Assessment of Propulsion System Integration via Process Modeling

by

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Abstract

The seaborne transportation of bulk cargo, goods and energy continues to intensify from year to year. At the same time, the awareness of environmental issues puts a pressure on commercial vessels to be more efficient, cost-effective and environmentally friendly. To meet these strict and often contradicting requirements, the engineering level and, hence the complexity of modern marine propulsion systems increase. The present stage of technological development provides many opportunities for improvement of the propulsion system efficiency. These include measures and devices for optimisation of the propulsion engine efficiency itself, as well as for optimisation of the propulsive effectiveness of a ship. However, the global property of the system does not equal to the superposition of properties of the constituent components, and thus the ultimate optimisation requires not only the highest efficiency from the individual components but mostly the efficient system integration. The propulsion system modelling and simulation technique plays a more and more critical role in resolving the aforementioned complexities. Especially as because the simultaneous assessment of performance, safety and reliability of propulsion system under real service conditions and transient operation modes are becoming important.

A system analysis methodology is applied to fulfil the needs of the sophisticated integrated propulsion system model-based study. The system analysis is a formal methodological framework for integrated dynamic processes modelling and simulation providing a holistic insight of the system performance and revealing essential interrelations between the sub-systems. The application of system analysis approach is illustrated via the modelling of a propulsion plant combined with an air lubrication system.

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Abbreviations

$\tilde{A}$: average area $[m^2]$
B_a: ship's hull breadth $[m]$
$C_{p.e}$: specific exhaust heat (at constant pressure) $[J\ kg^{-1}K^{-1}]$
$C_{p.a}$: specific air heat (at constant pressure) $[J\ kg^{-1}K^{-1}]$
C_r: resistance reduction coefficient $[-]$
D_p: propeller diameter $[m]$
d_p: ALS pipe diameter $[m]$
FMEP: mean friction pressure $[Pa]$
F_p: fuel pump rack index $[-]$
G_{als}: air mass flow to ALS $[kg\ s^{-1}]$
G_a: air mass flow through engine $[kg\ s^{-1}]$
G_c: air mass flow through compressor $[kg\ s^{-1}]$
G_{exh}: exhaust gas mass flow through turbine $[kg\ s^{-1}]$
G_f: fuel mass flow $[kg\ s^{-1}]$
g: gravitation acceleration constants $[m\ s^{-2}]$
h_{exh}: specific enthalpy of exhaust gas $[J\ kg^{-1}]$
h_{draft}: ship's hull draft $[m]$
IMEP: mean indicating pressure $[Pa]$
I_e: engine moment of inertia $[m\ s^{-2}\ kg]$
J_p: propeller advance ratio $[-]$
K_T, K_Q: propeller open water coefficients $[-]$
k_a: air gas specific heat ratio $[-]$
k_e: exhaust gas specific heat ratio $[-]$
$k_{1,2,3}$: regression coefficients $[-]$
l_p: ALS pipe length $[m]$
M_t: weight of ship hull $[kg]$
$m_{e.r}$: mass of exhaust gas in manifold $[kg]$
$m_{f.c}$: fuel mass per cycle $[kg]$
n_e: engine rotational speed $[s^{-1}]$
P_a: ambient air pressure $[Pa]$
P_{bp}: air pressure after bypass valve $[Pa]$
P_{exh}: exhaust gas receiver pressure $[Pa]$
P_c: air pressure after the compressor $[Pa]$
P_s: scavenging air receiver pressure $[Pa]$
Q_e: engine torque $[Nm]$
Q_p: propeller torque $[Nm]$
R_{als}: resistance of hull due to ALS operation $[N]$
R_a: air gas constant $[J\ kg^{-1}K^{-1}]$
R_{exh}: exhaust gas constant $[J\ kg^{-1}K^{-1}]$
R_t: total resistance of hull $[N]$
T_a: ambient air temperature $[K]$
T_{exh}: exhaust gas temperature (before turbine) $[K]$
T_c: compressor outlet temperature $[K]$
T_p: propeller thrust $[N]$
T_s: scavenging air receiver temperature $[K]$
t_a: air layer effective thickness $[m]$
t_p: thrust deduction factor $[-]$
U_p: propeller inflow velocity $[m\ s^{-1}]$
$V_{e.r}$: exhaust gas manifold volume $[m^3]$
V_c: swept volume of cylinder $[m^3]$
$V_{a.r}$: air receiver volume $[m^3]$
V_s : ship speed $[m\ s^{-1}]$
W_c: work of compressor $[W]$
W_T: work of turbine $[W]$
w_p: wake fraction $[-]$
z_c: number of engine cylinders $[-]$
μ : flow coefficient $[-]$
η_{iC}: compressor isentropic efficiency $[-]$
η_{iT}: turbine isentropic efficiency $[-]$
η_C: relative thermal efficiency $[-]$
τ_{tc}: time constant of TCH $[s]$
ρ: density of water $[kg\ m^{-3}]$

1. Introduction

The significant evolution in marine propulsion systems design has been triggered by the efforts to reduce the environmental impact and operational costs. These require to improve not only propulsion engine efficiency but also simultaneously addresses for the ship propulsive efficiency. Historically, the rules introduction followed by the evolution of ship design, Fig. 1 details steps of regulations introduction, followed by the corresponding trends in propulsion-related technologies development..

The reciprocating engine concept seems to remain the basis for propulsion power delivery. Therefore, the efficiency of fuel energy conversion into mechanical energy remains the driving factor of the propulsion system improvement in terms of an Energy Efficiency Design Index (EEDI). At the same time, stringent NOx emission regulation limits engine-related improvement of combustion process for efficiency. The aforementioned well-known trade-off, in turn, necessitates the efforts in developing new technologies and intelligent system integration approach in order to find better propulsion system solutions. The appearance of the trend to hybrid systems indicates the result of such efforts, also involving the development of systems integration solutions.

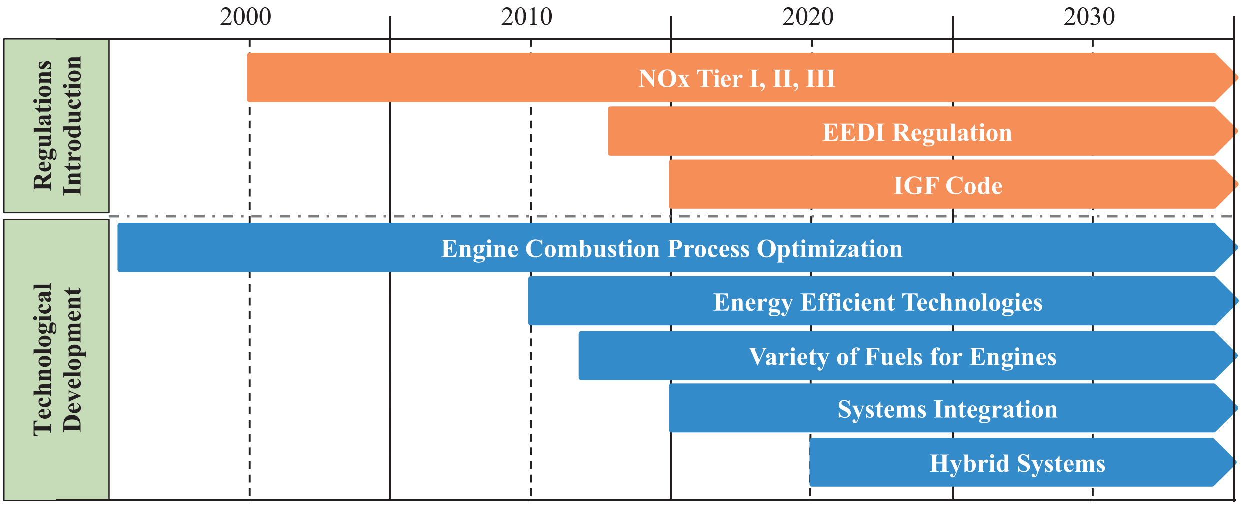


Fig. 1 Driving forces and Propulsion Development Trends

Many solutions to propulsion system improvement have been already developing and appeared in the market. The summary of the engine sub-systems and available solutions forming the framework of propulsion system ecosystem is illustrated in Fig. 2. However, a combination of various technologies, applied simultaneously, may not produce the expected improvement due to the contradiction effects or lead to a penalty in total efficiency at off-design conditions. Moreover, the ship has also a time-varying operation profile and volatile trading patterns, hence affecting the energy efficiency of the integrated propulsion system. Therefore, the selection of the most suitable solutions and configurations for a particular ship is a non-trivial task.

The challenge in propulsion plant design can be summarised as the integration of various heterogeneous mechanical and electrical components into one well-behaved system providing the ultimate efficiency at a broad range of operating conditions. In this respect, the system integration means the evaluation and optimisation of the system behaviour regarding state variables from different domains ensuring the proper interaction between the components. It is undeniable that such integration has to be done in an early ship and system design phase, thus a process modelling and simulation approach has great importance. However, owing to the complexity of the integrated propulsion system, the development of the modelling framework to cover the system in a holistic way is not an easy task.

The system analysis approach is the methodology to tackle the analysis of complex systems. Following the method, the system is hierarchically decomposed to the lower-level components, the information interface and physical variables are then determined to establish interconnections between the components. Finally, every component can be described by a generic and reconfigurable mathematical model in terms of input/output relationships. Such the approach can significantly aid the design process for new systems as well as the energy management, control optimisation and reconfiguration of existing vessels [1],[2].

The benefits of process modelling for assessment of propulsion system integration are illustrated via an example of evaluation the integration of propulsion engine and an air lubrication system. Various case studies have been conducted presenting the valuable results.

