A simplified model of turbocharged marine power plant

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A simplified model of a turbocharged marine diesel engine is developed. This model is simpler than the original rigorous model, which is obtained through the performance curves and based on the thermodynamic applications. The simplified model is suitable for stability studies of control system particularly the speed governor design. By comparison of these two models, the simplified model was shown to have good transient accuracy at different propeller load of the engine.

تتضح استخدامات التحكم الآلي في ماكينات السفن عند الحصول على الوضع الأمثل للماكينة عند التشغيل وخاصة من حيث الجوانب الاقتصادية. ولهذا كان من الضروري الحصول على نموذج رياضي يشتمل على العلاقات الديناميكية والثرموديناميكية للماكينة ذات الشحن الجبري وملحقاتها مع الرفاص. ويمكن الحصول على هذا النموذج إما بالتجارب العملية أو بالطرق النظرية التقريبية عند نقط التشغيل، وقد تمت مناقشة هذا النموذج بطرق مختلفة في أبحاث كثيرة. ولم تكن هذه النماذج بالسهولة في تكوينها أو التعامل معها، ذلك حيث أنها تتطلب معرفة دقيقة لبيانات جميع أجزاء الماكينة، بالإضافة إلى منحنيات الأداء اللازمة لهذه الأجزاء. ولذلك كان التفكير في عمل نموذج رياضي بسيط للماكينة، سهل في التكوين ومناسب للحفاظ على مستوى الأداء المطلوب للسفينة، كذلك يمكن من خلاله تصميم مسيطر للسرعة بدون إهمال عامل الأمان عند التشغيل. ويتعرض البحث لأحد النماذج الرياضية الصارمة، وقد تم تقسيمه إلى مجموعة من المنظومات مرتبطة بعضها البعض عن طريق تحديد دالة الانتقال الخطية لكل منظومة على حدي من حيث إشارات الدخل والخرج للمنظومة، ثم الحصول على الاستجابة اللحظية للمتغيرات المختلفة للنظام ككل، خاصة سرعة الماكينة، معدل تدفق الوقود، والقدرة المؤثرة عند التشغيل. بعد ذلك يعرض البحث كيفية استنباط النموذج المبسط للنظام الكلي المشتمل على الماكينة والرفاص مع الاستعاضة عن السلوك الديناميكي للشاحن الجبري بدالة معادلة، ثم وضع دوال الانتقال الخطية في صورة رسم تخطيطي للمراحل، ومن ثم الحصول على الاستجابة اللحظية لنفس المتغيرات السابقة، وبمقارنة النتائج لكل من النموذجين، يتضح أن النموذج المبسط، علاوة على سهولة استنتاجه، فهو يعطى دقة عالية من حيث الاستجابة اللحظية للمتغيرات الهامة، خاصة سرعة الماكينة، معدل تدفق الوقود، وقدرة الماكينة، بالمقارنة مع النموذج الأصلي الصارم عند أحمال تشغيل مختلفة للماكينة.

Keywords: Marine power plants, Modeling, Automatic control

1. Introduction

The degree of speed control of ship machinery affects the economics and optimization of the machinery configuration and operation.

The machinery systems are becoming increasingly difficult in the attempt to control the engine speed. This is because the complexity to model the marine power plant as well as the turbocharged diesel engine. In order to predict how this modeling is difficult, it is necessary to apply the physical relations on which the concept of system modeling is connected. Linearized models, however, are useful in studying the dynamic behavior of the engine parameters for small perturbations, for instance those occurring while trying to maintain constant speed when waves are encountered. In this article by dealing with a linearized model, it has been possible to obtain analytical expressions of the transfer functions involved and consequently explicit relations between the output characteristics and the parameters of the system. Such a model may be derived in an experimental or an analytical manner. Experimental approaches have been based on identification procedures such as [1-3]. Comprehensive analytical models, based on thermodynamic considerations, are derived in various works such as [4-7].

