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ANALYSIS OF THE WHOLE PROCESS MOTION CHARACTERISTICS FOR FPICPS USING A VALIDATED FAST-RESPONSE FORCE CONTROL MODEL BASED ON PMLSMS MATHEMATICAL MODEL

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ABSTRACT

As a promising linear energy conversion system, the free piston internal combustion powertrains system (FPICPS) has many advantages such as compact structure, short energy transmission chain and high fuel flexibility. The main parts of FPICPS consists of a two-stroke combustion engine, a permanent magnet linear synchronous machine system (PMLSMS) and a gas spring chamber. However, FPICPS has special structure of no mechanical constraints, and the extra degree poses a huge technical challenge for a series of operation processes such as start-up, continuous stable generation, emergency braking, overcoming misfire and unstable operation caused by potential disturbance. This paper concentrates on research on the precise, controllable and instant response characteristics of force of PMLSMS. It was found that the power adjustment controller on PMLSMS side can switch the operating mode under generation and motorized state with negligible delay compared to relay. So technically feasible control variable of force for PMLSMS was chosen and coupled with a force of PMLSMS controller design to implement a series of operation processes by identifying current operating status and different types of system mode, which could be applied in future FPICPS control system designs for different operating modes. The controller performance was seen to be satisfactory for switching between different operating modes without delay and of great significance in improving the robustness of FPICPS and improving the combustion efficiency by MATLAB/SIMULINK. Therefore, it may be beneficial to the application of FPICPS as range extenders in the way that synergize advantages of the free piston engine and functional control logic of the stable operation, promising in hybrid vehicles.

Keywords: free piston internal combustion powertrains system (FPICPS); permanent magnet linear synchronous machine system (PMLSMS); operation mode; power adjustment controller; force of PMLSMS controller; hybrid vehicles.

1. INTRODUCTION

The internal combustion engine (ICE) has become the most important power device indispensable in contemporary society, and its application scope covers almost every corner of social production and life. But with the dramatic increasing in the scale of ICE applications, oil as the main source of fuel for ICE has shown signs of shortage and environmental pollution is getting worse [1]. So hybrid powertrains has received great attention, and the free piston internal combustion powertrains system (FPICPS) has been given more expectations as the most potential hybrid application [2].

The free-piston diesel engine was firstly developed by Pescara [3]. Despite the potential advantages of the FPICPS, the no mechanical constraints have weaknesses leading to low reliability. So it’s necessary to require automatic control of the only moving part motion for the FPICPS. T.A. Johansen et.al proposed a control oriented dynamic analysis, and a novel computer-based piston motion control system [4]. The European Commission-funded Free Piston Energy Converter (FPEC) project developed a model-based controller, which was implemented in a real-time control prototype system and tested on a FPICPS simulation model [5]. ChenZhang et.al regulated the heat release process based on an advanced combustion control, namely the trajectory-based combustion control [6]. FPICPS could make full use of virtual crankshaft to operate continuously, equivalent to utilizing energy in the storage element to regulate the piston to follow a predefined trajectory [7]. A model predictive control approach is proposed to manage system constraints and to control piston position by regulating the fuel injection quantity and external electrical load [8]. Above all, the controller for FPICPS motion control ensures stable and robust operation.

It’s obvious that it has received extensive attention on its control issues since the development of FPICPS, but

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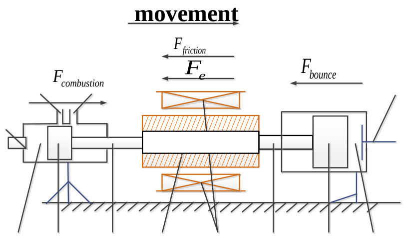
there are few control analysis for the whole motion process of FPICPS, and a reasonable application-oriented whole process control strategy has not been proposed. Starting process is a crucial technical challenge in the FPICPS operation [9], it is necessary to achieve the desirable compression ratio for ignition. Nevertheless, even with the implementation of successful start-up, it is still an urgent problem to successfully switch to generation mode. Huihua Feng et.al recommended a gradual motor/generator switching strategy in order to achieve smooth engine operation under generation [10]. In addition, the emergency braking of FPICPS has not been solved.

So this paper presents a dynamic mathematical model of FPICPS, show feasibility of practical method of controlling force of permanent magnet linear synchronous machine system (PMLSMS), and an application-oriented whole process control dynamic analysis, and a novel computer-based piston motion control system. Further investigation on the engine performance with the closed-loop force of PMLSMS controller was carried out.