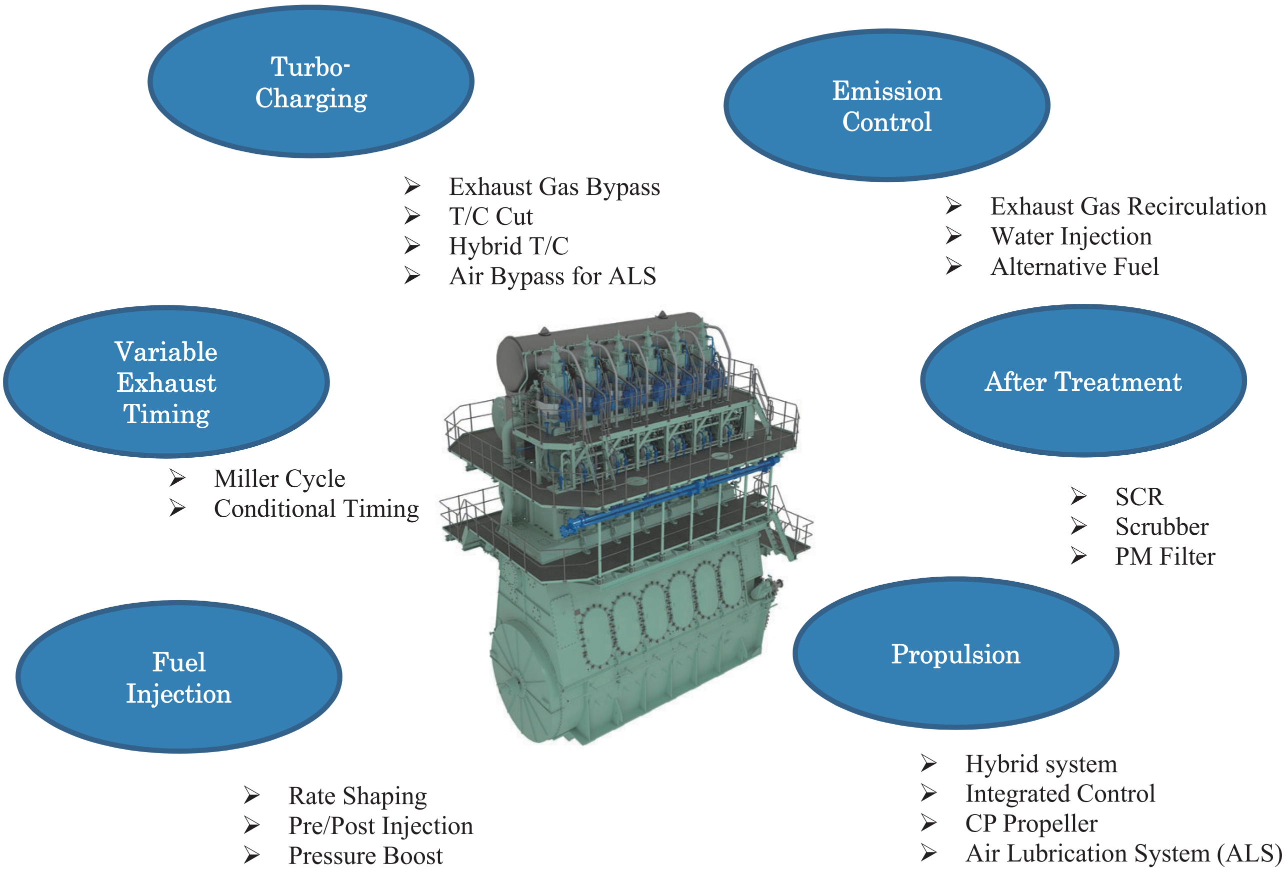


Fig. 2 Framework of the Propulsion Engine Ecosystem

2. System Analysis Framework

2.1 Basic principles of the system analysis method

Let us start by considering the definition of a system. With respect to the ship propulsion, the system can be defined as an ensemble of components and relations which transform input influences to output values for pursuing the objective function. System analysis is a method of studying a complex system by examining its component parts and their interactions. The method of system analysis implies the inclusion of several successive steps. At the very outset, the scope of the problem and thus boundaries of the system have to be determined. Thus, considering the energy efficiency of maritime transportation, the system boundaries can be set to a particular type and size of the ship. The results of the first step set prerequisites for the second and further steps, where the specification levels and interfaces, relevant to the problem scope are being identified. For instance, ship's hull performance can be subjected to a detailed hydrodynamic analysis or taken into account by a simplified performance characteristic. It is worth noting however, specification levels for different system components should be homogeneous to provide the adequate interface. The last but not least step consists in the system composition, where the system under analysis is hierarchically decomposed to constituent components with simultaneous identification of components interrelations and representative variables. As a primary example of the system composition, the propulsion plant may consist of two components – a propeller and an engine which are interfaced through a shaft. In the last analysis, every component is described by the mathematical model taking into account level of details and mutual coupling allowing integration to the complete model of system processes.

2.2 Mathematical background of the system analysis

Based on the selected specification level, a suitable mathematical modelling for every system's component is performed. The basic governing equations, representing the dynamic behaviour of a particular component, are based on a first-principle modelling approach, empirical relationships and regression models derived from the performance data. Therefore, in general case the mathematical model of a component may include:

- Set of ordinary differential equations (ODE) formulated in the form of Cauchy problem

$$\begin{cases} \dfrac{d\mathbf{X}(t)}{dt} = \boldsymbol{f}\{\mathbf{X}(t), \mathbf{U}(t), \mathbf{P}, t\} \\ \mathbf{Y}(t) = \boldsymbol{g}\{\mathbf{X}(t), \mathbf{U}(t), \mathbf{P}, t\} \end{cases} \tag{1}$$

where **X**, **U** and **P** are the vectors of differential variables, algebraic variables and parameters respectively.

- Set of linear algebraic equations

$$\mathbf{A}\,\mathbf{X} = \mathbf{K} \tag{2}$$

where **A**, **X** and **K** are the matrix of constants, a vector of solutions and vector of right-hand side coefficients respectively.

- Set of non-linear algebraic equations

$$\mathbf{H}(\mathbf{X}, \mathbf{Y}, \mathbf{U}, t) = \mathbf{0} \tag{3}$$

Besides, the system may include components in which process state variables, in addition to time, also depend on independent spatial variable and which are described by the set of nonlinear partial differential equations (PDE). The need in partial derivatives of quantities may appear when considering fluid flow and heat transfer phenomena. In order to incorporate these components into modelling framework, a method of line (MOL) is used to transform a set of PDE equations into a set of ODE equations. As an example, let us consider the transformation of a one-dimensional diffusion model with the given boundary and initial conditions and described by the following equation:

$$\frac{\partial u}{\partial t} - \alpha \frac{\partial^2 u}{\partial x^2} = 0, \qquad 0 \le x \le l, \qquad 0 \le t \le T \tag{4}$$

Following the method of lines, the spatial operator $\frac{\partial}{\partial x}$ is approximated by the finite difference resulting in a set of semi-discrete (discrete in space and continuous in time) ordinary differential equations:

$$\begin{gathered} \left.\frac{\partial u}{\partial t}\right|_i = \frac{\alpha}{\Delta x^2}(u_{i-1} - 2u_i + u_{i+1}), \qquad u_i(0) = 0, \qquad i = 2, \dots, N-1 \\ u_1 = u_1(t), \qquad u_N = u_N(t), \qquad \Delta x = \frac{l}{N-1} \end{gathered} \tag{5}$$

Thus, the complete mathematical model is formulated as the set of nonlinear differential algebraic equations (DAE), completed by the necessary initial conditions.

Moreover, the system modelling framework includes not only components models but also additional connectivity equations reflecting relationships between the components. The common types of connectivity equations relate to fluid flow, mechanical (rotational and transitional) and control signal connections. If for the first two connections the set of variables is definite, the control connections can contain any set of variables that are directly measurable quantities, such as pressure, temperature, speed, etc.

The set of coupled component dynamic models with the connectivity equations define the modular and multi-purpose modelling framework for a generic system. The next milestones for the implementation of system modelling framework are the selection of an appropriate software platform, the code development and the numerical solution scheme.

2.3 Software platform

For the implementation of system analysis framework, described above, a software platform “Simulation In Technic” (SimInTech) [3] has been selected. This software is intended for the detailed investigation and analysis of stationary and non-stationary processes in a wide variety of technical systems, whose dynamics can be described by differential and difference equations, continuous and discrete transfer functions and algebraic relations and logical conditions [4]. In addition, the SimInTech software offers universal modular graphic shell, which allows constructing the models in the form of block diagrams with capability for designing video frames to display and control the calculations.

An advantage of the SimInTech software is the availability of programming language block within a single graphical shell. The programming language block makes it possible to set algebraic relations and differential equations, as well as explicitly define input/output variables without the need to switch between workspaces and in this way custom blocks can be easily developed. Another important point which shows to the best advantage with respect to competitor software (the closest analogue is Matlab Simulink) is the vast set of ODE and DAE solvers including diagonally implicit Runge-Kutta methods. The former methods are effective in solving stiff ODEs and systems of differential-algebraic equations of indices higher than 1, which usually appears in the simulation of complex electrical and mechanical systems [5].

A library of components related to the ship propulsion plant has been developed in the SimInTech as shown in the next chapter. This library provides basic building blocks in addition to the rich standard technical library of SimInTech. Then, the system can be constructed through hierarchical flowchart synthesis of selected components. The resulted model can be easily reconfigured and tuned for different cases of numerical experiment.

3. System Analysis of Propulsion Plant with ALS

3.1 System description

The considered realistic case study is called to demonstrate the application and capabilities of the system analysis method to the assessment of ship propulsion plant integration. The system under consideration is one of the energy efficient and promising technologies - an air lubrication system (ALS) combined with a ship propulsion plant [6]. Air lubrication is the effect of hull frictional resistance reduction achieved by air bubbles under ship bottom [7], [8], [9], [10]. This effect is directly proportional to the equivalent air layer thickness defined as follows:

$$t_a = \frac{G_{als}}{B_a V_s} \tag{6}$$

The air flow rate G_{als} determines the pumping power required for air injection under the hull bottom. Thus for the ship with large breadth B_a advancing with speed V_s, the net power-saving becomes a trade-off between the power required to blow air and frictional drag reduction achieved by the air lubrication. Thus the selection of air delivery means determines the overall efficiency of the ALS.

The present trends of the Diesel engine developments, which are used for ship propulsion, directed towards improvement of thermal efficiency and reduction of exhaust gas emissions. As the result of these efforts, the efficiency of modern turbochargers (TCH) became overestimated for the engine need, and thus surplus energy can be utilised, to some extent, supplying air for the ALS operation. The main challenges of such system are imposed by the fact that air bleeding from the engine turbocharger, harmlessly for the engine, is possible only in narrow operational range. Moreover, the common practice of operating ships at low speeds and thus at partial loads of the propulsion engine further limits the utilisation of engine as the source of air. At the same time, waste heat recovery systems found an application to modern THCs, such as a turbo hydraulic system (THS) and a hybrid TCH [11], [12]. These systems, if used in reverse as a power take-in to the TCH, can assist the operation of turbo compressor and thus extend air supply needed for the ALS operation [13].

