IOP Conf. Series: Earth and Environmental Science **172** (2018) 012006 doi:10.1088/1755-1315/172/1/012006

Mathematical model of turbocharger as part of intelligent system component designed for technical operation of diesel engines and for training

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Abstract. The paper includes a basic module of a slow speed ship diesel engine turbocharger. Our experience in modelling and simulation makes it possible to produce flexible models. Next, a control system needs to have operational modules in real time, with sufficient range of precision. This is a light algorithm under Delphi area. Module makes up a part of smart intelligent pack. Pack is a software that combines and solves the task of exploitation and design of modern slow speed diesel engines. The module allows to construct the working mode line and to examine the behaviour of the operating point quasi-statically. The model is based on a quasi-static approach for real-time operation in a software package including a flexible input simulator and modules for solving constructive and operational tasks with graphical retrofit based on image recognition

1. Introduction.

Whether the current mathematical models of modern low-frequency marine diesel engines are up to date can determined by the following facts:

- The solution of systemic tasks through mathematical modeling replaces multiple ground experiments and reduces costs.
- Mathematical modeling gives clarity to processes and interrelationships (target functions, relationship between sub-themes) which is difficult, and in some cases impossible, for physical models.
- At this stage, sufficiently precise, flexible, adaptive and dynamic models are needed for management, technical diagnosis and training purposes.
- Physical modeling is still too expensive and time consuming, there is no unified memory of data in modern management systems.
- There is no known practical realization of trainable mathematical models, the requirements for real-time functionality of mathematical models are steadily increasing for management purposes.

2. A complex flexible mathematical model of a marine diesel engine for the purposes of technical diagnostics and management.

An efficient mathematical model has been developed taking into account the influence of actual processes in the exhaust and air supply systems, the laws of fuel supply, gas exchange and movement of the exhaust valve. Afterwards, accuracy, sensitivity, relevance and applicability are assessed and adapted by training with knowledge gained from the processing of experimental and model data for specific engines. Based on this, a software called Flexible Intelligent Package has been developed [2]. The publication presents a sophisticated, functional, adaptive mathematical model of a marine diesel engine with an isobar system of overfill with specifying the sub-models of the main components; reporting the dynamics of the turbocharger aggregates and their joint work with the piston part and the specified gas exchange model.

A system has been developed for training the universal mathematical model for the management of marine engines, which includes an optimization procedure for adapting the universal model to a specific engine with specified accuracy and adequacy.

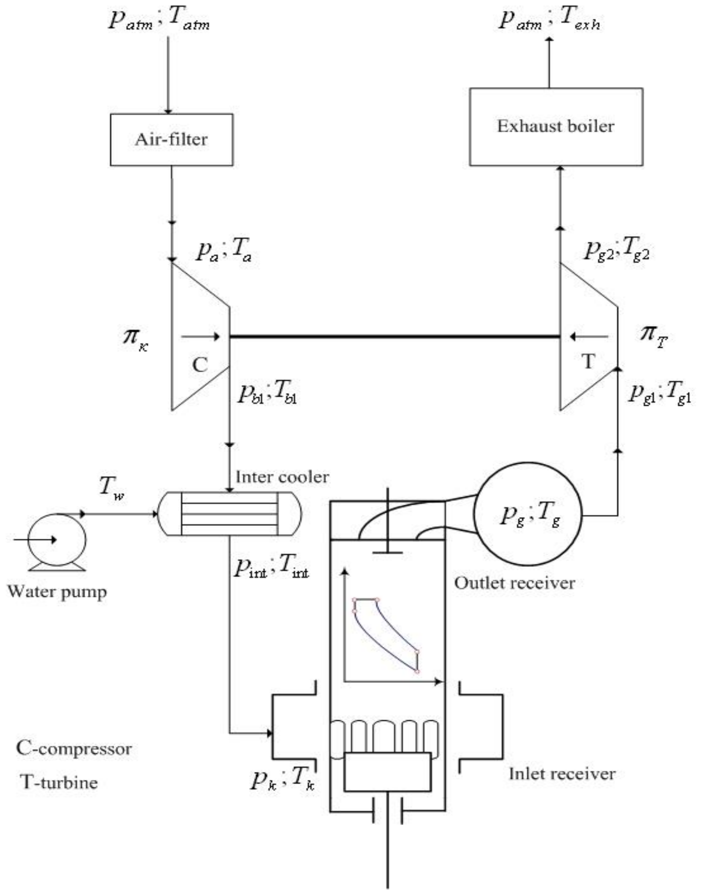

Figure 1. Structural diagram of a mathematical model.

