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Research on the intermediate process of a free-piston linear generator from cold start-up to stable operation: Numerical model and experimental results

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ABSTRACT

The free-piston linear generator (FPLG) has more merits than the traditional reciprocating engines (TRE), and has been under extensive investigation. Researchers mainly investigated on the starting process and the stable generating process of FPLG, while there has not been any report on the intermediate process from the engine cold start-up to stable operation process. Therefore, this paper investigated the intermediate process of the FPLG in terms of switching strategy and switching position based on simulation results and test results. Results showed that when the motor force of the linear electric machine (LEM) declined gradually from 100% to 0% with an interval of 50%, and then to a resistance force in the opposite direction of piston velocity (generator mode), the operation parameters of the FPLG showed minimal changes. Meanwhile, the engine operated more smoothly when the LEM switched its working mode from a motor to a generator at the piston dead center, compared with that at the middle stroke or a random switching time. More importantly, after the intermediate process, the operation parameters of FPLG were smaller than that before the intermediate process. As a result, a gradual motor/generator switching strategy was recommended and the LEM was suggested to switch its working mode when the piston arrived its dead center in order to achieve smooth engine operation.

1. Introduction

The new technologies to improve fuel efficiency and to reduce exhaust gas emissions are under widespread investigation due to the requirements for low fuel consumption and stringent emissions standards. Researchers not only pay attention to the technological improvements and performance optimizations for the traditional reciprocating engines (TRE), but also explore new efficient power units [1–5]. With their efforts, a novel linear hybrid-electric device named free-piston linear generator (FPLG) was proposed.

The FPLG combines a free-piston internal combustion engine and a linear electric machine (LEM) into a single unit. The general working principle is that the high-temperature and high-pressure gas after the heat release process in the cylinder drives the piston assembly to reciprocate, and the generator converts parts of the mechanical energy into electricity. Compared with the conventional internal combustion engine coupled with a rotate generator, the FPLG shows many potential advantages, *i.e.* reduced components, high energy conversion efficiency, high power density and fast transient response [1–4]. As a result, the FPLG has caught the attention of researchers all over the world. Pescara introduced the concept of a free-piston engine (FPE) for the first time in the 1920s [5]. However, the FPE development progressed slowly afterwards. As the mechanical production and the electronic-controlling technology are developing in the last two decades, researchers have achieved significant progress in terms of the FPEG numerical modeling and simulation, experimental test, and stable operation controlling strategies. Recent research progresses on these aspects will be summarized and presented respectively.

1.1. Numerical modeling and simulation

Researchers at West Virginia University established a comprehensive numerical model of the FPLG, including an engine model and the LEM model. Through the numerical simulation of those models, they analyzed the influences of different parameters on the output power of the FPLG and proposed the parameters optimization method [6]. Based on mathematical modeling and

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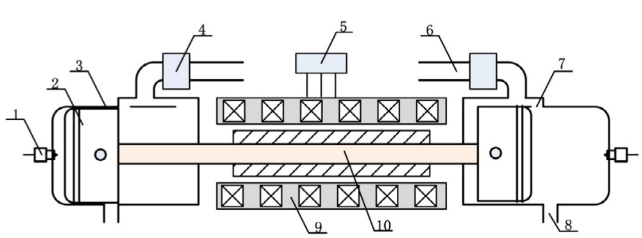
Nomenclature

FPLG	free piston linear generator	x_1	switching position (mm)
FPEC	free-piston energy convertor program	x_2	switching position (mm)
FPE	free-piston engine	p	in-cylinder gas pressure (bar)
TRE	traditional reciprocating engine	γ	ratio of specific heats (–)
LEM	linear electric machine	V	cylinder volume (m^3)
TDC	top dead center	Q_h	heat transfer loss (J)
ECU	integrated electronic control unit	Q_c	heat released from the combustion process (J)
m	moving mass of the piston assembly (kg)	C_f	viscosity friction coefficient (–)
F_f	friction force (N)	k_f	thrust coefficient of the motor (N/A)
F_m	thrust of the electric engine when the LEM runs as a motor (N)	I	current value in the starter coil of the motor (A)
F_g	electromagnetic resistance when the LEM runs as a generator (N)	k_ε	coefficient of the counter electromotive force of the generator (V/m/s)
p_L	pressure in the left cylinder (bar)	R_S	coil resistance (Ω)
p_R	pressure in the right cylinder (bar)	R_L	external load resistance (Ω)
$\varepsilon_1(x)$	step function	L	inductance of the generator (H)
$\varepsilon_2(x)$	step function		
x	piston position (mm)		

numerical simulation, Roskilly et al. at Newcastle University studied the characteristics of the FPLG, including piston dynamics, in-cylinder thermal-dynamics circulation, and the piston position controlling strategy [7–10].