Following the method of system analysis, the first step is to define the scope of the problem and the boundaries of the system under consideration. The present study is focused on the combined operation of a ship propulsion plant with the ALS unit, with characteristics similar as to those encountered in a generic 60000 DWT class bulk carrier. Thus, Fig. 3 illustrates the considered arrangement of the ALS system coupled with the propulsion engine. The scope and boundary of the problem are 1) to evaluate the integration of following heterogeneous systems: ship hull with the ALS, propulsion engine as a source of air and turbocharger assist system to support air bleeding from the engine; 2) to assess the control loops and operation modes of the system.

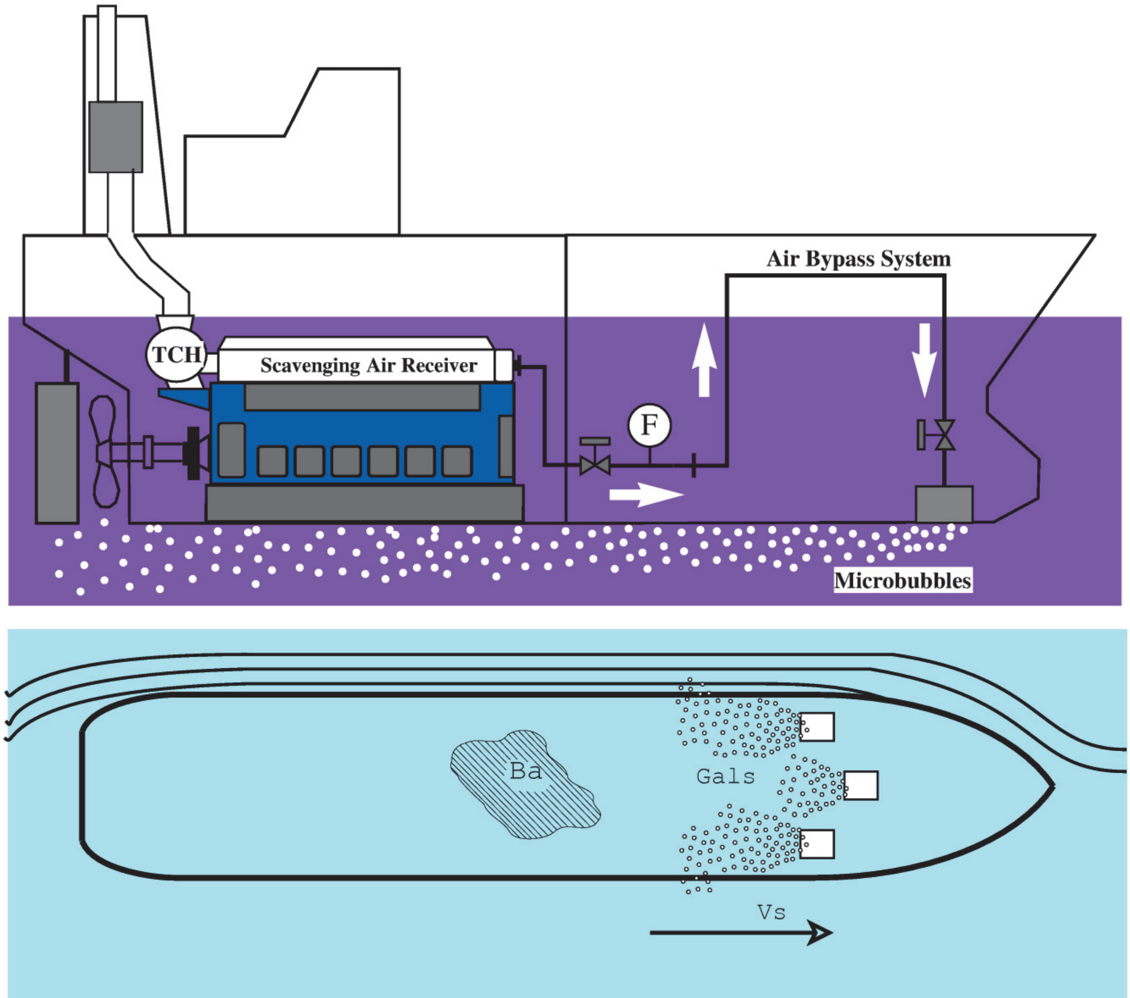


Fig. 3 Scope and boundaries of ALS system combined with propulsion plant

3.2 System model

Following the system analysis method the next step, after the definition of problem scope and boundaries, is the definition of functional arrangement, which consists in the hierarchical decomposition to the lower-level components models. Concerning the defined boundaries, the propulsion system is considered to be made up of four main functional elements: ship hull, propeller, propulsion engine and ALS [14]. Furthermore, the mutual interface between the elements has to be identified simultaneously.

Thus, the propeller and engine are linked through the rotational dynamics of a propeller shaft defined by the following equation:

$$2\pi I_e \frac{dn_e}{dt} = Q_e(n_e, p_s, \dots, t) - Q_p(n_e, V_s, t) \tag{7}$$

The forces balance between ship's hull resistance and propeller thrust links the hull and propeller sub-components through Newton's second law in terms of the ship speed:

$$M_t \frac{dV_s}{dt} = [1 - t_p] T_p(n_e, V_s, t) - C_r R_t(V_s, t) \tag{8}$$

Here, the friction reduction coefficient C_r, defined as:

$$C_r = \frac{R_{als}}{R_t} = f(V_s, t_a) \tag{9}$$

introduces the effect of air layer under ship's bottom. The ALS itself provides air flow from the engine to distribution under the ship's hull, determining the effective thickness of layer t_a. Therefore, the ALS consists of piping system, bypass valve attached to the engine and control system.

The functional diagram in Fig. 4 details the mutual interfaces as well as considered control loops.

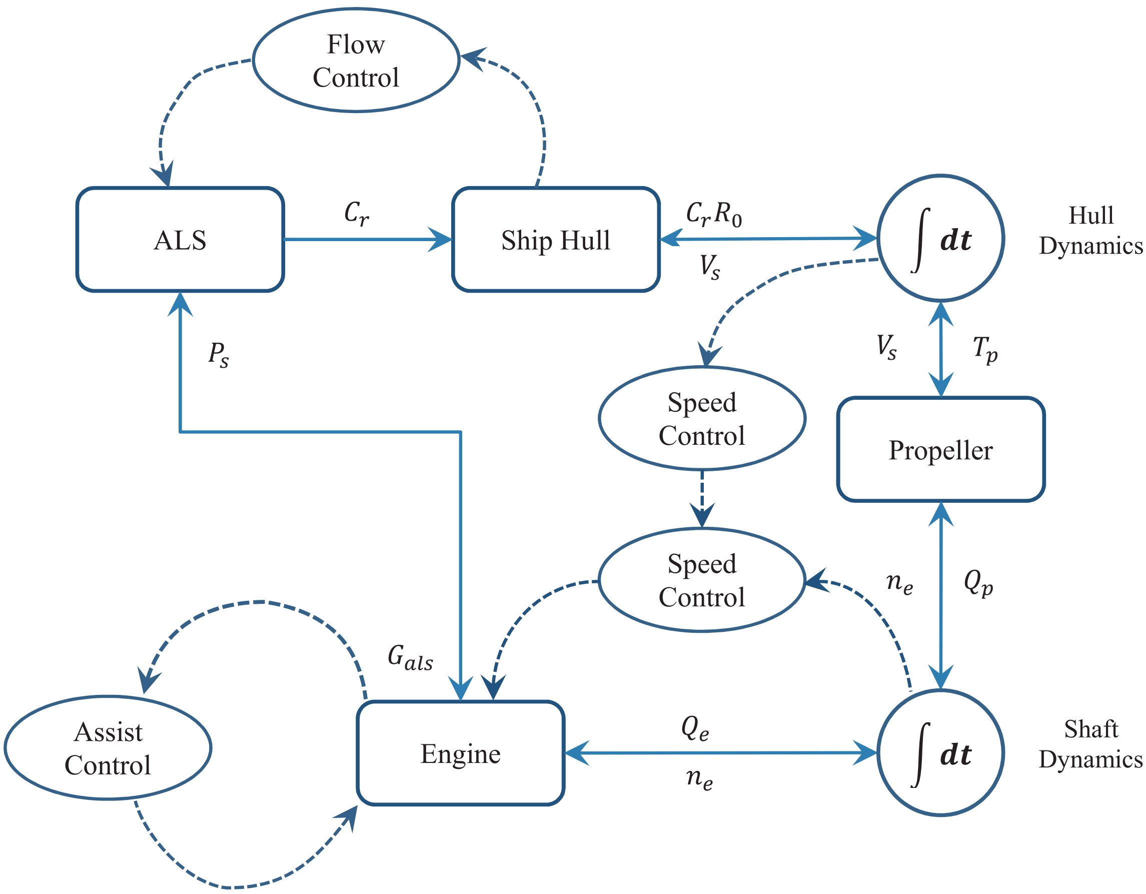


Fig. 4 System composition of the ship propulsion plant with the ALS

The preceding steps, performed in the framework of the system analysis method set prerequisites for the model organisation process. At this stage, every functional element is subjected to further hierarchical decomposition, and then the low-level components are described mathematically with sufficient adequacy to physical phenomena, taking into account required specification level and homogeneity of the total system model. As the result of this step, the library of components model has been developed on the software platform. General view of the library is shown in Fig. 5. The following chapters give the detailed overview of the underlying mathematical description of the functional elements.

