paynter [8], then it was developed by many authors, including Karnopp and Rosenberg whose contribution was the most important [7]. Some aspects of the method, e.g. heat exchange modelling, were developed in the Technical University of Gdańsk [1÷5].

Clue to the method was highlighted in [3]. Main advantages of the system modelling method are as follows :

- possible modelling of complex physical objects by means of simple repeatable elements [11]
- applying the uniform method to modelling the systems and processes of different physical nature
- mathematical description in the form of the state equations (SE) makes it possible to solve dynamic problems in the time domain directly, and the SE system itself introduces the cause-effect relations.

Every BG model structure consists of the external nodes comprising energy sources and accumulators and dissipating elements (Fig.1).

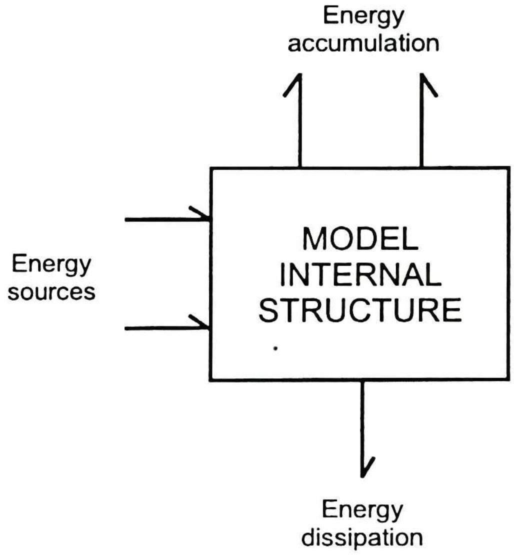

Fig.1. Structure of bond graph model

The model internal structure consists of three repeatable elements (Fig.2) :

- „one" nodes of the same generalized flow rate (Fig.2a)
- „zero" nodes of the same generalized effort (Fig.2b)
- nodes converting one energy form to another without any energy loss and accumulation (Fig.2c).

The latter kind of nodes are commonly used to describe such systems as : gear, transformer, electric motor, hydraulic final control elements.

The energy converter (PE element in Fig.2c) can be also applied to formally describe transition from one kind of the energy variables to another in order to simplify the model [9].

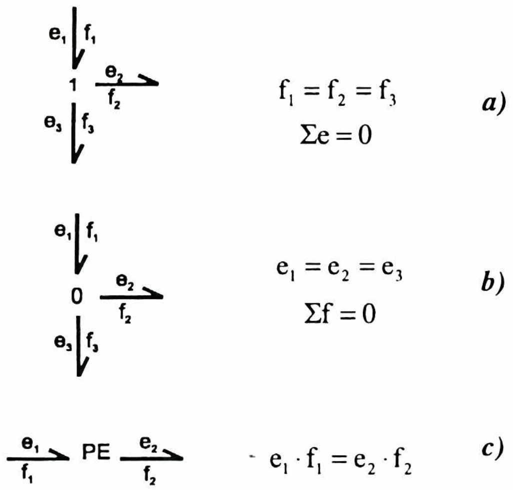

Fig.2. Bond graph model basic elements :
e – generalized effort, f – generalized flow rate, PE – energy converter

On the basis of BG model the state equations are generated „by hand" [12] or automatically [9].

Cause-effect analysis is an important element in preparing BG model [7]. The analysis makes it possible to avoid conflicts in determining the energy sources and to eliminate dependent energy accumulators. An example of the energy source conflict is to apply kinematic excitation to the inertial element, and the dependent accumulator conflict occurs if, for instance, the inertia moments of the electric motor and compressor rigidly connected to each other are treated as independent energy accumulators.

INSTALLATION MODEL

The installation is composed of :

- electric motor ME
- two-stage compressor S
- air coolers (interstage and final one) CM, CK
- air tank ZP
- consumer OD.

Course of changeable air consumption out of the installation is dependent on operation of the consumer (start-ups of the engine). A scheme of the installation is shown in Fig.3.

BG and SE modelling is aimed at describing the dynamic processes. The cause-effect model of the energy object is presented together with the state equations in Fig.4.