To assess the stability and to determine the effect of parameters on diesel-propeller set in marine power plant, a model of the diesel, which is considerably simpler than the engine designer's thermodynamic model, is required. This model needs to accurate over a wide load range. This precludes the use of a simple transfer function representation.

The aim, in designing propulsion control systems, is the development of a simpler system. This system must be easy to be handled in modeling and control. Also it should be suitable to keep a modern propulsion plant in its highest performance level. This system has to attain required engine dynamics, without neglecting any safety operation of the propulsion machinery.

The theme of the paper is to highlight the original rigorous model of the engine, then to describe a simplified diesel engine model. Lastly, the factors affecting accuracy and detailing the problems will be examined.

2. The original rigorous model of the engine

The turbocharged marine diesel engine can conventionally be divided into a number of sub-systems. The dynamics of some of these sub-systems are not considered very important with respect to the behavior of the total system. The models, which take into account, in more detail, the thermodynamic processes are available [6,7].

Fig. 1 shows the structure of the used model and contains all dynamic of the engine model. In applying this model, the various functions are obtained from the tendency of performance curves such as the compressor and the turbine, or data obtained from detailed thermodynamic models. Ideally these functions should include all the inputs that affect the output variable and should be stationary (time independent). Considering these sub-systems of the model in more detail, the load torque of the compressor Q_c can be

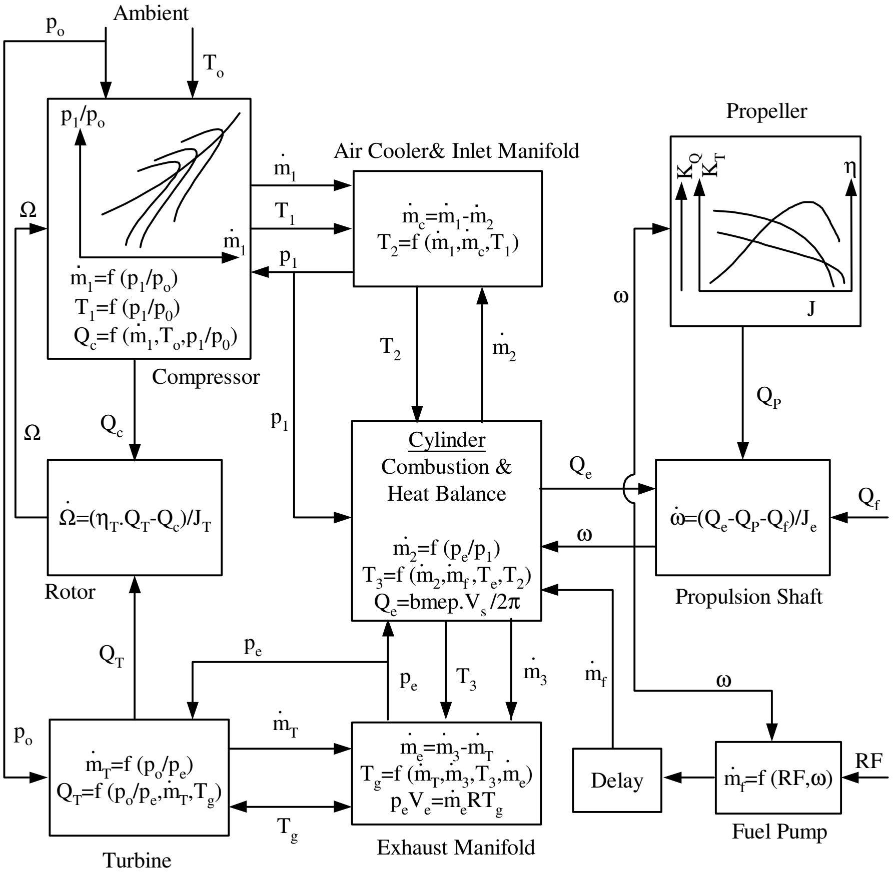

Fig. 1. Original rigorous model of marine power plant.