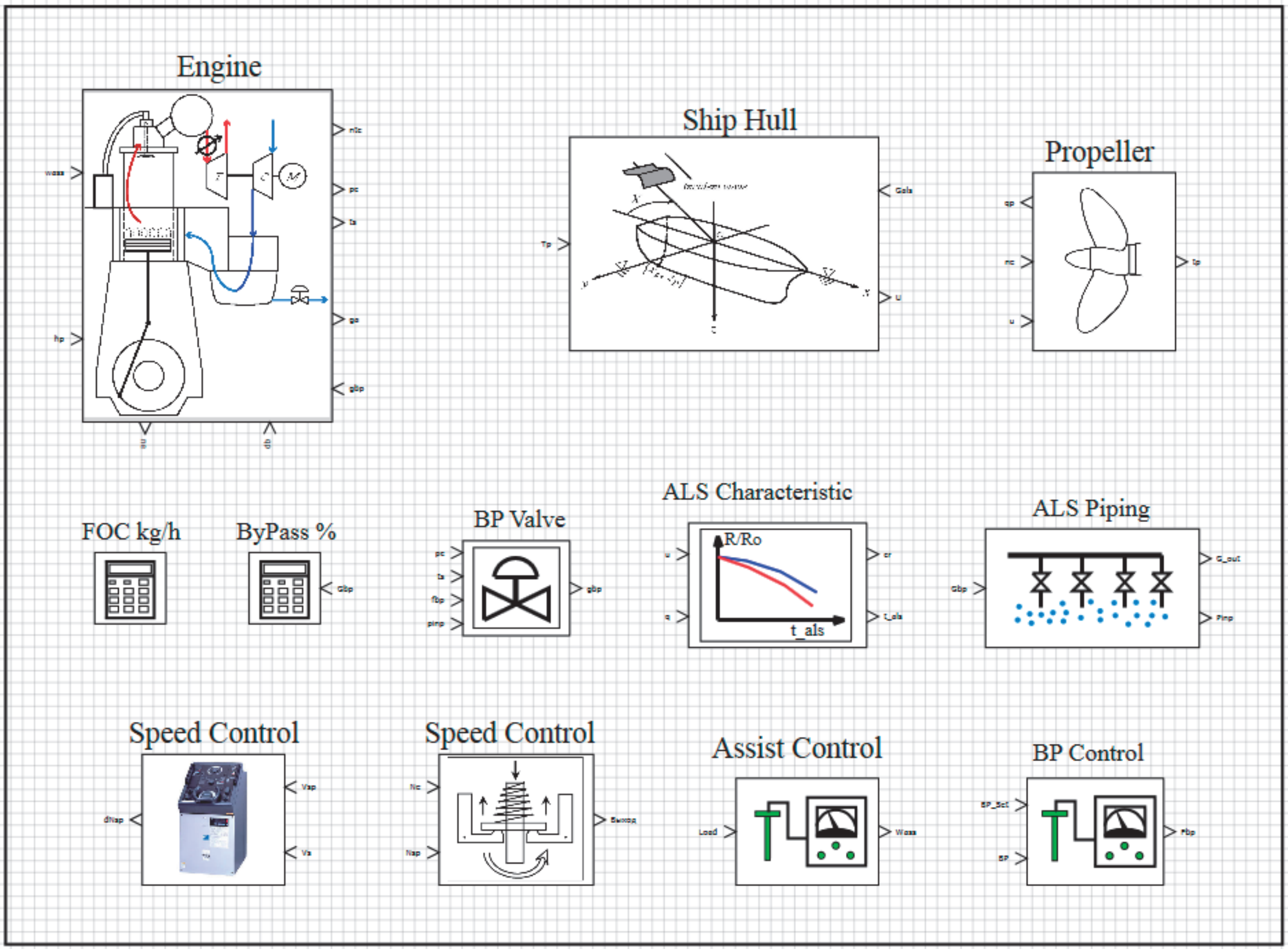


Fig. 5 Functional elements library developed on the simulation platform

3.3 Functional elements modelling

3.3.1 Engine

As was mentioned above, the vital characteristic of the mathematical description is the sufficient adequacy within the bounds of defined scope and system boundaries. The model should appropriately describe entities essential for the integration into the functional diagram of the total system and provide sufficient insight into the process.

The mean value modelling approach is gaining popularity in the field of propulsion engine simulation [15], [16]. The mean value engine models (MVEM) predict values of the engine thermodynamic states as well as mechanical dynamic states as the cycle-averaged values neglecting intermittent nature of the engine cycle. The generic MVEM for a turbocharged engine consists of four essential subsystems which describe the behaviour of the charge air receiver, exhaust gas receiver, cylinder unit and turbocharger unit. Besides, with respect to ALS system, the particular attention is drawn to the possibility of air bleeding from the charge air receiver and power take-in to the turbocharger. The diagram in Fig. 6 explains flowchart of the engine model.

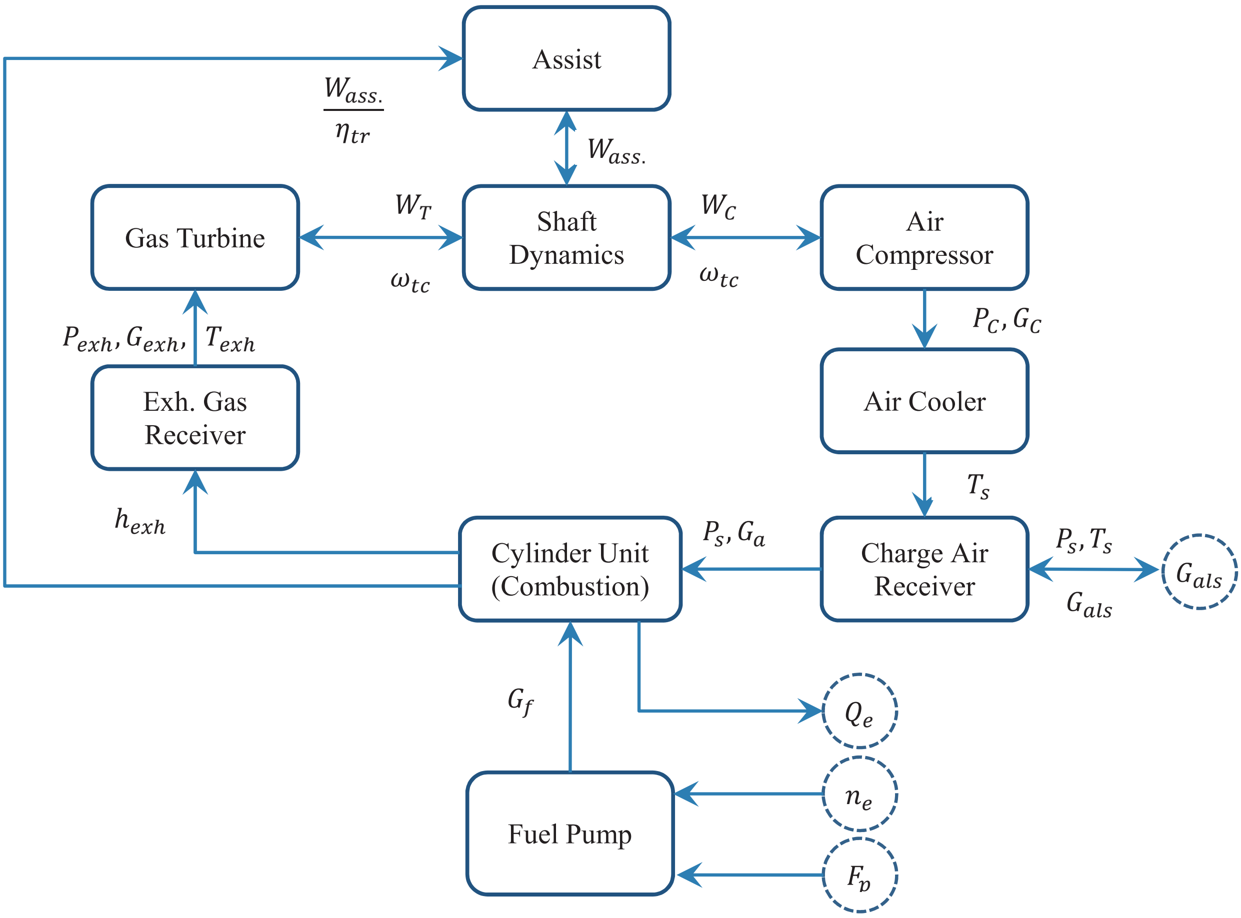


Fig. 6 Flowchart of the engine model

The key dynamic equations, necessary to describe the thermodynamic and dynamic states of the engine, can be obtained from conservation laws applied on the engine subsystems. The states of pressure and temperature in the charge air and exhaust gas receivers can be obtained from the conservation of energy and mass laws. Thus, the balance of mass flows from/to the air receiver determines the rate of pressure change in the following form:

$$\frac{dP_s}{dt} = \frac{R_a T_s}{V_{a.r}}[G_c - G_a - G_{als}] \tag{10}$$

It is assumed that the temperature of air T_s in the receiver is constant and is governed by an air cooler. It is worth mentioning here, that the last term G_{als} in Eq.10 relates to the operation of ALS system and is determined by the opening of a bypass valve, as explained in a separate chapter.

Two differential equations determining mass can describe the states of exhaust gas in the receiver $m_{e.r}$ and temperature T_{exh} of gas within the receiver. The ideal gas law is then determines the pressure P_{exh} in the receiver:

$$\frac{dm_{e.r}}{dt} = G_a + G_f - G_{exh}$$

$$\therefore P_{exh} = \frac{m_{e.r} R_{exh} T_{exh}}{V_{e.r}} \tag{11}$$

$$\frac{dT_{exh}}{dt} = \frac{k_e}{m_{e.r} C_{p.e}}\left[h_{exh}\{G_a + G_f\} - C_{p.e} T_{exh} G_{exh} - \frac{C_{p.e} T_{exh}}{k_e}\frac{dm_{e.r}}{dt}\right]$$

In mean value approach, the engine is considered as a series connected orifices, corresponding to the engine cylinder and the turbocharger turbine. Thus, air and exhaust gas masses passing through the engine and turbine can be estimated by a general equation for compressible flow through a nozzle orifice in the following form:

$$G = \mu\tilde{A}\frac{P_{in}}{\sqrt{R\,T_{in}}}\sqrt{2\frac{k}{k\ \ +1}\left\{\left[\frac{P_{out}}{P_{in}}\right]^{\frac{2}{k}} - \left[\frac{P_{out}}{P_{in}}\right]^{\frac{k\ \ +1}{k}}\right\}} \tag{12}$$

Here $\mu\tilde{A}$ stands for the effective average area of a corresponding orifice; p_{in}, p_{out} are the pressures across the orifice.