2. DYNAMIC MODEL DESCRIPTION OF APPLICATION-ORIENTED WHOLE PROCESS FOR FPICPS

2.1 FPICPS configuration

The designed spark-ignited FPICPS prototype is illustrated in Fig 1. The system is compromised two opposing chamber, respectively a combustion chamber and a gas spring chamber, and a PMLSMS is situated in the middle of two chambers. The only significant moving part of the FPEC consists of connecting rods, pistons and a permanent magnet for primary of PMLSMS, taking responsible for the transformation of mechanical energy and electrical energy. At the side of the moving part, the piston for the combustion chamber and cylinder head form a combustion chamber, including an air inlet, an exhaust vent, an ignition plug and a fuel injector. At the other side of the moving mass opposing the combustion chamber, the piston for the gas spring chamber and cylinder head form a gas spring chamber, including a one-way intake valve, which maintain the required basic pressure of the air spring during operation and adjust flexibly the different basic pressure of the air spring according to target setting to match different fuel characteristics. More information about the prototype development approach can be found in elsewhere [11].



1 Combustion chamber; 2 Piston for the combustion chamber; 3 Connecting rod; 4 Permanent magnet for primary of PMLSMS; 5 Stator secondary coil for PMLSMS; 6 Piston for the gas spring chamber; 7 Gas spring chamber; 8 One-way intake valve; 9 Intake port; 10 Exhaust port;11 Spark plug

Fig 1 Schematic diagram of the FPICPS prototype and kinetics analysis of the moving mass

2.2 Working principle

FPICPS can be divided into five stages, i.e. the starting process, the intermediate process from start-up to stable operation, the stable generating process, the generating process under potential system disturbance and the emergency braking process. The five stages are illustrated in Fig 2. Successfully implemented start-up methods can be divided into electric, pneumatic and hydraulic. The successful application of the conventional ICE is attributed to achieve a cold start-up by the use of an external motor. As a self-contained powertrains system, FPICPS itself contains an electric machine, so one practical method to start the FPICPS is to use the PMLSMS to produce the required force, ensuring self-consistency throughout the operation process. The starting process is divided into overcoming the static friction process and achieving the oscillation start-up process. The starting process is divided into overcoming the static friction process and the static friction process achieving the oscillation start-up process. The starting process is initiated by operating the PMLSMS as a motor, and the motor drives the moving part in order to overcome the static friction. This lays the foundation for the subsequent implementation of the start-up. Then it relays on the PMLSM as an electric motor to complete the gas supply process of the gas spring chamber. Finally, the moving part continually oscillates to a stable stage until it reaches the required conditions for successful ignition. During the starting process, the fuel injection and the ignition control system are all disabled. Once the FPICPS cold start-up process is completed, the PMLSMS will be switched to generator mode and simultaneously the fuel injection and the ignition control system are all enabled. The power regulator will have a slight delay during the switching process, and the vibration of the moving part will slightly fluctuate during the intermediate process. and electricity will be generated during the stable generating process. Full details on the starting process can be found in our previous publications [12]. After that entering the stable generation stage, continuously transferring electric energy to the DC power supply through the PMLSM. However, during the operation of the FPICPS, there always are potential disturbances, and the moving part motion of FPICPS is only determined by the instantaneous sum of the forces acting on the moving part. Force of FPICPS as part of the instantaneous sum of the forces acts as a part of the active regulation to prevent the disturbance from affecting the stability of the FPICPS. In addition to the above process, any powertrains system should have emergency braking performance. The PMLSM relies on the power regulator to switch to the motorized state, acting as a large damping force to brake the FPICPS and push the moving part to a static stable equilibrium point. The PMLSM is operated as a motor during the starting process and the emergency braking process, it outputs a driving force in the direction of the moving part velocity during the starting process and outputs a damping force in the opposite direction of the moving part velocity during the emergency braking process. While during the intermediate process, the stable generating process and the generating process under potential system disturbance, it will be switched to a generator and act as a resistance force afterward. Details of the specific movement process needs to be further investigated by MATLAB/SIMULINK.