The actual cycle is based on the concept of a physical-mathematical model of the components of the working process. This allows the elementary processes to be described by means of systems of private and ordinary differential equations expressing the laws not only of thermodynamics but also of aero-gas dynamics and chemical kinetics [1]. I'm going to discuss in more detail the processes in the turbocharger unit. For this purpose I will review the linear graphic model of the TA while analyzing separately the processes of transformation of energy in the compressor and turbine stage (Figure 2).

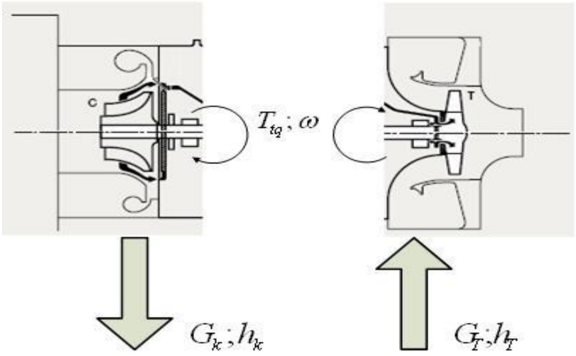

Figure 2. Processes of transformation of energy in the compressor and turbine stage

In linear graphical modeling, elements that transform or transmit energy are called converters. The main process of energy transformation in this type of unit is presented in Figure 2 by a two-input unit.

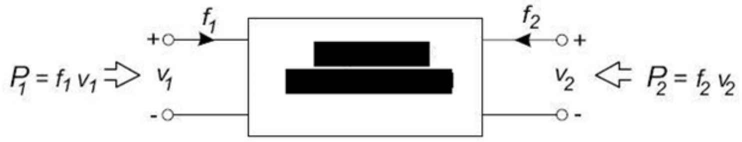

Figure 3. Two input element representing transformation of energy.

The definition of the two-input units is given by H. M. Paynter. There are two types of such units - a transforming unit and a "spinning" unit, which are presented in Figure 4.

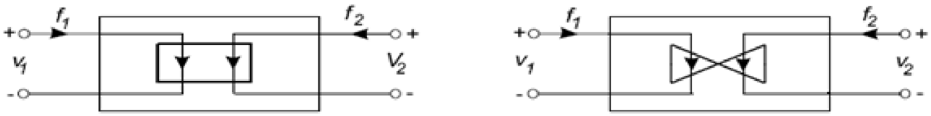

Figure 4. Transforming and spinning

The basic linear relation between the parameters of the two inputs is:

$$\begin{bmatrix} v_1 \\ f_1 \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} v_2 \\ f_2 \end{bmatrix}$$

With transforming converters:

$$c_{12} = c_{21} = 0 \quad c_{22} = -1/c_{11}$$

And with 'spinning' converters:

$$c_{21} = -1/c_{12} \quad c_{11} = c_{22} = 0$$

And the basic relation now is:

$$\begin{bmatrix} v_1 \\ f_1 \end{bmatrix} = \begin{bmatrix} TF & 0 \\ 0 & -1/TF \end{bmatrix} \begin{bmatrix} v_2 \\ f_2 \end{bmatrix}$$ for transforming converters and

$$\begin{bmatrix} v_1 \\ f_1 \end{bmatrix} = \begin{bmatrix} 0 & GY \\ -1/GY & 0 \end{bmatrix} \begin{bmatrix} v_2 \\ f_2 \end{bmatrix}$$ for 'spinning' converters, where TF is the degree of conversion and GY is the 'spinning' module.