The mass flow of fuel to the engine is proportional to the position of fuel pump rack F_p determined by a speed governor.

$$G_f = z_c m_{f.c} F_p n_e \tag{13}$$

The compressor air mass flow G_c into the receiver can be calculated from an equation for the isentropic work required for air compression:

$$W_c = \frac{C_{p.a} T_a G_c}{\eta_{ic}}\left(\left(\frac{P_c}{P_a}\right)^{\frac{k_a - 1}{k_a}} - 1\right) \tag{14}$$

Compressor power W_c is modelled as a dynamic power transfer between the turbine and compressor, approximated with a first-order system in the following form:

$$\frac{dW_c}{dt} = \frac{1}{\tau_{tc}}[W_T - W_c] \tag{15}$$

Here, W_T is the isentropic work of the gas expansion in the turbine, defined as follows:

$$W_T = C_{p.e} T_{exh} G_{exh} \eta_{iT}\left[1 - \left\{\frac{P_a}{P_{exh}}\right\}^{\frac{k_e - 1}{k_e}}\right] \tag{16}$$

The primary output of the engine model, required for integration to the total system, is the engine torque defined as follows:

$$Q_e = \frac{V_c z_c}{2\pi}[IMEP - FMEP] \tag{17}$$

Here, $IMEP$ and $FMEP$ are the Indicating Mean Effective Pressure and Friction Mean Effective Pressure correspondingly. The $FMEP$ is considered as an empirical function of the engine speed n_e and fuel pump rack F_p. The $IMEP$ is considered proportional to the fuel pump rack and modified with a correction coefficient (also referred to as relative thermal efficiency) accounting for a non-linearity between generated torque, supplied fuel quantity and actual air mass flow.

$$IMEP = \eta_c IMEP_{MCR} F_p, \qquad \therefore \eta_c = f\left(\frac{G_a}{G_f}\right) \tag{18}$$

In turn, the engine model requires following variables to be provided at input: shaft rotational speed, fuel pump rack position and air flow to ALS.

3.3.2 Hull-Propeller

The modelling of hull and propeller considers simple regression and/or interpolation models. Thus, the hull calm water resistance R_t is the regression model restored from the discrete points obtained from the estimation method proposed in [17]. The resulted total resistance is then modified by the friction reduction coefficient defined in Eq. 9.

$$R_t = k_1 V_s + k_2 V_s^2 + k_3 V_s^3 \tag{19}$$

The propeller thrust T_p and torque Q_p performance models, restored from the regression analysis coefficients obtained by open-water test of propellers [18], are given by:

$$\begin{aligned} T_p &= K_T(J_p)\rho n_e^2 D_p^4 \\ Q_p &= K_Q(J_p)\rho n_e^2 D_p^5 \end{aligned}, \qquad \begin{aligned} &\therefore J_p = \frac{U_p}{n_e D_p} \\ &\therefore U_p = [1 - w_p] V_s \end{aligned} \tag{20}$$

The ALS system tightly binds the hull, propeller and engine models: the ratio of air bleeding from the engine determines the resistance reduction of the hull. In turn, the resulted propeller thrust and torque affect the operation of the engine. Such the interactions may differ significantly depending on propulsion plant control objectives, which can be the ship speed or engine rotational speed either. In this respect, the control loops of integrated propulsion plant play an important role in achieving ultimate efficiency.

3.3.3 Air distribution system

Air distribution system aims to control the rate of air bleeding from the engine and to transport the air from the engine, which is located at the stern, to the distribution device located under the ship hull at the bow. Thus, the distribution system is composed of the bypass valve and pipe system network. The valve is modelled as a variable orifice, and the air mass flow is described by the model for compressible flow through a nozzle in the following form:

$$G_{bp} = \mu \tilde{A} \frac{P_s}{\sqrt{R_a\, T_s}} \sqrt{7\left\{\left[\frac{P_{bp}}{P_s}\right]^{\frac{2}{k_a}} - \left[\frac{P_{bp}}{P_s}\right]^{\frac{k_a+1}{k_a}}\right\}}, \qquad \therefore G_{bp} \equiv G_{als} \tag{21}$$

Here, $\mu \tilde{A}$ is the variable effective flow area of the valve; $\mu = f\left(\frac{P_{bp}}{P_s}\right)$ is the flow coefficient represented by an empirical function restored from valve manufacturer's data; $\tilde{A} = f(\theta)$ is the geometrical flow area of valve as a function of the position of a flap or other type of controlling means, depending on the valve design. The data are provided from the specification of the valve.

The flow through the valve is determined: 1) by the opening area of the valve, 2) by the pressure in the scavenging air receiver and 3) by the pressure at the inlet to the distribution system. In turn, when the gas flows through the extensive pipe network it suffers pressure losses due to friction and the issue is to find the pressure that should be applied to the air, after the bypass valve, to reach the outlet point at the bow ensuring the required mass flow. The hull’s draft determines the pressure at the outlet point at the bow:

$$P_{out} = P_a + \rho g h_{draft} \tag{22}$$

The mathematical model of gas flow in the pipe network can be deduced from the Navier-Stokes equations for compressible flow, considering conservation of mass, conservation of momentum and conservation of energy applied to the control volume depicted in Fig.7. In order to reduce the model to specification level adopted in the total system, the following assumptions were applied: the flow is isothermal ($T = idem$); no inertia terms; the equations were integrated in the circular cross-section to reduce dimension. The resulted set of PDE, describing one-dimensional compressible gas flow dynamic through the pipe network are obtained as follows:

$$\begin{aligned}&\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}[\rho u] = 0\\ &\frac{\partial}{\partial t}[\rho u] + \frac{\partial}{\partial x}p + \frac{f_r \rho}{2d_p}u|u| + \rho g \sin(\alpha) = 0\end{aligned} \quad , \quad \therefore P = \rho R_a T_a \tag{23}$$

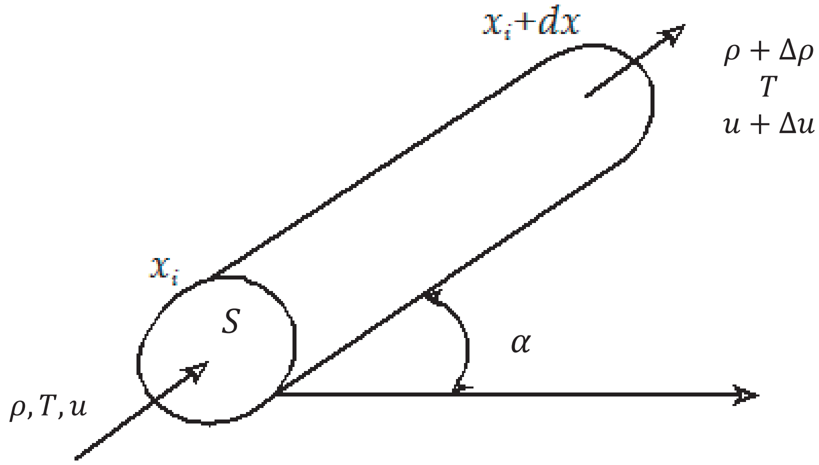


Fig. 7 Control volume of a pipe edge

Furthermore, to incorporate the gas flow model into the modelling framework the set of PDE has to be transformed to the set of ODE that conveniently can be done employing MOL with two points centred discretisation scheme. Simultaneously, the equations are transformed in terms of mass flow and pressure variables:

$$\begin{aligned}&\left.\frac{dP}{dt}\right|_i = -\frac{R_a T_a}{2A\Delta x}[-Q_{i-1} + Q_{i+1}] & \therefore i = 2 \cdots N-1\\ &\left.\frac{dQ}{dt}\right|_i = -\frac{A}{2\Delta x}[-P_{i-1} + P_{i+1}] - \frac{2 f_r R_a T_a}{\pi d_p^3 P_i} Q_i |Q_i| \quad , & \therefore \Delta x = \frac{l_p}{N-1}\end{aligned} \tag{24}$$

The pressure determines the conditions at boundaries: at the outlet point defined by the Eq. 22, and mass flow defined by the Eq. 21. The pipe friction factor f_r is introduced by the Colebrook-White correlation in the following form:

$$\frac{1}{\sqrt{f_r}} = -\frac{2}{3} log\left[\left\{\frac{1.547}{R_e\sqrt{f_r}}\right\}^{2.8335} + \left\{\frac{k_s}{3.7d_p}\right\}^3\right] \tag{25}$$

Owing to the flexibility of the software platform for developing custom blocks, the model of pipe network was realised using built-in programming language block as shown in Fig. 8.