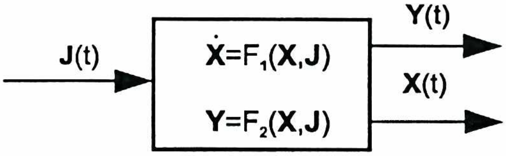

***Fig.4.** Cause – effect model of the object and general description of its state equations*
J – control vector, X – vector of state variables, Y – vector of output parameters

The commonly used, linear state equations are as follows :

$$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{BJ}$$
$$\mathbf{Y} = \mathbf{KX} + \mathbf{NJ} \tag{1}$$

where :

A,B,K,N – matrices of real number elements.

Application of BG and SE modelling makes describing the complex energy conversion processes in steady states easier. In steady state the state equations take the following form :

$$\dot{\mathbf{X}} = \mathbf{F}_1(\mathbf{X},\mathbf{J}) = 0$$
$$\mathbf{Y} = \mathbf{F}_2(\mathbf{X},\mathbf{J}) \tag{2}$$

In this case the elements of the control vector **J** are real numbers, and the state variable vector **X** and output parameter vector **Y**, whose elements are real numbers too, form the solution of the algebraic equation set (2).

In Fig.5 a general bond graph scheme of the complete compressed air installation is presented. It contains the electric motor as well.

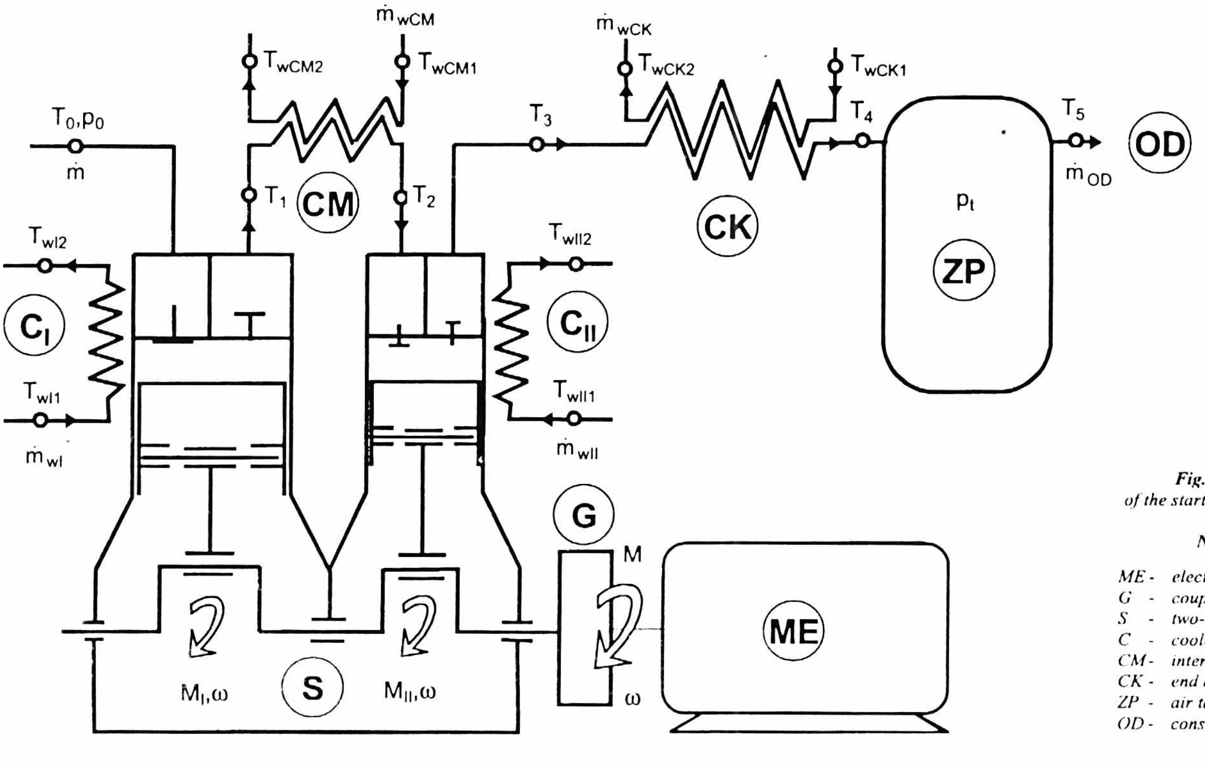

Fig.3. A scheme of the starting air installation

Notation :

ME -	*electric motor*
G -	*coupling*
S -	*two-stage compressor*
C -	*cooler*
CM -	*interstage air cooler*
CK -	*end air cooler*
ZP -	*air tank*
OD -	*consumer*

