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An experimental investigation into the starting process of free-piston engine generator ☆

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HIGHLIGHTS

- A prototype free-piston engine generator is developed and tested.
- The in-cylinder mixture was ignited successfully with the proposed control strategy.
- Two practical input parameters are selected for the future motor switching control.
- Three possible reasons of misfire are analysed.

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ABSTRACT

This paper presents an experimental investigation of the starting process of a prototype free piston engine generator (FPEG). Experimental test results show that during the motoring stage, the peak in-cylinder pressure and compression ratio increase in a non-linear manner and trend to reach a stable state after a number of cycles. The motoring force is suggested to be within a reasonable range. With a fixed starting force of 125 N, the in-cylinder air fuel mixture was successfully ignited at the fourth cycle with a compression ratio of over 9:1. The peak in-cylinder pressure for the first combustion cycle reached over 40 bar. The piston ran at high and relatively constant speed at the middle portion of the stroke. The peak piston velocity increases significantly to around 4.0 m/s. Cycle-to-cycle variation of the piston movement was significant and the engine misfired frequently. During the misfire cycles, the peak piston velocity decreased to nearly 2.5 m/s; and the piston dynamics were similar to the motoring process. Based on these, discussion on misfire and further stable running control, as well as the linear electric machine mode switch were presented.

1. Introduction

Free-piston engine generator (FPEG) is a novel type of energy conversion device that integrates a linear combustion engine and a linear electric machine [1]. Combustion in the chamber drives the piston reciprocates in a nearly resonant way and the linear electric machine converts part of the mover's kinetic energy to electrical energy. The effective efficiency is estimated to be up to 46% (including friction and compressor losses) at a power level of 23 kW and shows promising results with respect to engine performance and emissions [2]. Since the FPEG was first proposed, despite the interests it has attracted from all over the world [3–6], there has not been any stably operating prototype reported by now.

The FPEs were first proposed around 1930, and during 1930 to 1960 they were mainly used as air compressors and gas generators as they provided advantages over conventional combustion engines and gas turbines at that time [7]. In recent years, modern applications of the free-piston concept have been proposed for the generation of electric and hydraulic power, typically in hybrid electric vehicles [8–9]. Different prototype designs have been reported using the FPEG concept. The majority of these were, however, not commercially successful. This section gives an overview of known FPEG development, with an emphasis on reports where prototype performance data have been reported.

Researchers at West Virginia University described the development of a spark-ignited (SI) dual piston FPEG [10]. This 36.5 mm bore size prototype was reported to have achieved 316 W power output at 23.1 Hz, with a 50 mm maximum stroke. High

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cycle-to-cycle variations were observed particularly at low loads [11], which indicated an unstable operation. A two stroke compression ignition (CI) version linear engine prototype was also developed [11]. This CI engine had a similar mechanical arrangement to the SI prototype. The linear alternator interposed with the linear engine also operated as a starting device. In order to aid the cold start of the engine, each cylinder was equipped with a glow plug [12].

The research team in Sandia National Laboratories presented the design of a dual cylinder FPEG. The engine employed a homogeneous charge compression ignition (HCCI) and was aimed to operate on a variety of hydrogen-containing fuels. Test results from a compression–expansion machine showed nearly constant volume combustion with hydrogen, bio-gas, and ammonia at the equivalence ratio of approximately 0.3. The target efficiency was 50% overall considering 56% engine thermal efficiency and 96% generator efficiency [13]. In 2008, the dual cylinder free-piston engine configuration was changed into an opposed piston type, which was adopted to utilize the self-balance effect [14].

A European Commission-funded Free Piston Energy Converter (FPEC) project researched the subject of FPEG aimed at the development of an efficient new technology suitable for vehicle propulsion, auxiliary power units and distributed power generation since 2002 [2]. The prototype ran on diesel fuel, and was used primarily for testing in a test cell for validation of the specific FPEG issues. The converter was equipped with fuel injectors, pneumatic operated valves, cylinder pressure sensors, and translator displacement sensors. The combustion system is a Direct Injection, 2-stroke, two cylinder systems with electrical controlled valves and scavenging ports operating in HCCI mode on diesel fuel [15]. However, there has not been many test data reported by now.