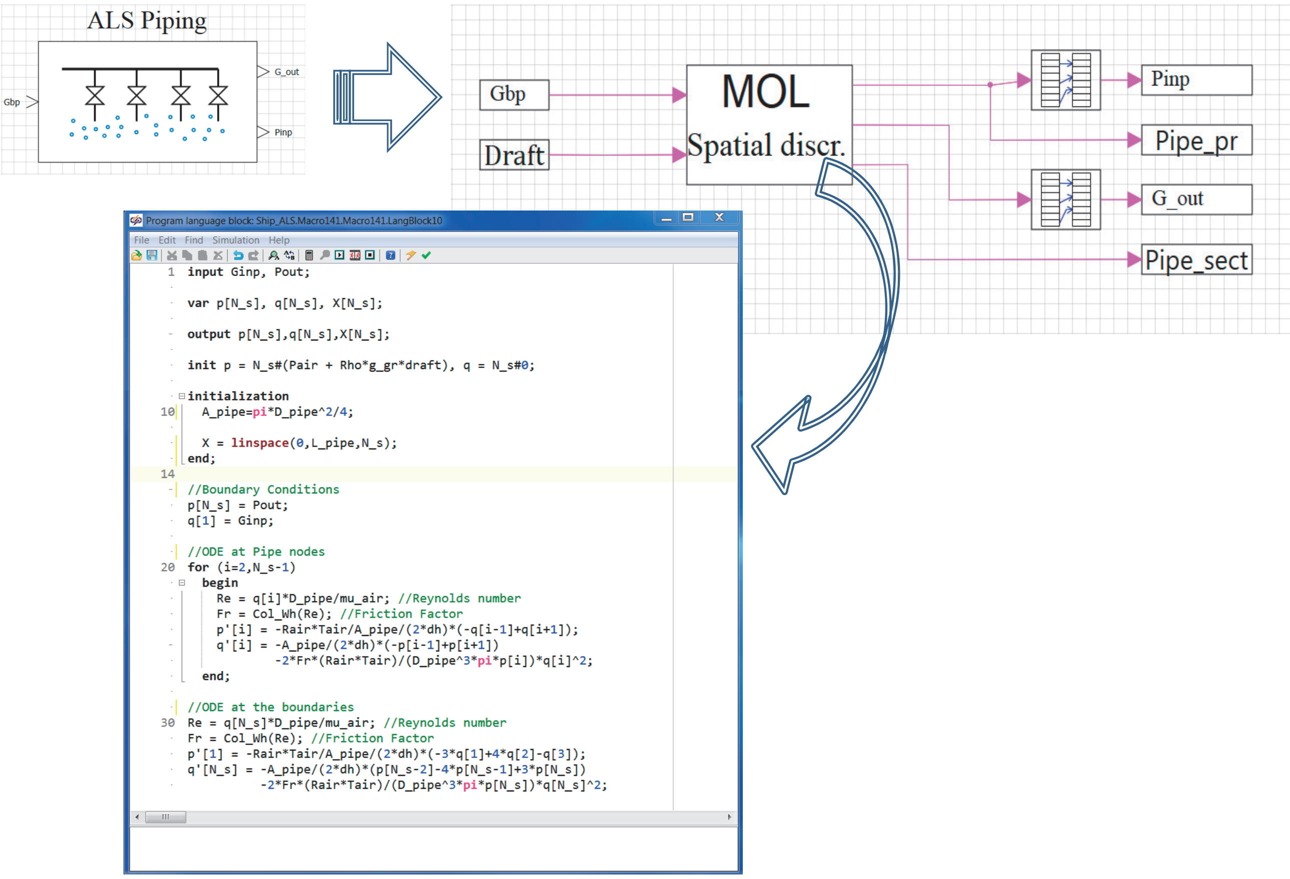


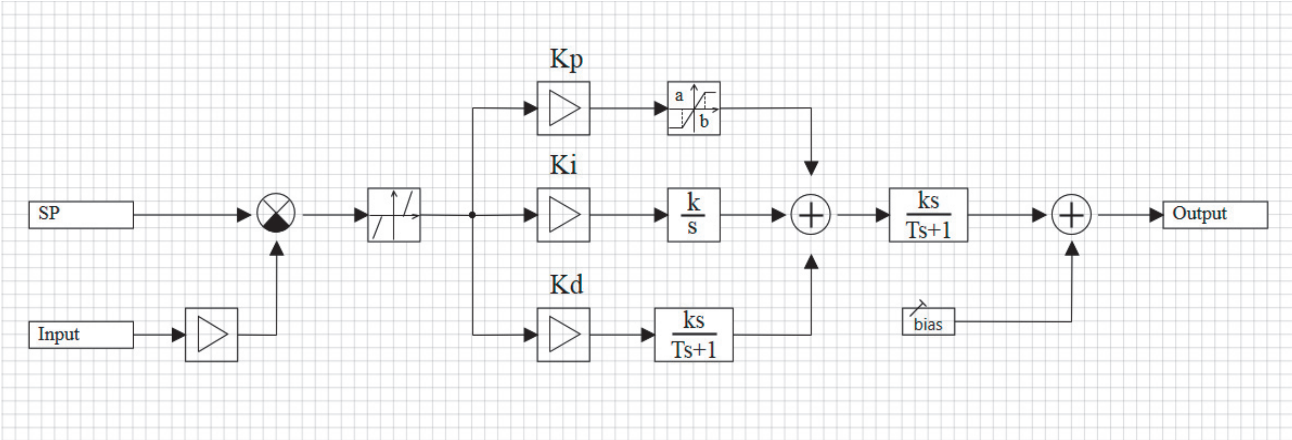
Fig. 8 Implementation of pipe network simulation on the software platform

3.3.4 Control loops

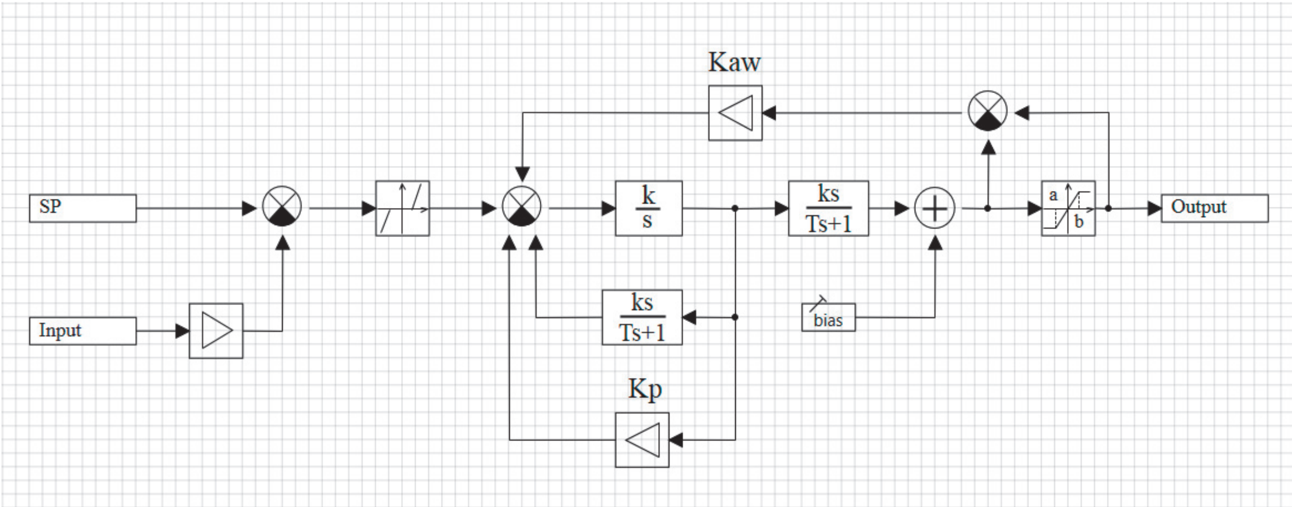
One of the primary goals of the system modelling framework is the conduction of dynamic simulation and components interaction assessment. Therefore, the integration of control loops and governor components simulation are of great importance.

From the functional diagram obtained during system composition step, the four control loops have become evident. The one control loop is the principal part of any propulsion plant – the engine speed control. The other three control loops relate solely to the application of the ALS. The required air flow to the ALS is controlled by the opening of the bypass valve, and this form one control loop. As the result of ALS operation and air bleeding from the engine, the pressure in scavenging air receiver drops and additional assist power is required by the TCH to restore the pressure, and this form another control loop. Last but not least, the third control loop aims at controlling the ship speed by affecting the engine rotational speed set point. Apart from stabilisation problem, the scheduling plans can also be implemented by continuous variation of the governors' set points (SP).

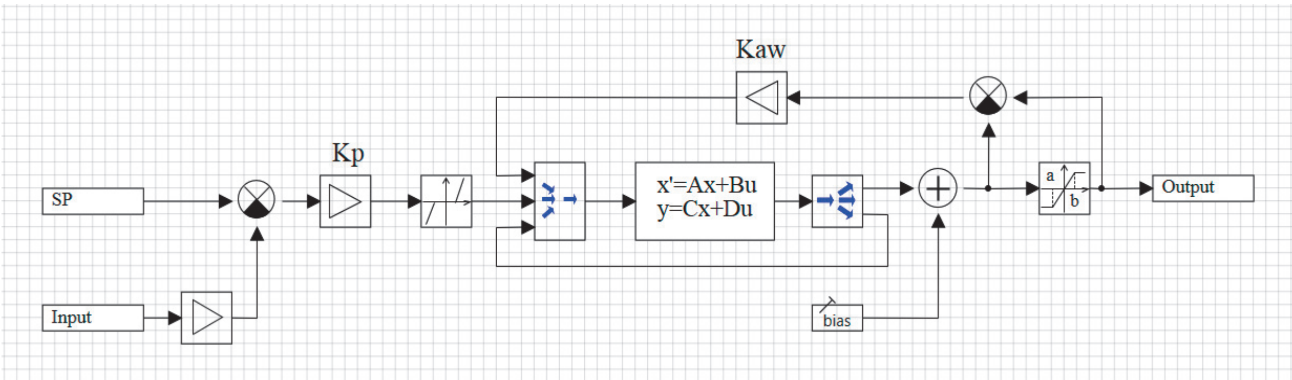
The various control algorithms have been developed using the standard library of technical blocks of the software platform. The typical structures are depicted in Fig. 9. These include a classical PID governor, proportional governor with transient feedback and proportional-integral governor formulated in a state-space form. Apart, various nonlinear elements are added into control algorithms, such as dead-band, hard limiters, etc.



a)　Classical PID governor (with inertial D-term)



b)　Proportional governor with a transient (isodromic) feedback



c)　PI governor in a state-space formulation

Fig.9 The applied control algorithms

3.4 Evaluation of system dynamics

After the developing of individual components blocks, comprising the dynamic models and resolving all interfaces and dependencies, the system-level model was built connecting corresponding blocks' input/output variables as shown in Fig. 10. Simultaneously, for the purpose of simulation process control and supervision, a video frame with the simple user interface (UI) has been developed as shown in Fig. 11. The simulation of system dynamics aims to highlight the impact and interference of control loops algorithms.

Before proceeding to the discussion on simulation results, one more vital point to be mentioned - the validity of the model. The validity of the integrated model is ensured by the precise formalisation of the processes which take place in the sub-models, by the validity of the particular sub-models and by establishing the sub-models based on the well-known and widely accepted methodologies. Thus, the engine model has been validated against actual performance and design data. The results can be found in [13], [16] and [19]. The effect of assist system droop and astatic control is confirmed experimentally in [20]. The validity of the hull and propeller models, as well as the effect of ALS on the hull resistance, has been confirmed through numerous experiments and full-scale tests. However, the results and details cannot be presented because the data used are the proprietary information of a shipyard and, therefore, cannot be disclosed.