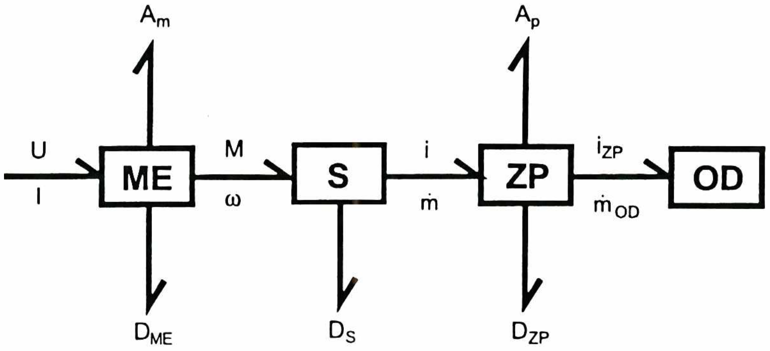

Fig.5. General bond graph scheme of the complete compressed air system
ME – electric motor, S – positive-displacement compressor with cooling system of the compressed air, ZP – air tank, OD – consumer, U, I – electric current and voltage, M, ω - rotational moment and angular velocity, i, $\dot{m}$ – air specific enthalpy and air mass flow rate, i_{ZP}, $\dot{m}_{OD}$ – air specific enthalpy behind the tank and mass flow rate of the air delivered to the consumer, A_m and A_p – mechanical and pneumatic energy accumulator, respectively

Problems of modelling the energy conversion processes occurring in a part of the installation, i.e. the compressor, coolers and tank, are highlighted below.

The driving moment M is assumed an independent control variable, and the output parameter vector comprises air and water parameters in an arbitrary point of the installation.

MODELLING THE STEADY-STATE PROCESSES

A steady-state operation process of the installation occurs if the air consumption out of the installation is invariable with time and equal to the compressor output, and ambient conditions are stationary. A bond graph scheme describing the energy conversion in the installation at the steady-state operation is presented in Fig.6. In the steady-state process conditions the air tank does not play any role and therefore it is dropped out of the bond graph scheme.