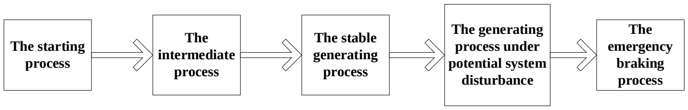


Fig 2 Working processes of the FPICPS**.**

2.3 General kinetic dynamic equation description

We established a reference coordinate system, taking the position of the top dead center (TDC) of the piston for the combustion chamber as the coordinate origin and the right side as the positive direction of the coordinate system. The position of TDC is located at a position from where the effective cylinder length of the combustion chamber is lower than the upper theoretical compression ratio by one. The state of force acting on the moving part is shown in Fig 1.

A dynamic equation of the moving mass can be expressed as:

$$m\ddot{x} = \vec{F}_{combustion} + \vec{F}_{bounce} + \vec{F}_{friction} + \vec{F}_{e} \qquad (1)$$

3. ADEQUACY VERIFICATION FOR METHOD OF A VALIDATED FAST-RESPONSE FORCE CONTROL MODEL BASED ON PMLSMS MATHEMATICAL MODEL

3.1 Mathematical control model of PMLSMS

PMLSMS could play the role of an electric motor and the role of a generator on the FPICPS. This is all attribute to the feasible technical scheme that the bidirectional power adjustment controller can smoothly switch the energy flow direction. So the bidirectional power regulator plays a vital role in the self-consistency of the FPICPS, is shown in Fig 5.

The stator secondary coils of PMLSMS are connected to the bidirectional power adjustment controller which can realize flexible conversion of three-phase alternating current (AC) and direct current (DC). The reciprocating motion of the moving part cuts the secondary windings of the stator, causing the three-phase secondary windings of the stator to generate Back EMF. And the correct matching of the back electromotive force value and the DC power supply constant voltage value in the power generation and electric state lays the foundation for reasonable and error-free transmission of the six-way modulation pulse width control signal. Back EMF is a function of velocity. So the Back EMF generated in the coils are expressed as:

$$\begin{aligned} e_a &= K_{EMF} \cdot \dot{x} \cdot \cos\left(\pi \cdot x / \tau\right) \\ e_b &= K_{EMF} \cdot \dot{x} \cdot \cos\left(\pi \cdot x / \tau - \frac{2 \cdot \pi}{3}\right) \\ e_c &= K_{EMF} \cdot \dot{x} \cdot \cos\left(\pi \cdot x / \tau - \frac{4 \cdot \pi}{3}\right) \end{aligned} \qquad (2)$$

Our research team chose Linear Motor Series P10-70x240 as FPICPS of linear machine. Its characteristics parameters are listed in table1.

TABLE I
Characteristics parameter of PMLSMS

Parameter	***Unit***	***Value***
Outer diameter of the permanent magnet	mm	70
Stator diameter	mm	340
Force constant K_{F_e}	N/Arms	81.6
Back EMF constant (ph-ph) K_{EMF}	V/(m/s)	69
Resistance(ph-ph)	Ohm	8.01
Inductance (ph-ph)	mH	11.6
Stator length	mm	340
Magnetic period (el. cycle) τ	mm	40

The electromagnetic force and dynamics equation are presented as follows:

$$F_e = \frac{1.5p\pi}{\tau}\left(\psi_d i_q - \psi_q i_d\right) = \frac{1.5p\pi}{\tau}\left(\psi_f i_q - \left(L_d - L_q\right) i_d i_q\right) \tag{3}$$

where p is number of pole pairs, $p = floor(\frac{StatorLength}{\tau})$, τ is pole pitch of PMLSMS, ψ_f is permanent magnet flux linkage, which foreign manufacturers do not provide clearly. In order to perform characteristic force of PMLSMS, we carried out a measurement work using a piezoelectric force sensor under the non- reciprocating state and the power adjustment controller regulate the d-axis current Id set to 0 by PWM control signals. As can be seen from Fig 3. , the characteristic of force to approximate to linear, which confirms that the linear scaling coefficient is close to the force constant in the characteristics parameter of PMLSMS provided by the manufacturer. But we failed to measure directly the force of PMLSMS during the generating operation. Therefore, we believed that the force of PMLSMS is proportional to the q-axis current Iq regardless of the mode of the operation, providing preconditions for rationally establishing the dynamic model of the moving part. Iq is obtained by transforming the clark and park coordinates of the three-phase current.