calculated from the air ratio p_1 / p_o, while the block of turbine calculate the turbine torque Q_T. The speed of the turbocharger Ω can be calculated as shown in the block of turbocharger rotor. The engine block contains the functional relationship between the engine torque Q_e over fuel flow rate $\dot{m}_f$, the air fuel ratio and the air pressure ratio p_e / p_1. The delay gives the first order lag approximates the average of the fuel pump by delay time of τ_c seconds. The fuel flow rate is controlled by the rack position RF and the engine speed ω in the fuel pump. The engine speed ω can be calculated from the engine torque Q_e, the friction torque Q_f, the propeller torque Q_p and the equivalent polar mass moment of inertia of engine, propeller and rotating parts J_e as shown by the block of the propulsion shaft. The propeller block gives the screw load characteristics of the propeller to give the propeller torque Q_p.

The analysis of the different components will lead to a coupled system of differential equations, which may include non-linearizations. This system of equations can be linearized at considered operating point to obtain first order differential equations, with the corresponding block diagram [6]. Due to the complexity of such a block diagram, it is preferable to use state-space approach for the implementation of the model. The state-space equations are of the form:

$$\dot{\mathbf{x}} = \mathbf{A}.\,\mathbf{x} + \mathbf{b}.\mathbf{u}, \tag{1}$$

$$\mathrm{y} = \mathbf{c}^{\mathrm{T}}.\,\mathbf{x}\ , \tag{2}$$

where the state vector $\mathbf{x}$ is

$$\mathbf{x} = [\omega\ \ \Omega\ \ m_c\ \ T_2\ \ \ m_e\ \ T_g\ \ D\ \ \ \dot{m}_f\ ]^{\,T}\,.$$

Solving eqs. (1) and (2), the transfer function will be,

$$\mathrm{G_j} = \mathbf{c}_\mathbf{j}^{\mathrm{T}}\ .\,(\mathrm{s}\,.\,\mathbf{I} - \mathbf{A})^{-1}\,.\,\mathbf{b}\,. \tag{3}$$

Based on the operation point data of the engine, and corresponding to vector $\mathbf{c}_\mathbf{j}^{\mathrm{T}}$, the transfer function and the transient response for each state variable can be obtained by the use of MATLAB program package.

3. The simplified model

In the following, the most important dynamic characteristics of the sub-systems will be considered.

The rate of the injected fuel $\dot{m}_f$, is controlled by the fuel pump rack position RF, and is proportional to the shaft speed ω as,

$$\dot{m}_f = \frac{e^{-\tau s}}{1+\tau_c\, s}\,.\,(K_p\,.\,RF\,.\,\omega)\,, \tag{4}$$

where τ is the dead time due to the discontinuity of the fuel injection and is approximated as half of the firing period of the engine [8]. τ_c is the delay time constant of the fuel pump which is equal to the time of one complete crankshaft cycle [9].

The turbocharger responds normally slowly to changes in the operating point of the engine. The slow behavior of the turbocharger does not influence the engine dynamics. Therefore, the turbocharger dynamics can be compensated [10]. In order to adjust the dynamic behavior of this simplified model to obtain the accuracy with that of the rigorous model, it is better to introduce a lead compensation transfer function as $(1+\tau_p\, s)/(1+\tau_m\, s)$, where τ_p and τ_m are the greatest time constants of the more accurate relationship $P_e / \dot{m}_f$ which can be obtained from the original rigorous model. This will compensate the steady state inlet air pressure from the instantaneous exhaust pressure ratio. Also, it models the observed slow dynamic of the turbocharger following a step change in fuel flow and hence gives the effective power of the engine P_e. The engine is considered to be a block with the fuel flow change $\dot{m}_f$ as input variable and the effective power change P_e as the output variable.

$$P_e = \eta_{ith} \cdot \eta_m \cdot CV . \frac{1+\tau_p}{1+\tau_m} . \dot{m}_f \, . \tag{5}$$

The model for crankshaft dynamics is easily considered,

$$\frac{d}{dt}\left(\frac{1}{2} . J_e . \omega^2\right) = \eta_m . P_e - P_l \, . \tag{6}$$

The propeller law may be approximated as [8];

$$P_l = K_l . \omega^3 \, . \tag{7}$$

Using nominal values RF, $\dot{m}_f$, P_e and ω for the non-linear previous eqs. (4) to (7) and applying Laplace-transformation may lead to the block diagram of the linear model in fig. 2, where the linearization factors are k_i ($i = 2,\ldots,6$). The variables are considered to be the small excursions from the equilibrium point as a function of the time.