In the simulation, the propulsion plant was set to run at 75% of MCR power, which corresponds to design speed of 13 knots. Then, the bypass valve control loop received an order to maintain the air bleeding rate 20% of the engine nominal airflow at given engine load. Furthermore, the two cases of propulsion plant control have been considered. The first case corresponds to a constant engine rotational speed. In this respect, the vessel speed is determined mainly by hull resistance. The second case corresponds to constant vessel speed. In this respect, the engine rotational speed setpoint is adjusted correspondingly. The transient processes in various systems are depicted in Figs. 12-14. On the figures with two frames, the upper part corresponds to the engine speed constant mode, whereas lower part corresponds to the vessel speed constant mode. It is worth mentioning here that any variable presented in the modelling framework can be subjected to supervision.

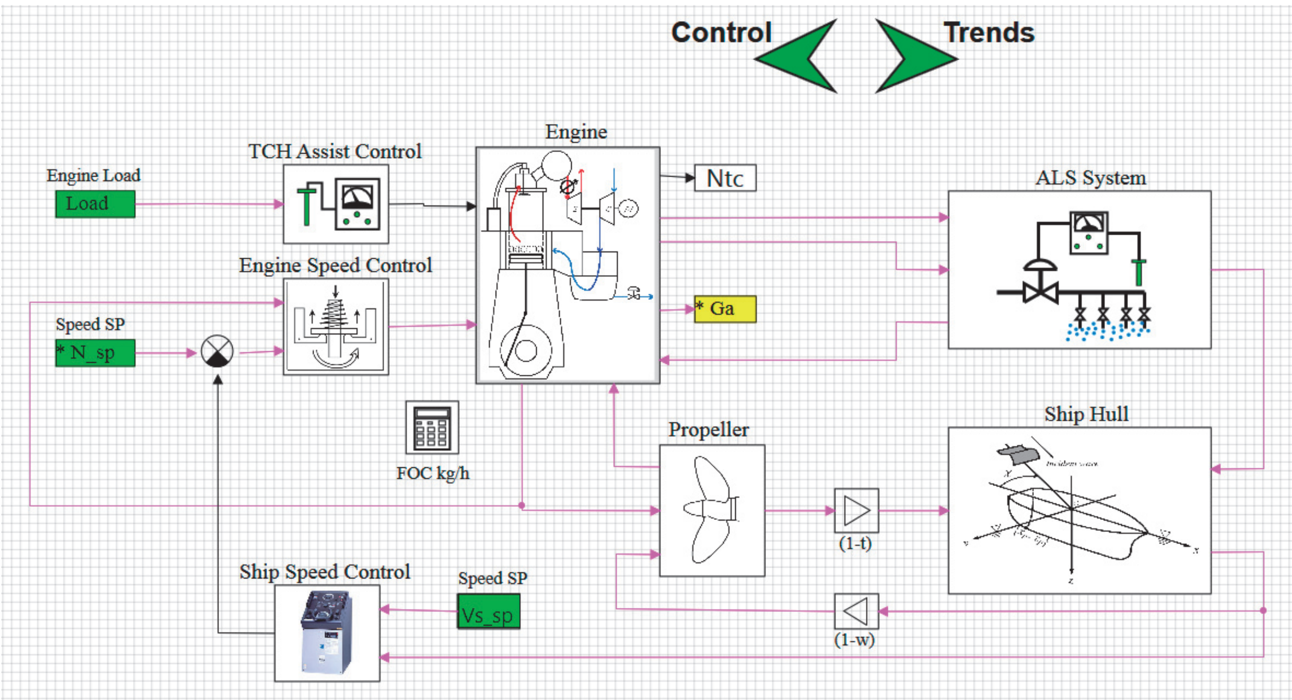


Fig. 10 Schematic diagram of the propulsion plant with the ALS realised on the software platform

The primary challenge in the combined operation of propulsion plant with ALS is that the significant air bleeding rate, together with a notable reduction in hull resistance, dramatically affects the performance of the propulsion engine due to the scavenging air pressure drop. This is because air bleeding act as a power take-off from the compressor at the same time power input from the turbine stays constant and even declining. In this respect, in order to restore power balance of the TCH and thus avoid engine performance deterioration, the additional energy is supplied by the assist system attached to the TCH. The control loop of assist system aims at maintaining the scavenging air pressure at the designed level. However, in such astatic control mode, the power consumption of assist system directly proportional to the air bleeding rate and the favourable net power-saving from the ALS system operation may not be reached. As was found in [13] and confirmed experimentally in [20] the solution is to employ droop control – allowing some difference between the designed scavenging air pressure and actual, as the result of assist system operation. The effect of droop control is apparently visible in Figs. 13 and 14a, where the assist power and FOC are depicted.