I consider the compressor and the turbine stage as two two-input power converters while looking for the degree of transformation between the fluid power and the mechanical power. I assume that power is transmitted without loss. The attitude of the variables is algebraic and independent of time, and is represented by coefficients that are constants and are linear.

The relationship between torque and flow is Euler's equation:

$$T_{tq} = -G_T\left(c_{u_{2T}} - c_{u_{1T}}\right)r_T \tag{1}$$

torque is a linear dependence on the consumption.

$$T_{tq} = -K_T G_T \tag{2}$$

therefore $$K_T = \left(c_{u_{2T}} - c_{u_{1T}}\right)r_T \tag{3}$$

If the energy is transformed without loss, the mechanical power is transformed as entirely fluid

the basic equations that express the relationship between

$$\begin{gathered} \boxed{P_m = P_{XT}} \\ \omega T_{tq} = G_T h_T \\ \omega K_T G_T = G_T h_T \\ \omega = \frac{h_T}{K_T} \end{gathered} \tag{4}$$

The parameters are:

$$\left| \begin{aligned} & T_{tq} = K_T G_T \\ & \omega = \frac{1}{K_T} h_T \end{aligned} \right. \tag{5}$$

Similarly, we will consider the connection between the parameters in the compressor stage (Fig. 5)

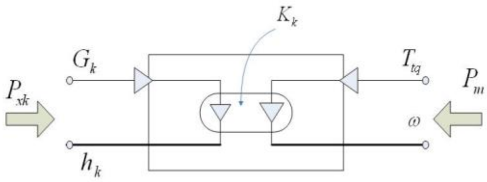

Figure 5. Graphic model of the compressor stage

And again I use the Euler equation and the assumption that the energy is converted without a loss

$$\begin{aligned} & \boxed{P_m = P_{XK}} \\ & \omega T_{tq} = G_K h_k \\ & \omega T_{tq} = G_K h_K \\ & h_K = \frac{\omega T_{tq}}{G_K} = \frac{\left(c_{u_{2K}} r_{2K} - c_{u_{1K}} r_{1K}\right)}{T_{tq}} \omega T_{tq} = \left(c_{u_{2K}} r_{2K} - c_{u_{1K}} r_{1K}\right)\omega \end{aligned} \tag{6}$$

Therefore the equations that express the relationship between the variables are:

$$\left| \begin{aligned} & G_K = \frac{1}{K_K} T_{tq} \\ & h_K = K_K \omega \end{aligned} \right. \tag{7}$$

For the turbine and the compressor consumption relationships, and their heat fluctuations can be presented in the following form:

$$\begin{aligned} & G_K = \frac{K_T}{K_K} G_T; \\ & h_K = \frac{K_K}{K_T} h_T \end{aligned} \tag{8}$$

By replacing the K_k and K_T coefficients in the equations, we obtain dependencies between the main components of the compressor and the turbine stage, which do not specify the losses.

$$\frac{G_K}{G_T} = \frac{\left(c_{u_{2T}} - c_{u_{1T}}\right) r_T}{\left(c_{u_{2K}} r_{2K} - c_{u_{1K}} r_{1K}\right)} \quad (9)$$

$$\frac{h_K}{h_T} = \frac{\left(c_{u_{2K}} r_{2K} - c_{u_{1K}} r_{1K}\right)}{\left(c_{u_{2T}} - c_{u_{1T}}\right) r_T} \quad (10)$$

By analogy with the analysis of the ideal cycles of gas turbine engines (Brighton cycle) I make a correlation between the thermodynamic parameters of the engine and the gas dynamics parameters of the turbocharger. With sufficient precision for practice, we can accept a relative difference between the power consumed by the compressor and the power generated by the turbine within 1-2%, i.e.

$$\Delta P = \left| \frac{P_T - P_K}{P_K} \right| .100 \le 2\% \quad (11)$$

The economical and reliable operation of ship diesel engine is only possible when the characteristics of all its elements - the compressor, the internal combustion engine and the turbine - are in concordance [4]. By concordance of the characteristics we mean the interconnection of all the main technical, operational, economical, gas-dynamical and constructive parameters of the internal combustion engine and turbocharger.

