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Development of a bond graph based model library for turbocharged diesel engines

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ABSTRACT

A model library for the turbocharged diesel engines using the pseudo-bond graph based on the three-level structure, technical component level, physical concept level and mathematical level, is presented. For each level, a general framework is explained. The detailed pseudo-bond graph models of each part of the engine as well as the mathematical models are presented. After that, a specific model for the 16PA6V-280STC turbocharged diesel engine is presented. Steady-state conditions of the model are validated with the experiment data. Dynamic conditions, such as the instantaneous load increase, rotational speed transient from 730 rpm to 1000 rpm, are simulated and validated. The evolutions of engine speed, load, rack position, of the dynamic processes are presented. Finally, the influence of the compression ratio and fuel supply advance angle on the specific fuel consumption of the diesel engine is studied on the 20-sim-Matlab co-simulation platform.

1. Introduction

Turbocharged diesel engines are widely used in various applications, for example, in power plants, marine propulsion systems, automobile industry, etc. They have shown advantages of proven reliability, superior efficiency, relatively high power to mass ratio, easy access to fuel and quick responses [1,2]. The working conditions of the diesel engine are directly related to the reliability and efficiency of the power device. A model for the analysis of the system performances can provide benefits for the development and verification of new technologies by reducing cost and accelerating the process. Therefore, a complete and accurate model library for the turbocharged diesel engines is quite necessary [3,4].

Most energetic dynamical systems can be represented as bond graph model [5], and their behavioral model, consisting of differential algebraic equations (DAEs), can be derived from the model through well-established algorithmic way [6,7]. Bond graph is a modeling method based on energy flow. It allows simplifying the representation of various coupled physical phenomena, including the variable causality, by using unified variables for all the physical domains (effort and flux) whose product equals the transmitted power [8–12]. Compared with the other modeling methods, bond graph models are relatively easy to understand with the following characteristics: (1) It is a unified language for all physical domains; (2) The dynamic characteristics of the system are visually revealed in a concise graphical manner; (3) The system state equations are established in a regular way so that it can be automatically generated by computer. On the other hand, the bond graph model can also be applied to the monitoring and control of system [6], fault diagnosis and isolation [13,14], and fault tolerant control [15]. Therefore, the bond graph has become a powerful tool for modeling and dynamic analysis of the complex systems [16–19]. The application of the bond graph is limited in practical processes since the product of effort and flow variable pairs is not always power. Therefore, the concept of pseudo-bond graph was proposed by Karnopp [20,21]. In pseudo-bond graph, the product of effort variable and flow variable is no longer power but the generalized power. As long as the effort and flow are connected correctly in pseudo-bond graph, the bond graph theory can be effectively applied to any systems. Literature [6,9,10,18] are suggested for the basics of bond graph theory.

Bond graph has been applied to the modeling and simulation of engines for quite a long time. In 1975, Margolis [22] introduced a model of two-stroke internal combustion engine dynamics using the bond graph technique. In 1979, Karnopp [21] presented the double bond pseudo-bond graphs for compressible thermo-fluid systems, and based on which, Engja et al. [23] developed a bond graph model of diesel engines for transient performance in 1983. In

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Nomenclature

$Aeff$	effective air cross-section of the valve, m^2
A_{wall}	exchange surface area of the cylinder wall, m^2
c_v	air specific heat capacity at constant volume, J/kg.K
c	sound velocity, m/s
d_v	valve head diameter, m
g_e	specific fuel consumption, g/kW.h
$\dot{H}$	enthalpy flux of air, W
h	specific enthalpy of air, J/kg
h_v	valve lift, m
H_u	low heat value of the fuel, J/kg
h_{wall}	heat transfer coefficient of air, W/m^2.K
Itc	inertia of the turbocharger, kg. m^2
K_P	proportional gain
$lcom$	equivalent length of the compressor duct, m
m_{in}	intake air mass, kg
m_{ex}	exhaust air mass, kg
mf	mass of the fuel, kg
$mcyl$	mass of air in the cylinder, kg
m_{exh}	exhaust gas mass through the turbine, kg
$mcycle$	cyclic fuel mass injected per cylinder, kg
mp	premixed combustion quality factor
m_d	diffusion combustion quality factor
N	rotational speed, rpm
p	pressure, Pa
p_{com}	supercharged air pressure, Pa
$p_{\max}$	peak pressure in the cylinder, Pa
P_e	effective power, kW
Qf	heat released by the fuel, J
Q_{wall}	heat crossing the cylinder wall, J
Q_d	fuel fraction for diffusion combustion
R	rack position, mm
Rg	specific gas constant, J/kg.K
T_I	integral time constant
T_D	Derivative time constant
T	temperature, K
$Texh$	exhaust gas temperature, K
$T_{\max}$	maximum combustion temperature, K
Tie	gas temperature in the exhaust pipe, K
u	specific internal energy of air, J/kg
Up	piston velocity, m/s
$Vcyl$	volume of the cylinder, m^3
x	piston displacement, m
X	ratio of burned fuel mass to cyclic injection mass
X_1	premixed fuel fraction(varied with time)
X_2	fuel fraction for diffusion combustion(varied with time)

Greeks symbols

δ_v	valve seat angle, rad
τ	torque, N.m
φ	crankshaft angle, rad
φ_b	beginning point of combustion, rad
φ_e	endpoint of combustion, rad
γ	specific heat ratio
η_{turb}	turbine efficiency
μ	flow coefficient
ϕ	leading angle of premixed combustion, rad

Subscripts

atm	atmospheric
cyl	cylinder
com	compressor
ex	exhaust
exh	exhaust gas
in	intake
p	compressor plenum
ref	reference
tc	turbocharger
turb	turbine
wall	cylinder wall
v	valve

Bond graph symbols

R	resistance element
C	capacitance element
I	inertia element
S_e	source of effort
Sf	source of flow
TF	transformer element
GY	gyrator element
MTF	modulated transformer
MGY	modulated gyrator
f	flow
e	effort

2002, Granda [24] developed a single cylinder internal combustion engine model using the pseudo-bond graph, and extended it into an eight-cylinder engine model. Bera et al. [25] presented a full bond graph model of engine thermodynamics with valve timing, combustion and mechanism modeling, etc. Merzouki et al. [18] integrated a complete engine model with vehicle model and studied the dynamics of integrated model. Creyx et al. [12] presented an dynamic model of the expansion cylinder of an open joule cycle Ericsson engine using the bond graph formalism and several dynamic phenomena are included. Rakopoulos et al. [3] introduced a very detailed historical overview of diesel engine modeling in the last thirty years, in which various modeling methods such as the filling and emptying model, the mean value model of an engine, are distinguished from a systematic point of view.

Despite the long history of modeling of engines, relatively few models are in a systematic approach. Library based modeling has the advantages of fast modeling and superior efficiency [1,2]. One can establish the required model efficiently based on the library for different engines. In 1998, Breunese et al. [1] studied the architecture of a library of reusable models and divided it into three levels, as shown in Fig. 1, which are technical component level, physical concept level and mathematical level. In the technical component level, the system is viewed as a concrete object or device composed of technical components. In the physical concept level, the system is viewed as a network of physical concepts or processes that constitute the dynamic behavior. In the mathematics level, the system is viewed as a set of mathematical relations (equations) that quantitatively describe the dynamic behavior. This kind of structure enables good continuity and reusability of the model library. In the following year, Chow et al. [4] introduced an overall structure of an engine system model. They decomposed the system into four levels, namely, elements, models, governing laws/ equations and sub-models. Yum et al. [2] presented a model library