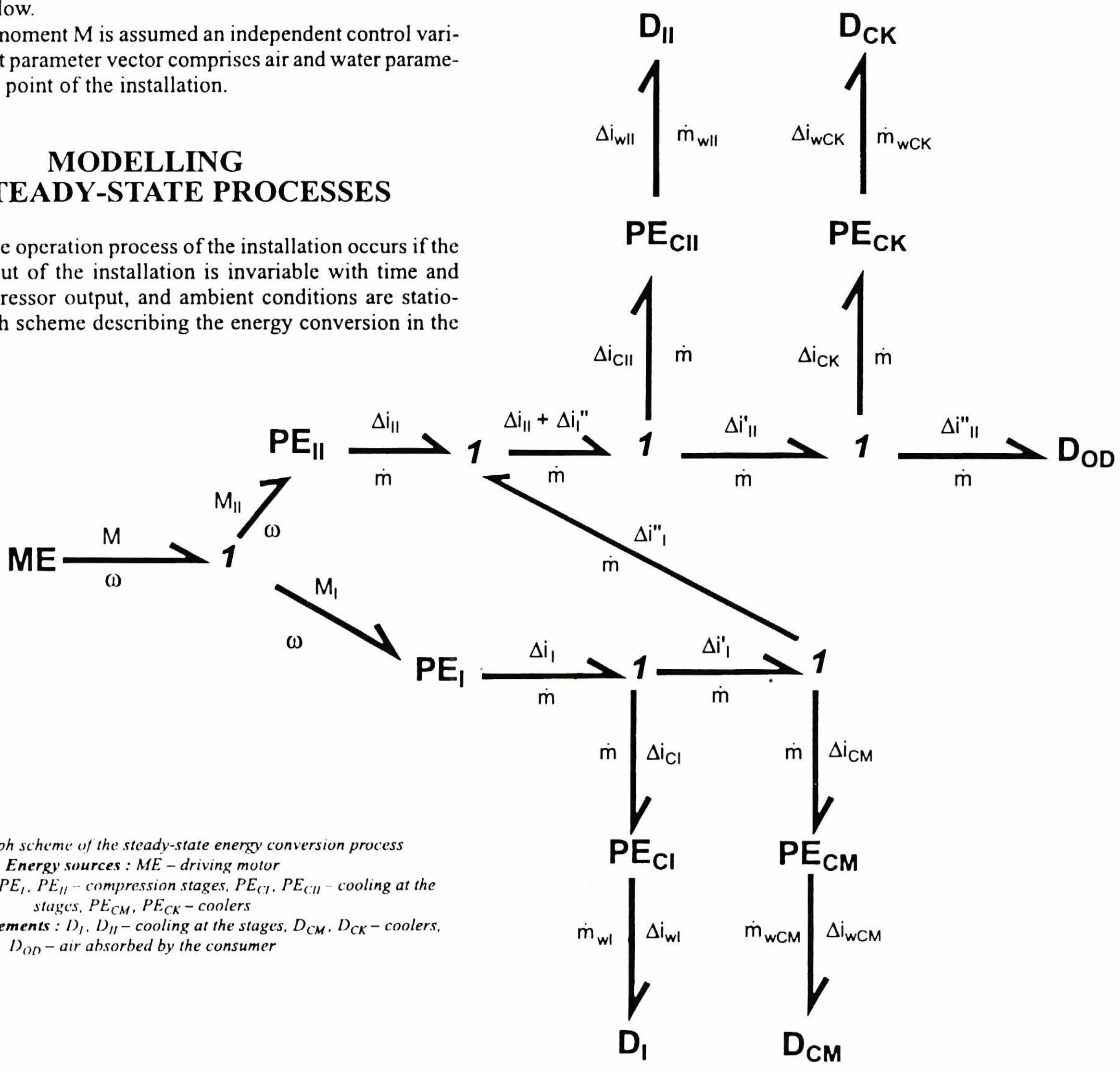

Fig.6. Bond graph scheme of the steady-state energy conversion process
Energy sources : *ME – driving motor*
Energy converters : *PE_I, PE_{II} – compression stages, PE_{CI}, PE_{CII} – cooling at the stages, PE_{CM}, PE_{CK} – coolers*
Energy dissipation elements : *D_I, D_{II} – cooling at the stages, D_{CM}, D_{CK} – coolers, D_{OD} – air absorbed by the consumer*

Relationships between the construction and operation parameters and generalized efforts (M, Δi, Δi_w) and flows (ω, $\dot{m}$, $\dot{m}_w$) applied in the model were established on the following simplifying assumptions :

- volumetric efficiency and energy efficiencies of both compression stages are equal
- air temperatures at the suction side of each stage (T_0, T_2) are approximately equal
- energy dissipation to environment occurs through cooling water only
- no external leakage happens.

Relationships between the construction and operation parameters and generalized efforts and flows take the following form :

- rotational moments :

$$M_I = \frac{1}{2\pi\eta} p_0 \lambda V_I \ln \frac{V_I}{V_{II}}$$

$$M_{II} = \frac{1}{2\pi\eta} p_0 \lambda V_I \ln \frac{p_t V_{II}}{p_0 V_I} \tag{3}$$

- air specific enthalpy changes at particular compression stages and coolers:

$$\Delta i_I = M_I \frac{2\pi R T_0}{\lambda V_I p_0}$$

$$\Delta i_{II} = M_{II} \frac{2\pi R T_0}{\lambda V_I p_0}$$

$$\Delta i'_I = c_p (T_1 - T_0)$$

$$\Delta i'_{II} = c_p (T_3 - T_0) \tag{4}$$

$$\Delta i''_I = c_p (T_2 - T_0)$$

$$\Delta i''_{II} = c_p (T_4 - T_0)$$

- water specific enthalpy changes :

$$\Delta i_w = c_w (T_{w2} - T_{w1}) \tag{5}$$

- mass flow rate of the air delivered by the compressor (i.e. compressor output) :

$$\dot{m} = \omega \frac{\lambda V_I}{2\pi} \frac{p_0}{R T_0} \tag{6}$$

In (3), (4), (5) and (6) the following notation is applied :

V - displacement volume of the compressor
n - rotational speed
λ - volumetric efficiency
η - isothermal efficiency
R - gas constant
c_p - air specific heat at constant pressure
c_w - water specific heat.