The research group at Sandia National Laboratory simulated the operation of the FPLG with a zero-dimensional thermal-dynamics model and described the heat transfer, scavenging, and friction sub-models. After initial simulation, they established a more detailed thermal-dynamics model in order to compare the influences of different parameters on the engine emission and thermal efficiency [11]. The free-piston energy convertor program (FPEC) sponsored by the European Union started from 2002 [12,13]. The FPEC dynamic and the controlling model, established by Erland Max, were coupled with the thermal-dynamics model, heat release model, and dynamics model, among which the thermal-dynamics model was used to describe the changes of in-cylinder gas pressure and temperature during stable operation process.

Researchers at Czech Technical University conducted a mathematical model of the FPLG and set up a relatively complex mathematical model with Matlab/Simulink and DSPACE simulation platforms. They simulated the FPLG dynamics, thermal-dynamics, heat transfer and power electronics [14,15]. Researchers at Beijing Institute of Technology carried out a zero-dimensional mathematical simulation of the FPLG and predicted the engine operation frequency, the piston dynamics, in-cylinder gas pressure, temperature, engine indicated efficiency, the system output power, etc. They analyzed the influence of the parameters on the operation of the FPLG, and also conducted a CFD mathematical simulation of the scavenging process and combustion process, in order to discuss the influences of the major parameters of the scavenging process on the scavenging efficiency and the influence of the piston motion on the combustion process [16–19]. In general, researchers mainly focused on the simulation of the FPLG in terms of the piston dynamics and thermal-dynamics. Some of the numerical models were validated with the test data from FPLG prototypes, and the experimental results of FPLG will be introduced in the next section.



1. Spark plug 2. Piston 3. Cylinder 4. Fuel injector 5. External load 6. Air-intake tube 7. Scavenging port 8.Exhaust port 9. Stator 10. The connecting rod

Fig. 1. The prototype structure of the FPLG.

1.2. Experimental test

Researchers at West Virginia University developed a spark-ignited FPLG prototype [20,21]. According to the experiment results, the mean piston velocity was 2.37 m/s, the engine operation frequency was approximately 23.1 Hz, and the output power was up to 313 W. However, unstable combustion and frequent misfire were reported. A two-stroke compression engine prototype was then developed, the engine bore of which was 75 mm, with a maximum stroke of 71 mm. While the designed compression ignition FPLG prototype was found to be difficult to start, and there has not been any test data reported. Researchers at Sandia National Laboratory designed a FPLG prototype and tested several fuels that were full of hydrogen on a rapid compression-expansion machine by applying homogeneous charge compression ignition (HCCI) combustion mode, and the thermodynamic cycle was found to be similar to Otto cycle process [22]. Experiments suggested that when hydrogen, ammonia, methane and natural gas were used, the energy conversion efficiency and the NO_x emission could be the same as the fuel cell.

The FPEC prototype sponsored by the European Union adopted in-cylinder injection mode, two-stroke mode port scavenging process, and solenoid valve mechanism [12]. However, there is a lack of test reports regarding the prototype. Researchers from the Czech Technical University designed a FPLG prototype, for which, as experimental data indicated, the operation frequency was 27 Hz, the output power was up to 650 W, and the electricity generation

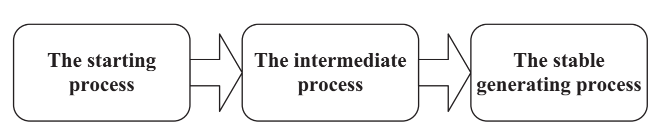


Fig. 2. Working processes of the FPLG.