4. Results

In this section the modeling will be applied to a two-stroke Sulzer 5RTA58 marine diesel engine at 50%, 75% and 100% propulsion load. The steady state values of these loads were used to generate the functions in relation to the turbocharger and the propeller charts. The transient values were used to generate the other functions. Having obtained the original rigorous model for the diesel engine, from the manufacturer's detailed thermodynamics model, the block diagram of fig. 1 was used to obtain the overall response of the engine-propeller system. These time responses were then compared to another set of responses obtained from the block diagram of the simplified model of fig. 2. In these responses, a step function of rack position change was applied, the transient response of the engine speed, the fuel flow rate and the effective power at 50%, 75% and 100% propulsion load are shown in figs. 3, 4 and 5, respectively. Table 1 shows the maximum differences of transient responses and the steady state responses between the two models at each load. At all these loads the maximum transient speed error between the simplified and rigorous model is less than 10% of the maximum speed deviation up to 5 s, whereas at the steady state condition the difference is not exceeds 2.5%. That is due to the time delays incorporated in the air cooler and the inlet manifold. The fuel flow rate matches nearly closely with a maximum difference less than 3%. Only at 75% load, the difference exceeds 5%. This is due to introducing the dead time τ and the delay time τ_c in the calculation of the fuel flow rate of the simplified model. The maximum effective power difference is less than 10% and the simplified model is faster than the original rigorous model, resulting in more torque output and consequently more effective power slightly earlier. That is due the compensation transfer function of the supercharger dynamics in the simplified model.

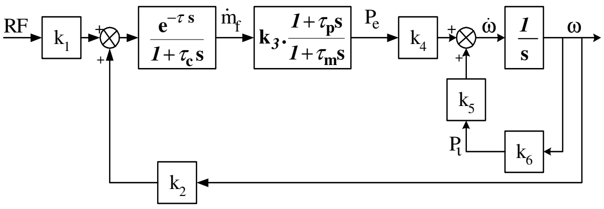

Fig. 2. Simplified linear model of marine power plant.

Table 1
Steady state accuracy

		Max. error %	Error at s.s. %
50%	ω	8	2
	$\dot{m}_f$	3	1.5
	P_e	8	1
75%	ω	10	2.5
	$\dot{m}_f$	5	1.4
	P_e	10	1.6
100%	ω	9	1.5
	$\dot{m}_f$	3.5	2
	P_e	9	1

5. Conclusions

Modeling of original rigorous turbocharged marine diesel engine for the purpose of marine propulsion plant simulation is accomplished through application of the fundamental equations, and supplemented by empirical relationships. The analysis can be chosen