DYNAMIC PROCESS MODELLING

Time-changeable air demand of the consumer (due to variable rotational speed of the engine during its start-ups) causes dynamic energy conversion processes within the installation. The bond graph scheme which describes the energy conversion in the system at such conditions is presented in Fig.7. Descriptions of the energy conversion processes connected with cooling at the particular stages and air cooling in the interstage and final coolers are omitted in the scheme. The processes are taken into account by assuming approximate values of the energy dissipated at the particular points of the installation, e.g. the following values for the presented example of the installation :

$$D_I = 0.22 M_I(t)\omega \qquad D_{CM} = 0.72 M_I(t)\omega$$

$$D_{II} = 0.33 M_I(t)\omega \qquad D_{CK} = 0.4 M_{II}(t)\omega$$

The presented scheme describes energy conversion processes on the assumption that the air absorption changes cause only „moderate" changes of air parameters within the installation (e.g. changes of the air tank pressure $p_t(t)$ do not exceed 30% of the tank pressure

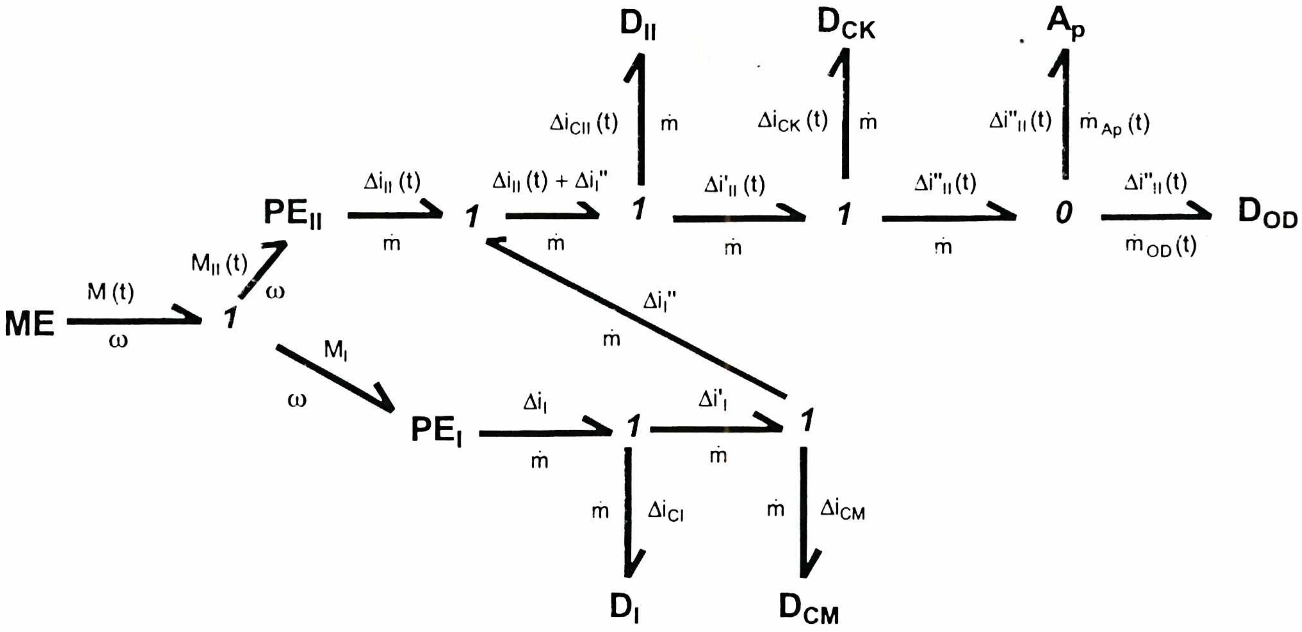

Fig.7. Bond graph scheme of the dynamic energy-conversion process
PE_{II} - modulated energy converter (2nd stage of the compressor), A_p - energy accumulator (air tank)

during the steady-state operation of the system). On the assumption the following influences were neglected :

- ➔ influence of the air absorption change on operation of the 1st stage of compressor as well as on the efficiency and volumetric efficiency of the 2nd stage of compressor
- ➔ influence of the air temperature change in the tank on the compressor forcing pressure $p_t(t)$ (the temperature T_{ZP} was assumed constant and corresponding to the air temperature at forcing side, T_4 during steady-state operation of the system).