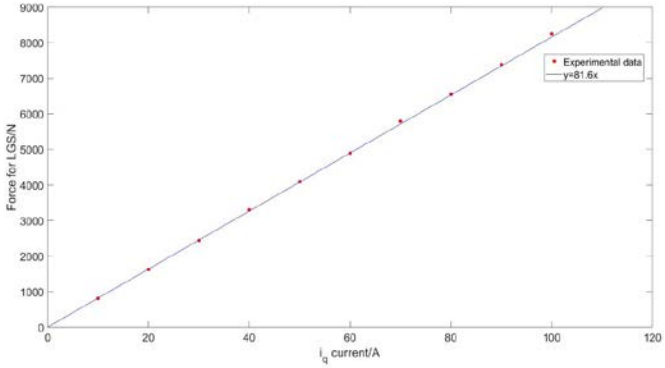


Fig 3 Force-current characteristic of the PMLSMS

3.2 Force of PMLSMS controller design for the whole process

Dynamical characterization of the moving part based on the above, it is found that FPICPS can be simplified to a vibration system because the movement of the moving part is determined by the joint force of the four forces acting on it. At the start of FPICPS, the static friction is relatively large and the PMLSMS is in a cold state, so force of PMLSMS rises slowly until the moving part moves. Since FPICPS is an extremely asymmetric system, the static balance point is not easy to find and the air leakage in the cylinder is more serious. Therefore, we would set the moving part after the position where the exhaust port is opened, and then the gas spring chamber pressure is relieved to the atmospheric pressure. At this point, the FPICPS can maintain a static balance. When the moving part overcomes the static friction force, according to the principle of the vibration system, a constant force acting on mover is controlled in accordance with the speed [13].

4. SIMULATION

The simulation results of FPICPS oriented whole process are shown in Fig 4. Since the FPICPS is an asymmetrical system, when the last time the moving part stops moving, we would try to drag it back to the position where the exhaust port is open by PMLSMS, making it stand still. Then depressurize the gas spring chamber. So the moving part is stationary near 0.048m, the position where after the exhaust port is opened. As we can see, the moving part stops at 0.048m. Since the static friction force is greater than the dynamic friction force, the given force of PMLSMS output rises slowly until the maximum static friction is overcome, and then an excitation force of PMLSMS based on the principle of the oscillating system, whose size is constant and in the same direction as velocity. During this state, the moving part can be simplified to forced vibration system, because the motion state of the moving part is determined by the instantaneous force acting on it, of which cylinder pressure is related to displacement, friction and excitation force of PMLSMS is related to velocity. So it is linearized to the same form with the single degree-of-freedom forced vibration system with viscous damping. Since the excitation force is a positive and negative alternating rectangular wave, the Fourier transform can be performed and then it is processed into a frequency-dependent sinusoidal excitation force. When this small damped oscillating system is consistent with the excitation frequency, it can enter a stable oscillation state.

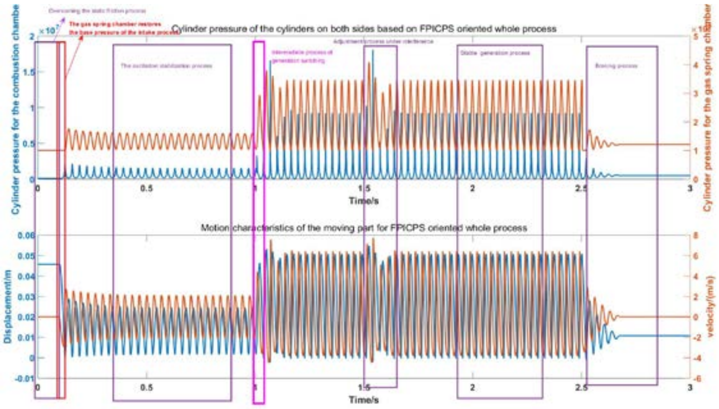


Fig 4 Dynamic characteristics of the moving part based on FPICPS oriented-whole-process

However, one of the cycles is the gas spring chamber intake process, which requires a known force to ensure a one-time return to the base pressure, so this process needs to be constantly tried to match a reasonable constant force to avoid early convergence into the stable phase, is shown in Fig 5. The dark area in Fig 5. confirms that it has entered the stabilization phase. So we chose exciting force greater than 250N. Then continue to pay attention to the intermediate process in Fig 4., it's found that some slight fluctuations in the intermediate process, but the time is not long, all attribute to the bidirectional power adjustment controller. An unconstrained motion system is very susceptible to external interference. We used 20% less energy fluctuations in the two cycles as external disturbances. At this time, the energy output is quickly filled by the bidirectional power adjustment controller according to the target compression ratio of the combustion chamber for 10, ensuring restabilizing between the top and bottom dead points. It can be seen from Fig 4 that the four cycles can successfully filter out the influence of fluctuations, playing the role of the conventional ICE flywheel. In order to In order to prove the self-consistency of the integrated FPICPS as a powertrains system, we immediately simulated the braking conditions, quickly shut down the fuel injection and ignition system, ensuring no external energy input, and simultaneously controlled force of FPICPS opposite to the velocity direction, constantly consuming kinetic energy. And the moving part quickly stops in 4 cycles.