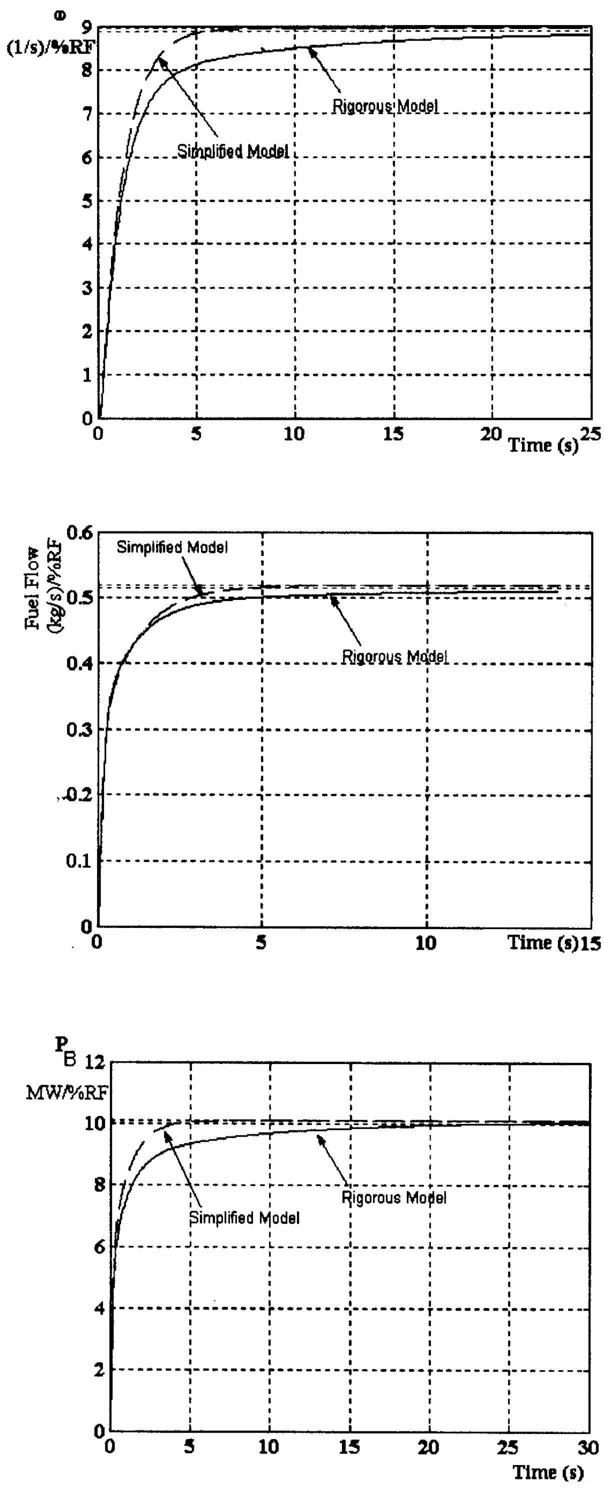

Fig. 3. Dynamic response of engine speed, fuel flow rate and effective power with respect to rack position step function, at 50 % Load.