On the assumption of the linear increase of the air consumption during engine start-ups :

$$\dot{m}_{OD}(t) = kt$$

the change courses of the driving moment $M_{II}(t)$ of 2nd stage of compressor and that of the entire compressor, M(t), are described by the following relationships resulting from the state equation solution :

$$M_{II}(t) = \frac{1}{2\pi\eta} p_0 \lambda V_I \ln \frac{p_t(t) V_{II}}{p_0 V_I}$$

$$M(t) = M_I + M_{II}(t) = \frac{1}{2\pi\eta} p_0 \lambda V_I \ln \frac{p_t(t)}{p_o} \qquad (7)$$

where :

$$p_t(t) = \frac{RT_{ZP}}{V_{ZP}}\left(\frac{p_{ZP}V_{ZP}}{RT_{ZP}} + \dot{m}t - \frac{1}{2}kt^2\right)$$

At t = 0, the air parameters (p_{ZP},T_{ZP}) in the tank of V_{ZP} volume correspond to those behind the final cooler (p_t,T_4) during the steady-state operation of the system.

COMPUTATION EXAMPLE

Calculations were performed for different installations equipped with the compressor (-s) of the following parameters :

- ⅄ forcing pressure : p_t = 3 MPa
- ⅄ 1st stage cylinder diameter : d_I = 195 mm
- ⅄ 2nd stage cylinder diameter : d_{II} = 86 mm
- ⅄ piston stroke : s = 140 mm
- ⅄ rotational speed : n = 1000 rpm

In the calculations the changeable air consumption was assumed, corresponding to the demand for several successive start-ups of the engine, occurring within short time intervals. In Fig.8,9 and 10 calculation results of the change courses of the air tank pressure for three different starting air installations (of different volumes of the tank and number of the compressors) are presented.

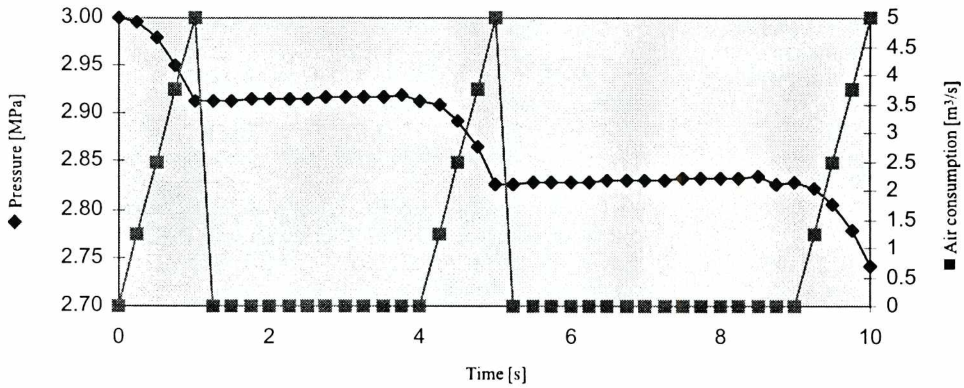

Fig.8. Pressure change in 3 m³ air tank

(one compressor applied in the installation)

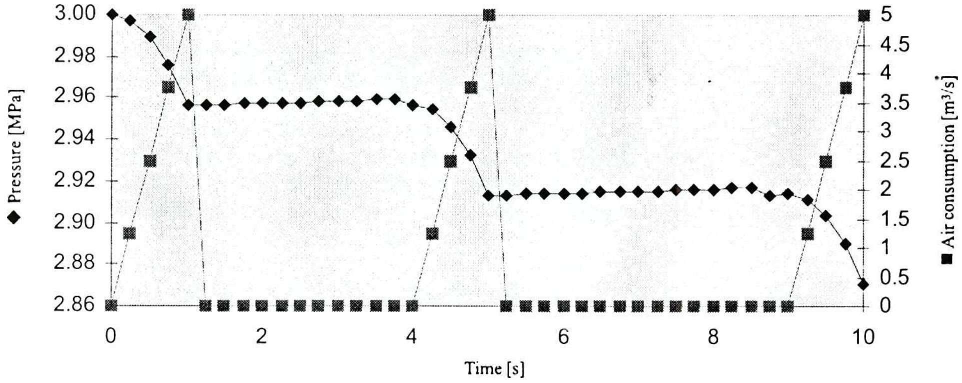

Fig.9. Pressure change in 6 m³ air tank

(one compressor applied in the installation)