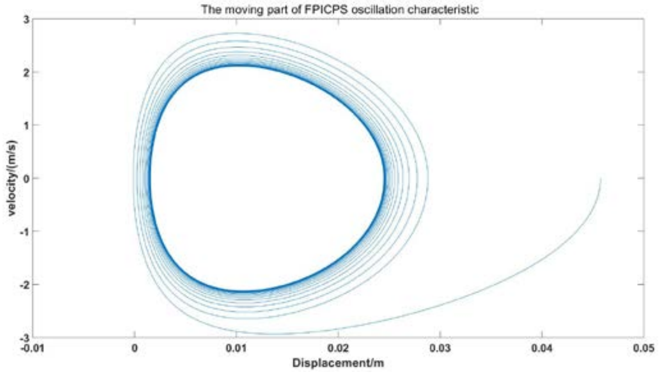


Fig 5 The moving part of FPICPS oscillation characteristic

The FPICPS controller designed in this paper has the function of operation mode identification and adjust energy output according to energy state. As the only significance moving part undertakes responsibility for the conversion of electrical energy and mechanical energy, adjusting the energy state depends on the interaction force between the magnetic fields, that is, force of PMLSMS, is shown in Fig 6. The target motor force is constant under the electric state, and is continuously adjusted according to the state of the compression ratio during generation. However, the actual force of PMLSMS does not follow the target, and there will be fluctuations at high velocity. These are derived from the response characteristics of electrical components in the PMLSMS.

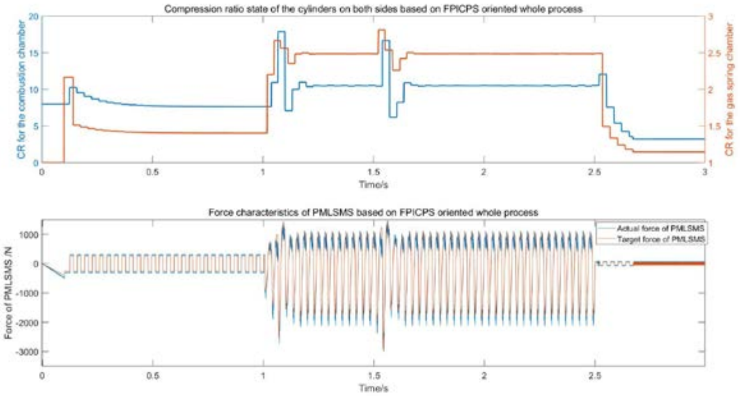


Fig 6 Controller effects based on FPICPS oriented-whole-process

Hence, by controlling force of PMLSM applied to the moving part of FPICPS, the piston stroke could be adjusted for power management, is shown in Fig 7. In transient generation operation of the moving part of FPICPS, the power may either exceed or lag behind load demand. But in order to reflect the energy regulation process, we chose a DC power supply that can accept input in any state. If the PMLSMS is operating in an electric state, the bidirectional power regulator regulates the energy direction, and the energy storage device can also operate under power supply conditions. This successfully helps us to prove that as long as a reasonable power regulation circuit appied to power battery is designed, the load can follow the motion of the moving part. However, when selecting the DC power supply, it is necessary to pay attention to the contradiction between the DC regulated voltage and the back electromotive force. In Fig 7., we can see that the DC side effective work is positive, and then becomes negative, in the whole operation of the FPICPS. This confirms that the initial system movement requires external energy supplement, but the final system outputs energy to the energy storage unit which is in a state of charge, which fully proves the self-consistency of the FPICPS as a powertrains system. In addition, it is found that the ripple on the side of the energy storage is more serious, which puts forward strict requirements on the design of the electrical circuit. It is found from the curve of the power characteristic that the instantaneous power calculated by the DC side is fluctuating, and the power converted by force of PMLSMS is relatively stable, because this power is obtained by the time division of the total work obtained by the rectangular division method, that is, the average power. This is the reason that the power of PMLSM is declining during braking process. In addition, we found that the instantaneous power on the DC power supply side still fluctuates during braking process. In fact, this is the current blocking state.