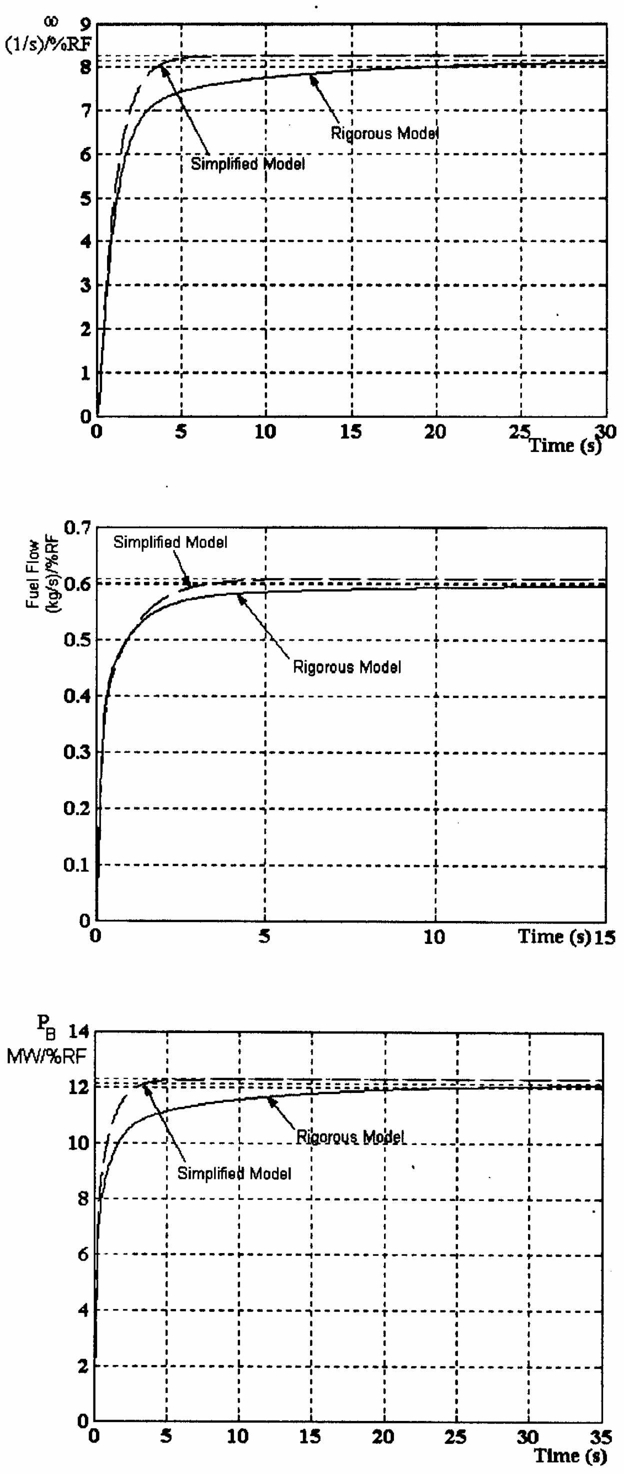

Fig. 4. Dynamic response of engine speed, fuel flow rate and effective power with respect to rack position step function, at 75 % Load.

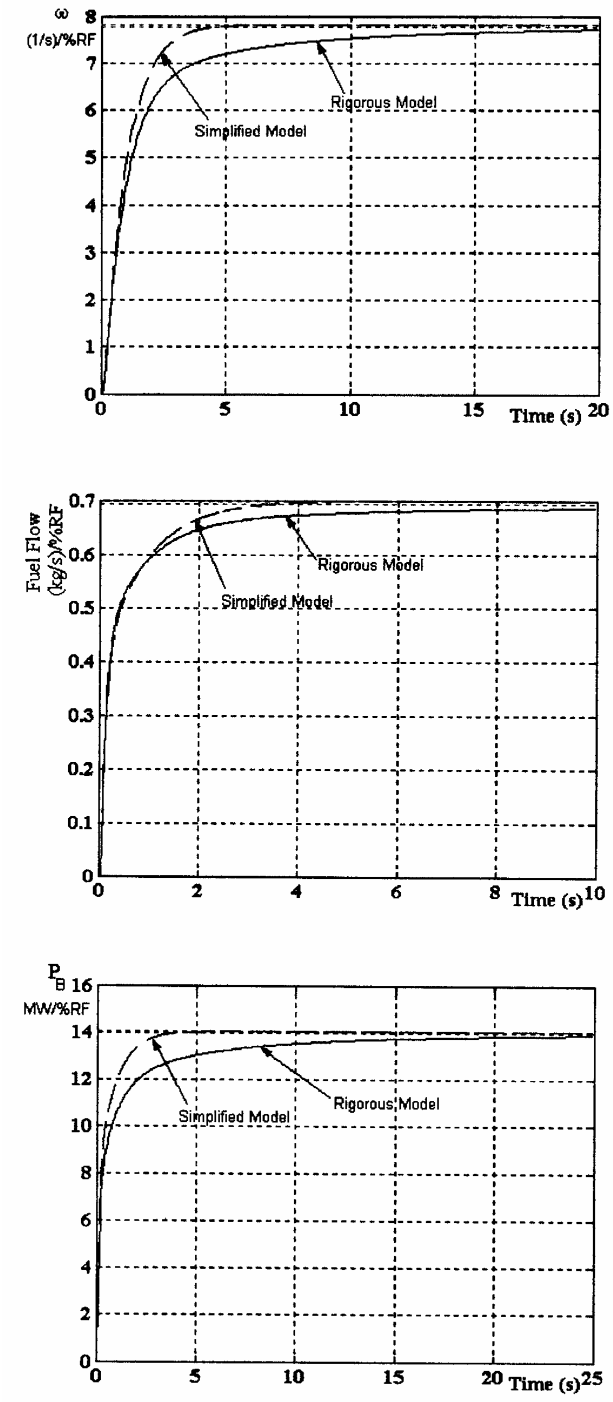

Fig. 5. Dynamic response of engine speed, fuel flow rate and effective power with respect to rack position step function, at 100 % load.

