Ocean Engineering 136 (2017) 218–232

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Mean value modelling of diesel engine combustion based on parameterized finite stage cylinder process

Congbiao Sui[a,b], Enzhe Song[a], Douwe Stapersma[b], Yu Ding[a,*]

[a] College of Power and Energy Engineering, Harbin Engineering University, Harbin, China
[b] Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, The Netherlands

ARTICLE INFO

Keywords:
Diesel engine
Combustion process
Mean value model
Combustion parameter
Modelling

ABSTRACT

Mean value diesel engine models are widely used since they focus on the main engine performance and can operate on a time scale that is longer than one revolution, and as a consequence use time steps that are much longer than crank-angle models. Mean Value First Principle (MVFP) models are not primarily intended for engine development but are used for systems studies that are become more important for engine users. In this paper two new variants of Seiliger processes, which characterize the engine in-cylinder process with finite stages are investigated, in particular their ability to correctly model the heat release by a finite number of combustion parameters. MAN 4L20/27 engine measurements are used and conclusions were drawn which Seiliger variant should be used and how to model the combustion shape for more engines. Then expressions to calculate the combustion parameters have been obtained by using a multivariable regression fitting method. The mean value diesel engine model has been corrected and applied to the simulation of a ship propulsion system which contains a modern MAN 18V32/40 diesel engine in its preliminary design stage and the simulation results have shown the capability of the integration of MVFP model into a larger system.

1. Introduction

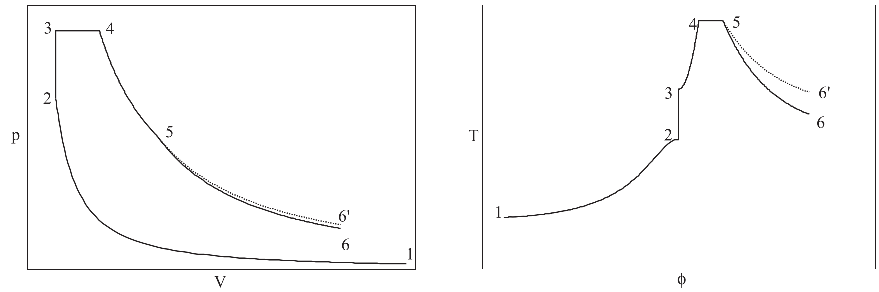
The diesel engine has nowadays been dominantly used as prime mover of medium and medium-large devices, such as truck driving, land traction, ship propulsion, electrical generation, etc., owing to its reliability and good efficiency. The in-cylinder process during which the fuel is combusted and work delivered is the most crucial part of the diesel engine working processes. The in-cylinder process of a diesel engine is extremely complex, due to the complicated changes of the mass, energy and composition of the working medium. Whether the in-cylinder process is conducted properly or not has direct influences on the power prediction, fuel economy and emission behaviour etc. of a diesel engine (Lino and Christopher, 2010; Asprion et al., 2013).

With the rapid development of testing and computing technology, the in-cylinder process of diesel engines has been investigated quite deeply and in considerable details. A great variety of diesel engine in-cylinder process models have been developed using different methods and with different levels of detail due to various research and application purposes. Generally, an in-cylinder process model with higher accuracy is more complex, requiring more input parameters, longer calculation time and always are more difficult to adapt to different engines operating conditions (Guan et al., 2014; Payri et al., 2011). When a large system in which a diesel engine works as a subsystem of the whole system, for instance, the ship propulsion system, ship power generating system, ship heat recovery system, diesel engine electronic control system etc., is modelled and investigated, an in-cylinder model with high accuracy and complexity is not necessary, otherwise the system model will have a poor real-time capability and a bad adaptability to variable operating conditions (Woodward and Latorre, 1984).

Mean value models of diesel engine in-cylinder process taking both simplicity and accuracy into consideration have been widely used in the modelling of large systems. The in-cylinder process *mean value* models focus on the main engine performance parameters such as the air-fuel ratio, maximum in-cylinder pressure and temperature, engine brake power, etc., rather than the in-cycle variations with steps of a crank angle (Theotokatos, 2010). Mean value models have been extensively applied in the investigation of the transient behaviour of diesel engine and simulation at system level due to their simplicity and sufficient accuracy (Murphy et al., 2015). Much research on mean value modelling of diesel engines has been conducted using different approaches, such as the regression-based and the thermodynamics-based mean value models. Regression-based mean value models have inherent limitations just predicting the input-output relationships and

* Correspondence to: Room 912, Power Building, College of Power and Energy Engineering, Harbin Engineering University, No. 145, Nantong Street, 150001 Harbin, China.
E-mail address: dingyu@hrbeu.edu.cn (Y. Ding).

http://dx.doi.org/10.1016/j.oceaneng.2017.03.029
Received 30 October 2016; Received in revised form 20 February 2017; Accepted 13 March 2017
0029-8018/



(a) p-V diagram

(b) T-φ diagram

Fig. 1. six-point Seiliger process definition (Ding, 2011).

neglecting the underlying physical and thermodynamic process of the diesel engine, due to their heavy dependence on the regression analysis of the experimental data (Moskwa and Hedrick, 1992; Kao and Moskwa, 1995). Thermodynamic-based mean value models are derived from the basic physics and thermodynamics which can predict the physical and thermodynamic causalities of the engine working processes rather than algebraic equations just representing the input-output relationships (Maftei et al., 2009; Lee et al., 2013; Grimmelius et al., 2007; Miedema and Lu, 2002).