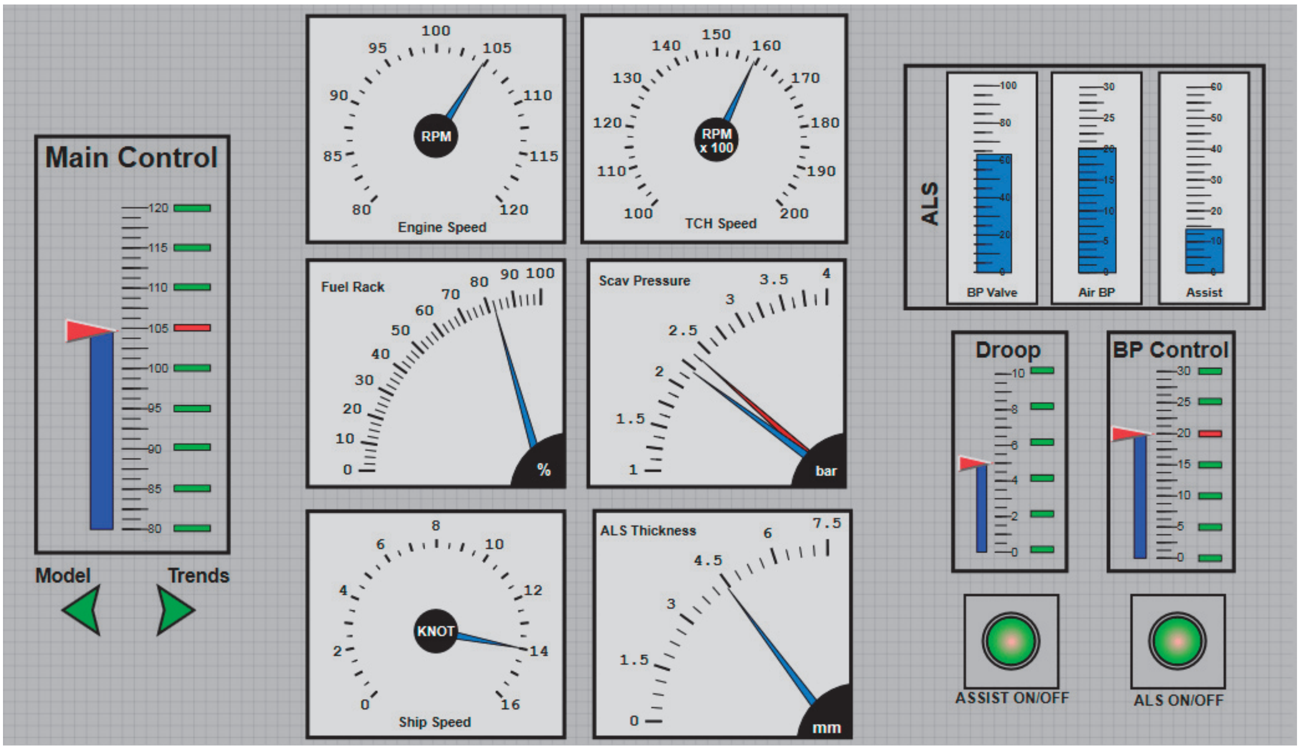


Fig. 11 The UI of propulsion plant control and supervision

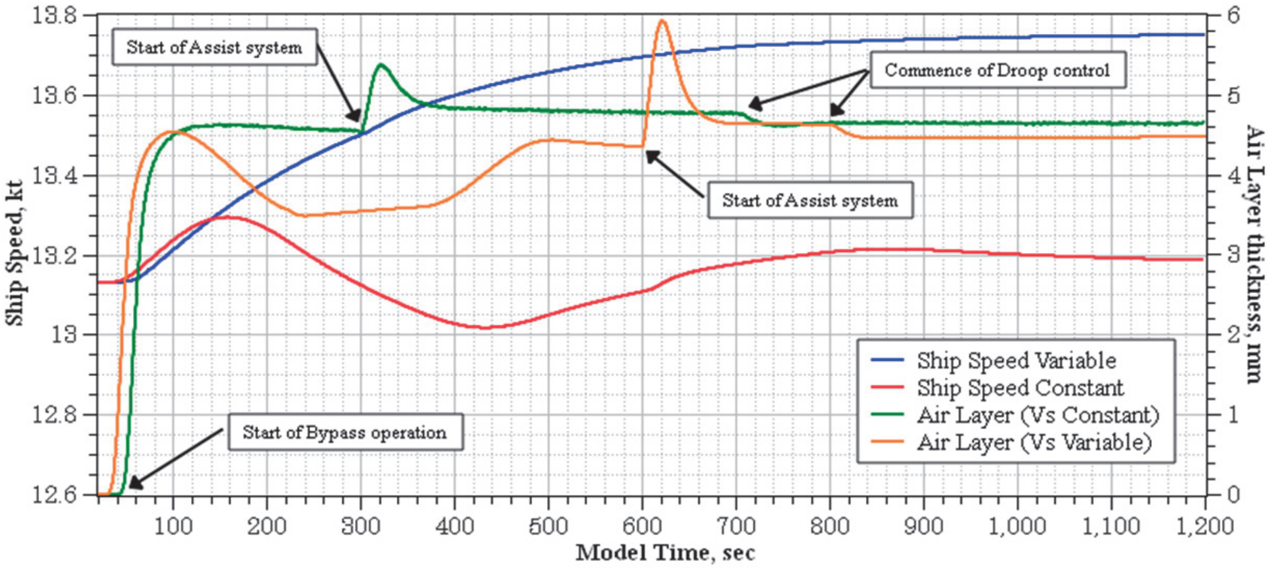


Fig. 12 Transient processes of the ship speed and air layer thickness

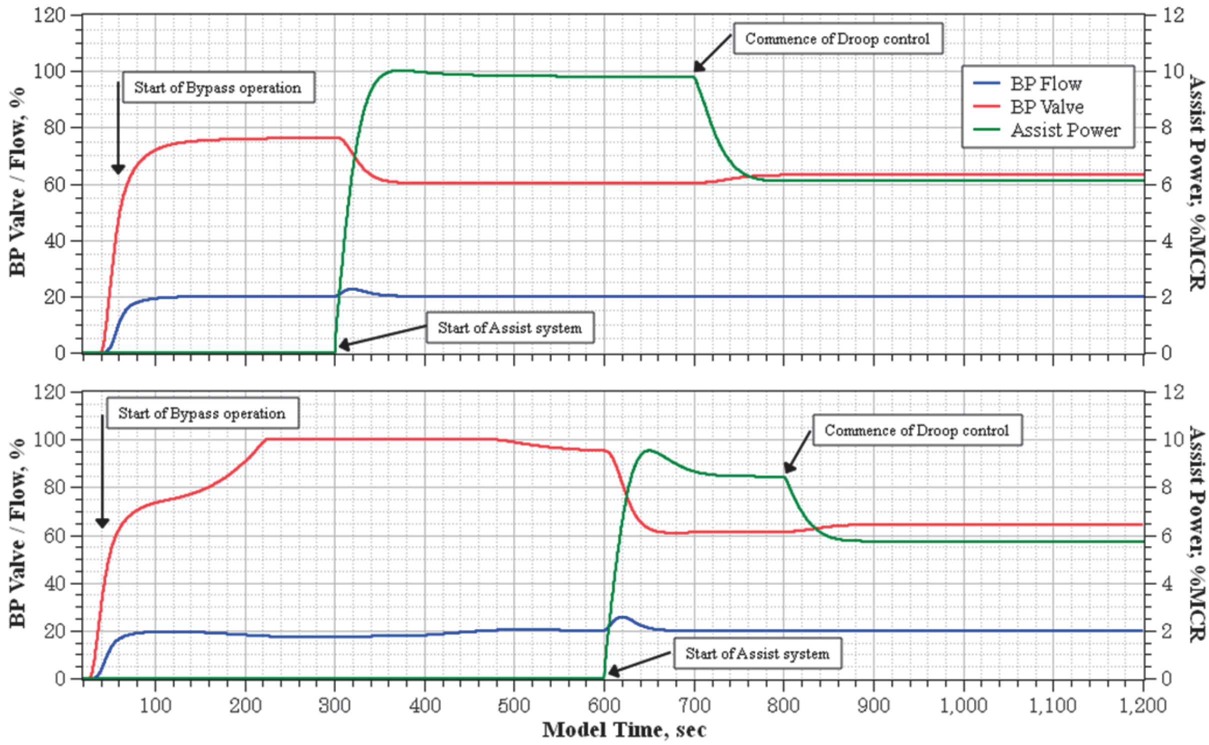
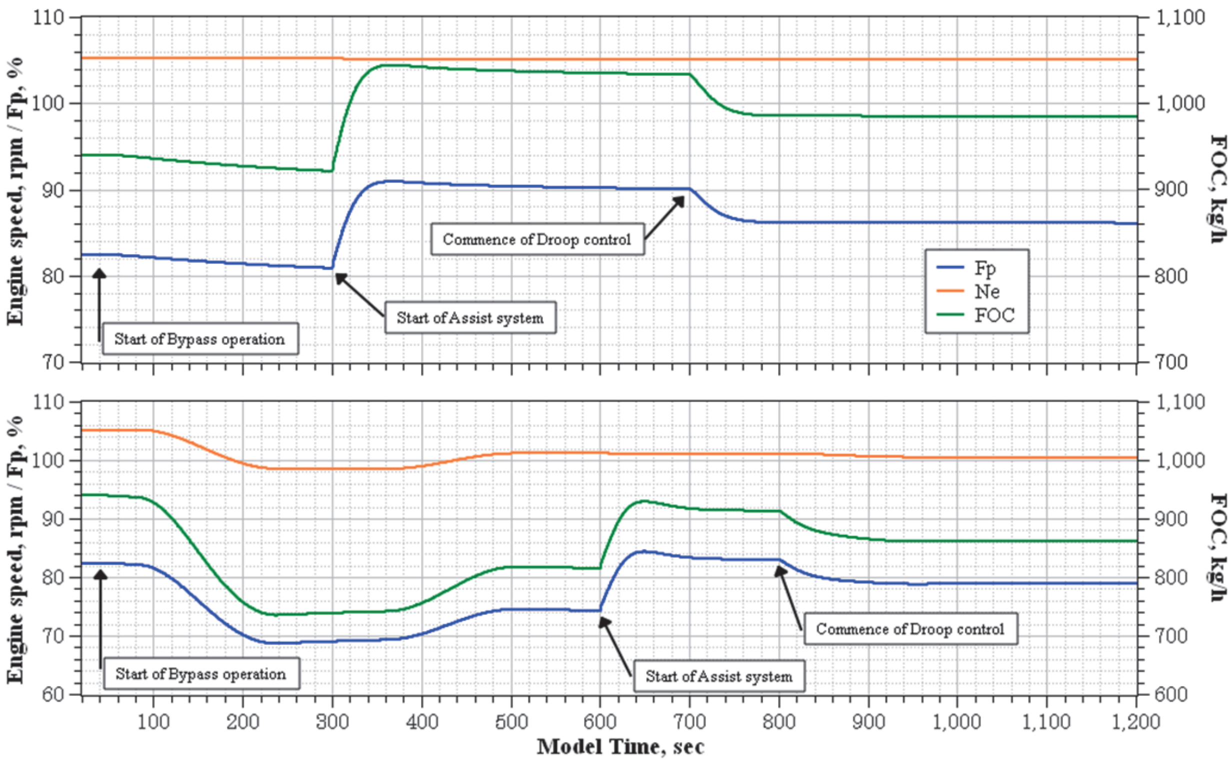
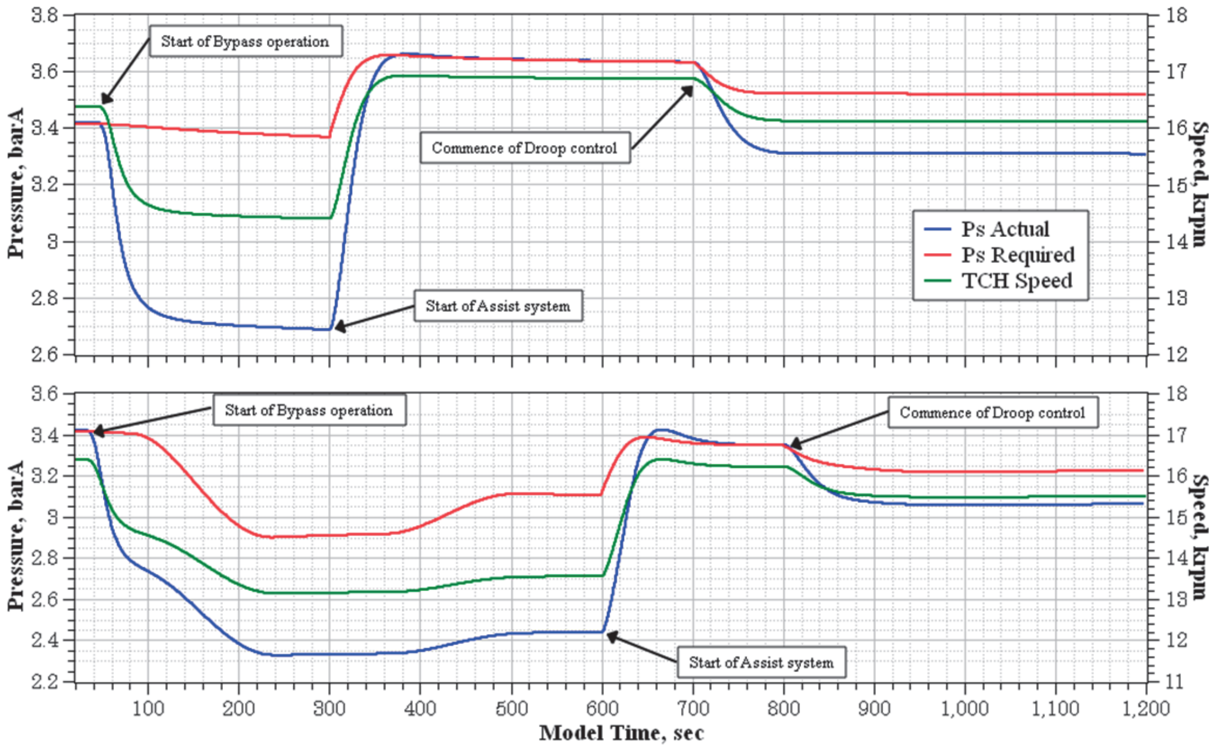


Fig. 13 Transient processes of the bypass valve and assist system



a) Engine speed, fuel pump rack and FOC



b)　TCH speed and scavenging air pressure
Fig. 14 Transient processes of the engine and turbocharger

4. Conclusions

In this report, a general flow of system analysis methodology has been presented. In the last analysis, the methodology was applied to assess the integration of propulsion plant with the ALS system. The developed system modelling framework provides understanding system behaviour through simulation giving insight to complex transients and revealing essential interactions between the components. The developed components models, presented in this paper, are suitable for synthesis of integrated propulsion plant and performing steady-state and dynamic simulation as well as handling of optimisation problems using the same model. The models are fully parametrized, and their structural design can be easily modified to fit the different scope of the problem, and also modifications necessary to introduce additional components, for instance, Controllable Pitch Propeller (CPP) or Waste Gate Valve, are of small complexity. In particular, instead of simple energy flow to the TCH's assist system, the full model of electrical and mechanical components can be considered to assess the transient processes and control problem in the energy transmission system. Similarly, the ship's hull model can be refined to reflect the dynamics of actual sea state.

Last but not least, the system modelling framework is highly suitable for model-based applications such as virtual experimentation and digital twin. The last relates to linking the real world data to a systems model focusing on the various aspects of a product in the real-time and under real-service dynamic conditions.

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