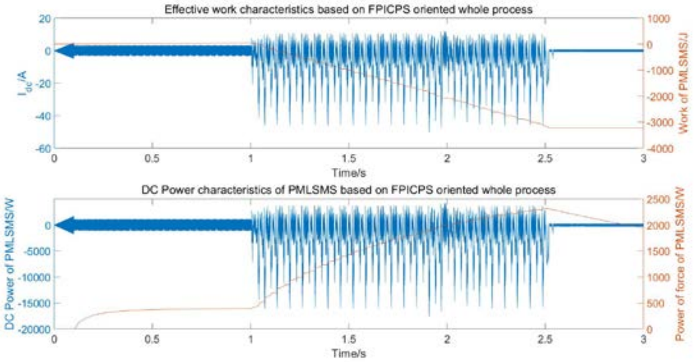


Fig 7 Energy flow characteristics based on FPICPS oriented-whole-process

The FPICPS is a strong electromechanical coupling device, and the thermal energy of the fuel is converted into mechanical energy, then is converted into electrical energy. The mechanical efficiency in this process is about 35%, and the electrical energy conversion efficiency is about 81%. The electric energy conversion efficiency of PMLSM is inferior to that of rotating electric machines, but it is applied in internal combustion engines, which improves the thermal efficiency of two-stroke internal combustion engines and demonstrates the advantages of variable compression ratio and fuel compatibility.

5. CONCLUSIONS

This paper described mathematical model and the simulation results of the FPICPS during the starting process, the intermediate process from start-up to stable operation, the stable generating process, the generating process under potential system disturbance and the emergency braking process, including transient response of the transformation process. In addition, a reasonable and detailed description of the flow state of electrical energy was made. The results indicate that:

(1)Rationality of PMLSMS as a conversion element for energy flow.

(2)Proof of the bidirectional characteristics for the power adjustment controller.

(3) Rationality of force of PMLSMS controller design for the whole process.

(4)A self-consistent proof of FPICPS as the powertrains system.

(5)The advantages of being a range extender application and the rationality of its application to hybrid vehicles.

REFERENCE

[1] Jankowski, A., Kowalski, M., Environmental Pollution Caused by a Direct Injection Engine, Journal of KONES, Vol. 22, No. 4, pp. 113-138, Warsaw 2015.

[2] Hansson J , Leksell M . Performance of a Series Hybrid Electric Vehicle with a Free-Piston Energy Converter[J]. IEEE, 2006:108-113.

[3] Mikalsen R, Roskilly AP. A review of free-piston engine history and applications. Appl Therm Eng 2007;27(14):2339–52.

[4] Johansen T A, Egeland O, Johannessen E A, et al. Free-piston diesel engine dynamics and control[C]// American Control Conference, 2001. Proceedings of the 2001. IEEE, 2001.

[5] Hansson J. Analysis and control of a hybrid vehicle powered by free-piston energy converter. Phd Dissertation; 2006.

[6] Zhang C, Sun Z. Trajectory-based combustion control for renewable fuels in free piston engines[J]. Applied Energy, 2017, 187:72-83.

[7] Li K, Zhang C, Sun Z. Transient Control of a Hydraulic Free Piston Engine[C]// American Control Conference. IEEE, 2013.

[8] Gong X, Zaseck K, Kolmanovsky I, et al. Modeling and predictive control of Free Piston Engine Generator[J]. Proceedings of the American Control Conference, 2015, 2015:4735-4740.

[9] Effect of closed-loop controlled resonance based mechanism to start free piston engine generator: Simulation and test results[J]. Applied Energy, 2016, 164:532-539.

[10]Feng H , Guo C , Jia B , et al. Research on the intermediate process of a free-piston linear generator from cold start-up to stable operation: Numerical model and experimental results[J]. Energy Conversion and Management, 2016, 122:153-164.

[11]H. Kosaka et al., Development of free piston engine linear generator system part 1-investigation of fundamental characteristics, SAE Technical Paper, 2014.

[12]Jia Boru, Tian Guohong, Feng Huihua, et al. An experimental investigation into the starting process of free-piston engine generator. Appl Energy 2015.

[13]Research on Variable-Load Control for Stable Operation of Free-Piston Engine Generator [D]. Beijing Institute of Technology, 2017.