from the background of equations and relationships to produce a model that in its simplicity or its complexity suits the needs of this simulation. In this paper, the rigorous model has been assembled and outlined by materials necessary for marine diesel engine modeling. The studying of this model without regulator for a unit step change in fuel rack position reveals its stability as a self-regulating plant, which can be attributed principally to the large inertia of the rotating masses.

A simplified model for the diesel engine has been introduced in order to facilitate the control system design, which is suitable to keep a modern propulsion plant at its highest performance level. In the simple model, the turbocharged has been eliminated from the model, as its influence on the overall performance is insignificant. Therefore a lead compensation transfer function, obtained from the thermodynamic model, is introduced. The transfer function of the engine in the simplified model has to be noted approximately equals to that obtained from the rigorous model. Also the dead time due to the discontinuity of the fuel injection and the time delay of the fuel pump have been introduced. It has to be noted that the simplified model does not represent actually the turbocharged engines with respect to performance and power, but it is suitable to facilitate the study of the control system design of the engine.

The simplified model achieves the steady state accuracies of better than 2.55% of the steady state speed deviation condition at 75% propeller load, compared to the original rigorous model, while the steady state fuel flow rate is better than 2% over the same load. The transient power accuracy for 75% load is better than 1.6%.

The simplicity and accuracy of this simplified model make it well suited for stability studies of control system particularly the design of the speed governor.

Nomenclatures

$\mathbf{A}$	is the system matrix,
$\mathbf{b}$	is the control vector,
$\mathbf{c}^T$	is the output vector,
CV	is the calorific value of fuel (kJ/kg),
D	is the dummy variable,
J_T	is the polar mass moment of inertia of

	turbocharger (kg.m^2),
J_e	is the equivalent polar mass moment of inertia of engine, propeller and rotating parts (kg.m^2),
K_l	is the proportionality constant for propeller load ,
K_p	is the fuel pump constant,
$\dot{m}_1$	is the air flow from compressor (kg/s),
$\dot{m}_2$	is the air flow from cooler (kg/s),
$\dot{m}_3$	is the $\dot{m}_2+\dot{m}_f$ (kg/s),
$\dot{m}_c$	is the air flow rate stored in air cooler and inlet manifold (kg/s),
$\dot{m}_e$	is the accumulated gas in exhaust manifold (kg/s),
$\dot{m}_f$	is the fuel mass flow rate (kg/s),
$\dot{m}_T$	is the rate of gas mass flow inlet to the turbine (kg/s),
p_o	is the ambient pressure (bar),
p_1	is the supercharging air pressure (bar),
p_e	is the exhaust gas pressure (bar),
P_e	is the effective power (kW),
P_l	is the power absorbed by propeller (kW),
Q_c	is the compressor torque (kJ),
Q_e	is the engine torque (kJ),
Q_f	is the frictional torque (kJ),
Q_p	is the propeller torque (kJ),
Q_T	is the turbine torque (kJ),
s	is the laplace factor,
T_o	is the ambient temperature (K),
T_1	is the outlet temperature from compressor (K),
T_2	is the air temperature after air cooler (K),
T_3	is the gas inlet temperature to exhaust manifold (K),
T_g	is the exhaust gas inlet temperature to turbine (K),
u	is the input variable,
x	is the state vector,
y	is the output of the system,
η_{ith}	is the Indicated thermal efficiency of engine,
η_m	is the mechanical efficiency,
Ω	is the turbocharger speed (1/s), and
ω	is the engine speed (1/s).

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Received January 23, 2003
Accepted March 31, 2003