An algorithm for calculating the turbocharger has been developed. The input database for the algorithm is related to the mathematical model of the processes in the piston part of the slow speed diesel engine.

The equilibrium turbocharger mode includes the known equation of dynamics and equilibrium conditions in the non-compressor and turbine moments [3]. The primary equations are non-linear, and by Taylor's decomposition they are linearized, and then the system is obtained:

$$\left| \begin{array}{l} dT_{tqk} = \frac{\partial T_{tqk}}{\partial p_k} .dp_k + \frac{\partial T_{tqk}}{\partial \omega_k} d\,\omega_k \\ dT_{tqk} = \frac{\partial T_{tqk}}{\partial p_k} .dp_k + \frac{\partial T_{tqk}}{\partial \omega_k} d\,\omega_k \\ dG_k = \frac{\partial G_k}{\partial p_k} .dp_k + \frac{\partial G_k}{\partial \omega_k} .d\,\omega_k \\ dT_{tqT} = \frac{\partial T_{tqT}}{\partial \omega_k} .d\,\omega_k + \frac{\partial T_{tqT}}{\partial p_{g_1}} .dp_{g_1} + \frac{\partial T_{tqT}}{\partial T_{g_1}} .dT_{g_1} \\ J_K . \frac{d\omega_k}{dt} + F_k . d\omega_k = \frac{\partial T_{tqT}}{\partial p_{g_1}} .dp_{g_1} + \frac{\partial T_{tqT}}{\partial T_{g_1}} .dT_{g_1} - \frac{\partial T_{tqk}}{\partial p_k} .dp_k \end{array} \right. \quad (12)$$

The result is the equation $T \frac{dx}{dt} + x = -k_n . \mu_n - b_1 \frac{d\mu_n}{dt} - k_b . \mu_b - b_2 \frac{d\mu_b}{dt}$ (13)

where $x = \frac{\Delta p_к}{p_{к_0}}$, $\mu_n = \frac{\Delta n_{дв}}{n_{дв_0}}$, $\mu_b = \frac{\Delta B_e}{B_{e_0}}$.

After the corresponding assignments and substitutions, a linear differential equation is obtained:

$$\left(T_0 + \tilde{T} t\right) \frac{dx}{dt} + x = C_0 + C_1 t + C_2 t^2 \quad . \quad (14)$$

This deductive approach is to determine the turbocharger performance of an undetermined slow speed diesel engine regime. In new constructions and availability of manufacturer data for the dependencies used, MM can be updated. To find the functional relationship between $\mathbf{p_к}$ and $\mathbf{n_д}$, the similarity theory is used.

3. Program product FLEX Turbo.

The package was developed in DELFI environment [5,6]. The easy access for programmers non-specialized in the software environment of this type is the main reason for choosing it. The software complex is built on the modular principle. The modules are arranged hierarchically according to their importance, location and communication between them. A special place is assigned to the main sources of energy of the ship - the main engines. A simplified diagram of ship propulsion complex is presented in Figure 6.

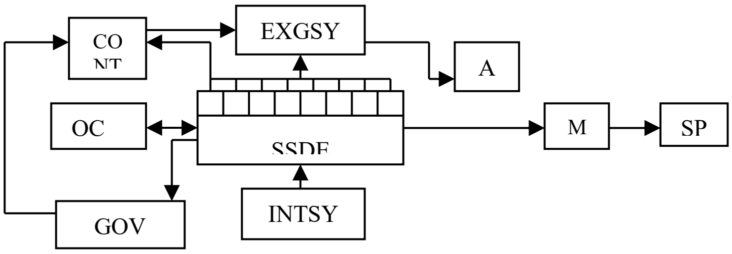

Figure 6. Structural diagram of MM.

