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Development and validation of a free-piston engine generator numerical model

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ABSTRACT

This paper focuses on the numerical modelling of a spark ignited free-piston engine generator and the model validation with test results. Detailed sub-models for both starting process and steady operation were derived. The compression and expansion processes were not regarded as ideal gas isentropic processes; both heat transfer and air leakage were taken into consideration. The simulation results show good agreement with the prototype test data for both the starting process and steady operation. During the starting process, the difference of the in-cylinder gas pressure can be controlled within 1 bar for every running cycle. For the steady operation process, the difference was less than 5% and the areas enclosed on the pressure–volume diagram were similar, indicating that the power produced by the engine and the engine efficiency could be predicted by this model. Based on this model, the starting process with different starting motor forces and the combustion process with various throttle openings were simulated. The engine performance during stable operation at 100% engine load was predicted, and the efficiency of the prototype was estimated to be 31.5% at power output of 4 kW.

1. Introduction

As an alternative to conventional engines, free-piston engine generator (FPEG) is a promising power generation system due to its simplicity and high thermal efficiency therefore has attracted considerable research interests recently [1–6]. It integrates a linear combustion engine and a linear electrical machine into a single unit. Combustion in the engine chambers drives the translator to reciprocate in an almost resonant way and the linear electric machine converts part of the mover's kinetic energy to electricity. The thermal efficiency was estimated to be up to 46% (including friction and compressor losses) at a power level of 23 kW and the research showed promising results with respect to engine performance and emissions [7].

However, as the piston motion of the FPE is not restricted by the crankshaft mechanism, the piston is free to move between its top dead centre (TDC) and bottom dead centre (BDC), therefore the piston is only influenced by the gas and load forces acting upon it. This induces to problems such as difficulties in engine start, misfire, unstable operation and overall complex control strategies [8]. As a result, there has not been any stably operating prototype reported by now. Despite the research specifically addressing the modelling of FPEG, most researchers tended to adapt simplified ideal models widely used in conventional engines to simulate FPEG. Moreover, since free-piston engines have specific operating characteristics compared to conventional engines, the validation of the free-piston engine model still needs to be acknowledged.

Christopher M. Atkinson along with the co-researchers in West Virginia University developed an engine computational model with the combination of dynamic and thermodynamic analysis. The dynamic model consisted of an evaluation of the frictional forces and the load of the engine. The thermodynamic analysis consisted of an evaluation of each process that characterise the engine cycle based on the First Law of Thermodynamics. A time-based Wiebe function was used to calculate the heat release during the combustion process. The parameters used were based on test data collected from a running prototype, including in-cylinder pressure, displacement and velocity. A parametric investigation was also performed to predict the behaviour of the engine over a wide operating range [9–11].

Mikalsen and Roskilly presented a modelling investigation of a free-piston engine generator and they discussed the feasibility of the implemented models. The sub-models to simulate the in-cylinder combustion were based on existing single-zone models commonly used in conventional diesel engines. The output parameters of the model were validated against test data from a Volvo