Mean value models of diesel engine that were applied for modelling of marine diesel engines and simulation of ship propulsion system have been extensively reported in the published scientific literature. Theotokatos (Theotokatos, 2008) has investigated the transient response of a ship propulsion plant using a mean value engine model. Vrijdag (Vrijdag et al., 2010) has applied the diesel engine model for the control of propeller cavitation in operational conditions. Baldi, F (Baldi et al., 2015) has developed a mean value diesel engine model that has been used to investigate the propulsion system behaviour of a handymax size product carrier for constant and variable engine speed operation. Michele Martelli (M Martelli, 2014) has developed a ship motion model taking into account all six degrees of freedom and a propulsion plant model that includes the mean value model of the diesel engine. In these models at system level, it is generally sufficient to predict the global behaviour of the engine and it is less important and unnecessary to investigate the engine thermodynamics deeply (Altosole and Figari, 2011).

The thermodynamic-based MVFP models were originally developed by Delft University of Technology (TU Delft, the Netherlands) and Netherlands Defence Academy (Grimmelius et al., 2007). A MVFP model of diesel engine MAN L58/64 has been built based on the basic five-point Seiliger process by Miedema (Miedema and Lu, 2002), and the simulation results have shown the behaviour of a few important parameters in the dynamic process. Schulten (Schulten, 2005; Grimmelius et al., 2007) has built a MVFP diesel engine model based on the basic six-point Seiliger process and has used the engine model to investigate the interaction between diesel engine, ship and propeller during manoeuvring.

In this paper, firstly, a thermodynamic-based MVFP diesel engine model based on the *advanced* six-point Seiliger cycle will be introduced and the systematic investigation of the combustion parameters under various operating conditions will be presented based on MAN 4L20/27 diesel engine measurements. Then a MVFP model of MAN 4L20/27 that is built based on the *basic* six-point Seiliger cycle will be shown. The combustion parameters mathematical models of the MVFP model are derived by multiple regression analysis of experimental data and are validated. The model originally built for the diesel engine MAN 4L20/27 are then corrected and used to model diesel engine MAN 18V32/40, after which the engine mean value model has been applied to the simulation and performance prediction of the propulsion system of a large semi-submersible heavy lift vessel (SSHLV) during its preliminary design stage in order to verify the integration of the MVFP model into a larger system. The results of the mean value diesel engine modelling and application will be analysed.

2. Model description and measurement investigation

2.1. Characterization of the in-cylinder process

The diesel engine in-cylinder process can be parameterized by finite stages in different kinds of Seiliger processes, providing a simple and reliable method for mean value modelling of the cylinder process. Often the 5-point Seiliger process with two combustion stages is used (Dual Cycle) but in order to model combustion adequately a 6-point Seiliger process offering 3 or 4 stages of combustion is deemed necessary here.

2.1.1. Six-point Seiliger cycle

In this paper both the basic and advanced 6-point Seiliger cycles are investigated. Fig. 1 shows the six-point Seiliger process model. The stages can be described as follows:

1–2: polytropic compression;
2–3: isochoric combustion;
3–4: isobaric combustion and expansion;
4–5: isothermal combustion and expansion;
5–6: polytropic expansion indicating a net heat loss, used when there is no combustion in this stage (basic);
5–6′: polytropic expansion indicating a net heat input caused by late combustion during expansion (advanced).

2.1.2. Parameterization of the in-cylinder process

The Seiliger process can be described by a finite number of parameters that fully specify the process together with the initial (trapped) condition and the working medium properties.

The definition of the Seiliger stages and the Seiliger parameters are given in Table 1. Among these Seiliger parameters a, b and c are the combustion parameters indicating the isochoric combustion stage, isobaric combustion stage and isothermal combustion stage respectively. The polytropic compression exponent n_{comp} and effective compression ratio r_c model the polytropic compression process while

Table 1
Seiliger process definition and parameters.

Seiliger stage	Seiliger definition	Parameter definition	Seiliger parameters
1–2	$\frac{p_2}{p_1} = r_c^{n_{comp}}$	$\frac{V_1}{V_2} = r_c$	r_c, n_{comp}
2–3	$\frac{V_3}{V_2} = 1$	$\frac{p_3}{p_2} = a$	a
3–4	$\frac{p_4}{p_3} = 1$	$\frac{V_4}{V_3} = b$	b
4–5	$\frac{T_5}{T_4} = 1$	$\frac{V_5}{V_4} = c$	c
5–6 (5–6′)	$\frac{p_5}{p_6} = r_e^{n_{exp}}$	$\frac{V_6}{V_5} = r_e$	r_e, n_{exp}