The choice of the Delphi environment for the implementation of the model is mainly due to the fact that the Delphi programming language is a traditional continuation and refinement of the Object Pascal language. Variables, as in any other programming language, are of several types which allow partial combination of the environment with the imposed world-class multimedia software. Here we can recommend an application even such as Flash, which was previously believed to be incompatible with Object Pascal. The main argument for the use of Delphi is the modular principle in the realization of the final FLEX TURBO software. Although Object-Oriented Programming also uses other advanced languages such as C / C ++ Visual Basic, Delphi has been introduced into simulators by world-known manufacturers such as Turbo Diesel 2.0 and Virtual Engine Room by Dr. Stefan Cluj; Kongsberg; Maritime Software, and others. Unlike in Visual Basic and C ++, in Delphi variables cannot be assigned randomly, which is an advantage in our case of application. The database and the constraints associated with the process simulation are embedded in the software and can be retrieved by default. The wide range of components and modules developed by Delphi makes it extremely easy to develop the product. This allows to focus on the complex model and its improvement.

The software is designed to visualize the joint work of the piston and the turbocharger unit of modern low-frequency marine diesel engines [3]. After starting the main panel, an image is obtained as shown in Figure 7.

The next step is entering the mass dimensions of the particular ship engine to set up the model. The input data panel has default values.

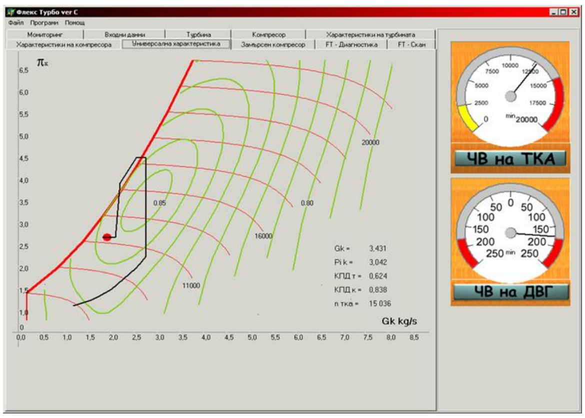

Figure 7. Control panel of the software product and preview of cost performance of a centrifugal compressor

The software dynamically visualizes the turbocharger unit's operating point on the universal feature of the centrifugal compressor. The mathematical model allows to observe the trajectory of the point when changing the ship engine mode factors. The character of the trajectory indicates a process that does not coincide with the hysteresis cycle discussed in previous versions of the product for loading and unloading the engine. Figure 7 depicts the graphics panel of cost performance of the input data for the mathematical model. The latter allows the pumping limit to be altered as a function of the operating factors and the contamination of the flow path of the compressor. Similar is the way of using the software product for simulated contamination of the flow part of the compressor.

The software is designed to meet the standards and requirements of ISO 9000-2000 and has the potential of further adjusting from a European to a North American metric standard. This makes it universally applicable to the turbocharger research by leading manufacturers from around the world.

4. Conclusion

The complex approach to using mathematical models in multi-purpose software is limited at this stage by the capabilities of the manufactured hardware. The realization of such a multi-purpose complex is useful for assisting the experts in day-to-day solving of the two basic engineering tasks - design and exploitation, and also for maintaining the connection between the two by means of feedback forms. When analyzing the behavior of the turbocharger, it should be taken in consideration that any change in the cost performance results in a corresponding change in the line of work modes. For example, if there is a decrease in the area of the windows as a result of contamination during the operation of the ship diesel engine, the air flow through the internal combustion engine also decreases and the cost performance is moved to the left of the initial position. At the same time, the airflow through the compressor is also reduced, and therefore the turbocharger operating mode line is also moved to the left, i.e. closer to the pump area. Analogous changes occur in the sailing characteristics of ships in the tropics as a result of an increase in the temperature of the air sucked up by the compressor. This possible move of the turbocharger line closer to the pump area must be taken into account when conforming the characteristics and operating ship diesel engine.

The airborne contamination of the ship diesel engine during operation results in an increase in the resistance of the treadmill, a reduction in air consumption, and discrepancies in ship diesel engine characteristics. Successful operation of ship diesel engine with poorly conformed characteristics of the compressor-ship diesel engine-turbine is virtually impossible. It is therefore necessary to quickly find and eliminate the causes of discrepancies in the characteristics.

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