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Nomenclature

A	piston area (m^2)
A_{cyl}	the in-cylinder surface area in contact with the gas (m^2)
$A_{leakage}$	leakage area (m^3)
A_f	friction parameter (−)
D_f	friction parameter (−)
C	capacitance of the circuit
C_d	combustion duration (s)
C_D	discharge coefficient
C_v	specific heat capacity at constant volume (J/kg K)
C_p	heat capacity at constant pressure
d	cylinder diameter (mm)
d_0	reference cylinder diameter
E	average temperature of lubrication oil at liner (°C)
f	overall scaling factor (−)
F_e	load force from the linear generator (N)
F_f	friction force (N)
F_l	gas force from the left cylinder (N)
F_m	force output from the linear electric machine (N)
F_r	gas force from the right cylinder (N)
F_{sl}	gas force from the left scavenging pump (N)
F_{sr}	gas force from the right scavenging pump (N)
H_e	enthalpy of the exhaust air (J)
H_i	enthalpy of the intake air (J)
H_l	enthalpy of the air leaked from the piston rings (J)
h	heat transfer coefficient (W/m^2 K)
i	current of the circuit (A)
K_A	proportionality constant for the thrust force of the motor
K_v	friction parameter (−)
L	inductance of the circuit
m	moving mass of the piston assembly
m_{air}	mass of the in-cylinder gas (kg)
$\dot{m}_{air}$	mass flow rate of the in-cylinder gas (kg/s)
p	in-cylinder pressure (Pa)
p_0	reference pressure or ambient pressure (Pa)
p_s	pressure in scavenge case (Pa)
Q_c	heat released from the combustion process (J)
Q_{in}	overall heat input for each cylinder in one running cycle
Q_{ht}	heat transferred to the cylinder wall (J)
$\dot{Q}_{ht}$	transferred heat flow rate (J/s)
R	resistance of the circuit
T_0	air temperature in the scavenging pump (K)
T_w	average temperature of the cylinder wall surfaces (K)
t_s	time at which the combustion process starts
x	mover's displacement
U	internal energy of the in-cylinder gas (J)
V	instantaneous cylinder volume (m^3)
V_s	volume of scavenge case (m^3)
v	axial velocity of piston (m/s)
v_p	mean piston speed (m/s)
λ	fuel mass fraction burned
γ	ratio of heat capacities
ϕ	magnetic flux
θ_0	reference temperature (°C)

TAD1240 six-cylinder, turbocharged diesel engine. The results showed that it was able to predict real trends of the free-piston engine for varying engine operating conditions [8].

Goldsborough et al. at Sandia National Laboratories analysed the steady-state operating characteristics of a free-piston engine using a zero-dimensional, thermodynamic model with detailed chemical kinetics, and heat transfer, scavenging, and friction submodels. Hydrogen was used as fuel. The simulation identified the critical parameters affecting the engine performance, and suggested the limits of possible improvement compared to conventional internal combustion engines. However, validation of the free-piston engine model was difficult due to the limited experimental data available from their prototype [12].

Zuo et al. at Beijing Institute of Technology provided numerical simulation on piston motion. A time-based numerical model was developed in Matlab to define the piston motion profiles. Multi-dimensional gas flow in the scavenging process of the free-piston engine was studied based on the numerical simulation results. A wide range of design and operating options including stroke length, valve overlapping distance, operation frequency and charging pressure were investigated to evaluate their effects on the scavenging performance. The measured in-cylinder pressure and scavenging pressure were used as the boundary conditions for their model development [13,14].

Nemecek Pavel at Czech Technical University described modelling and control of a free-piston generator. The model was based on simplified thermodynamic processes. Assumptions of ideal gas and ideal reversible processes were adapted. Despite the simplifications of the model, simulations results showed good agreement with the real system. However, the development of more precise thermodynamic identification was suggested for further work [15].

Free-piston engine is commonly modelled using simplified zero-dimensional models. Most of the reported models used idealised close system processes, in which no heat or mass transfer was considered [16–18]. However, the actual system cannot be assumed as isentropic close system because when the engine usually operates at relatively low speed, the effects of heat transfer and gas leakage become significant and cannot be simply neglected. Meanwhile, when the charge temperature rises above the wall temperature, heat is transferring from the air to the wall, which affects the piston's dynamics as well [19]. Thus, the ideal gas relationship is not sufficiently accurate for the present modelling of the FPEG. Moreover, friction force in previous models was considered to be a constant value, which is not accurate either. Furthermore, there has not been any model validation reported due to the limited test data available from operating prototypes.

This paper focuses on a spark ignited free-piston engine generator. Detailed sub-models for both starting process and steady operation were derived and developed in Matlab/Simulink. The compression and expansion processes were not regarded as ideal gas isentropic process; both heat transfer and air leakage were taken into consideration. Model validation was undertaken with the test data from a running prototype, which showed good agreement. Using this model, the starting process and steady operation performance were analysed.

2. Model description

2.1. Holistic model structure

The numerical model primarily aims to precisely describe the piston motion which is governed by the Newton's second law. Therefore an engine dynamic model was developed on the top level. The specific forces acting upon the pistons are determined by the in-cylinder gas thermodynamic processes, mechanical friction force and linear electric machine force. Thus three sub-models