The approach by the Beijing Institute of Technology used a loop scavenged, carburetted free-piston, double-ended cylinder arrangement with a linear alternator; the bore of the engine was 34 mm, and the effective stroke was 20 mm [16]. Experiments results showed that the engine misfired every one or two cycles [16]. For the compression ignition FPEG prototype developed by the same group, the cylinder bore and stroke were enlarged to 62 mm and 86 mm respectively. If a compression ratio of 15 was required at the end of the compression stroke to enable self-ignition, the corresponding in-cylinder pressure force was over 11 kN, which made it practically impossible to start the engine at one compression stroke without an largely oversized electric linear machine [17].

Pempek Systems Pty. Ltd., an Australian company, was one of the research leaders in this area. Their conceptual free piston engine generator design aims the power source of a high performance hybrid vehicle which has a top speed of 160 km/h and 0–100 km/h acceleration of only 5.4 s. This vehicle will also be equipped with a brake recovery system. They conceptually designed a 25 kW free piston engine generator which has 50% engine thermal efficiency and over 93% of the generator efficiency [18].

The German Aerospace Centre (DLR) developed an FPEG prototype [19–22]. It consisted of three main subsystems: an internal combustion engine (ICE) converting chemical energy into kinetic energy, a linear generator (LG) converting kinetic energy into electric energy and a gas spring (GS) storing energy and inverting the piston movement. At 21 Hz, a power output of roughly 10 kW had been measured. Increasing the frequency up to 50 Hz should lead to a power output of 25 kW of a single piston FPEG system [19,20].

The FPEG prototype developed by Toyota Central R&D Labs Inc. was thin and compact [23,24]. The developed FPEG consisted of a two-stroke combustion chamber, a linear generator, and a gas spring chamber. A power generation experiment was carried out, and the results demonstrated that the prototype operated stably for a long period of time, despite of the abnormal combustion during the test [24]. The unique piston motion and its effect on combustion and power generation in the FPEG prototype were experimentally analysed [23].

FPEG can be divided into three categories according to piston/cylinder configuration: single piston, dual piston and opposed piston [25]. The basic operation principles are equal for each concept; differences between the concepts are the number of combustion chambers and compression stroke realization [25]. There has been successful implementation of the single piston type, coupled with a gas spring chamber [20,24]. However, despite the problems being reported, the dual piston configuration remains the most popular layout due to the following advantages over single piston and opposed piston configurations:

1. The only moving part is a linear magnet mover coupled with pistons at each end and placed between two opposing combustion chambers. This allows a simple and more compact device with higher power to weight ratio.
2. It eliminates the need for a rebound device, as the combustion force drives the piston assembly to overcome the compression pressure in the other cylinder.

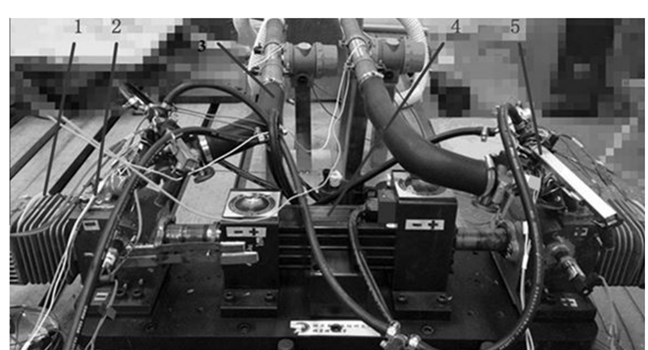
Because of the potential advantages above, the dual piston type FPEG is adopted in the prototype reported in this paper. A newly designed FPEG prototype has been built to validate the feasibility of the technical scheme of dual piston FPEG. This paper describes the configuration of the newly designed system as well as the fundamental test results. Based on these, discussion on misfire and further stable running control, as well as the linear electric machine mode switch were presented.

2. FPEG prototype

2.1. Prototype specification

The FPEG prototype is demonstrated in Fig. 1. This prototype is a dual piston, two-stroke, spark-ignited, uniflow scavenging engine. It is integrated with a dedicated bench of steel plates, constructed to reduce the vibrations during testing. The specifications of the prototype are summarised in Table 1. More details about the prototype have been presented in our previous paper [26,27], and the carburettor has been replaced by a port fuel injection (PFI) system for a more precise air fuel ratio control.

The PFI system with integrated electric fuel pump and fuel filter conveys the required amount of fuel from the tank to the injectors at a constant pressure. The fuel is injected into the intake manifold



1 Cylinder; 2 Scavenging pump; 3 Air intake manifold;
4 Linear electric machine; 5 Fuel injection system

Fig. 1. The prototype of free-piston engine generator.