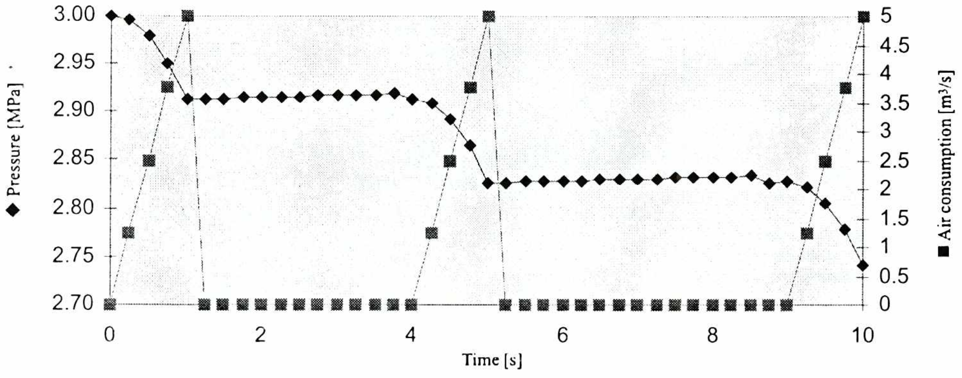

Fig.10. Pressure change in 3 m³ air tank

(two compressors applied in the installation)

CONCLUDING REMARKS

- The bond graph method makes it possible to model the complex physical objects and processes of different physical nature by means of simple repeatable elements.

- Application of the method to modelling the starting air installation simplifies analyzing the processes (either steady or unsteady ones) which occur at an arbitrary point of the installation.

- In modelling the thermal processes it is convenient to assume the specific enthalpy increment as the generalized potential and the mass flow rate as the generalized flow rate. Application of this approach was not found by the authors in the available literature sources.

- The example air pressure changes in the air tank during starting the engine, determined by means of the elaborated models, are qualitatively consistent with usual practice of ship power plant operation in spite of the application of many simplifying assumptions. Switching-on the starting air compressors during several starts of the engine executed one by one in short time intervals does not practically influence the course of air pressure changes in the air tank in the same time (Fig.8 and 10).

NOMENCLATURE

c_p – air specific heat at constant pressure
c_w – water specific heat
D – energy dissipation element
BG – bond graphes
i – air specific enthalpy
i_w – water specific enthalpy
k – constant
$\dot{m}$ – mass flow rate of the air through the compressor, i.e. its output
$\dot{m}_w$ – mass flow rate of water
M – compressor driving moment
n – rotational speed
p_0 – ambient pressure
p_t – compression pressure
PE – energy converter
R – gas constant
SE – state equation
t – time
T – air temperature
T_0 – ambient temperature
T_w – water temperature
V – displacement volume of the compressor
Δi – air specific enthalpy increment (change)
$\Delta i', \Delta i''$ – air specific enthalpy change at coolers
Δi_w – water specific enthalpy increment
η – isothermal efficiency
λ – volumetric efficiency
ω – angular velocity

Indices

I, II – first and second stage of compressor, respectively
CK – end air cooler
CM – insterstage air cooler
ZP – air tank

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Current report

TECHNICAL UNIVERSITY OF SZCZECIN
FACULTY OF MARINE TECHNOLOGY

KINEMATIC EXCITATION SIMULATOR

Department of Shipboard Mechanisms and Cranes, Technical University of Szczecin, elaborated a stand for research on amplitude – frequency characteristics of different shipboard equipment, necessary during designing and building such devices.

The structure and drive of the kinematic excitation simulator, which models assumed motion parameters, was designed and built by the Department's team. Its mechanical part consists of three main elements :

⇒ the spatial frame of 4600 x 4600 x 5000 mm
⇒ the movable traverse of 3000 kg mass and
⇒ the set of platforms.

The traverse and set of platforms can move along vertical guides. The vertical motion is forced by hydraulic cylinders. The set of platforms is also able to perform the motions which correspond to ship motions in regular waves. The traverse and frame are fitted with the system of pulleys which makes leading four independent tension members possible, and the set of platforms is equipped with the foundation to fix the shipboard equipment to be tested.

The electro-hydraulic drive of the simulator makes it possible to control the position, speed and acceleration of the traverse and set of platforms, as well as the angular inclination of the foundation of the set. The maximum speed of the traverse under 116 kN load is 0.77 m/s , and at 240 kN load – 0.37 m/s. The maximum speed of the set of platforms is 1.50 m/s, and the inclination of the rotable foundation – up to 10°.

Sixteen measured variables are possible to be continuously recorded at the stand.

The authors of the project in question are : Mieczysław Hann, Assoc.Prof.,D.Sc., Włodzimierz Rosochacki, D.Sc., and Wiesław Jóźwiak, M.Sc.