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Research on the engine combustion characteristics of a free-piston diesel engine linear generator

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ABSTRACT

The free-piston diesel engine linear generator (FPDLG) shows a great deal of merits due to its unique structure and operation characteristics. For this reason, most researchers mainly investigated on the FPDLG characteristics. However, there has not been any report on the engine operation characteristics. So this paper focuses on the engine operation characteristics of the FPDLG during the generating process. According to the experimental results, it is found that the output power of the designed prototype can reach 5.16 kW with the thermal efficiency of up to 38.5%. Experimental test results are obtained and processed both in time and crank-angle coordinates. Compared to the conventional diesel engines, the ignition delay of the FPDLG is shorter and the premix combustion quality is better. By analyzing the operating cyclical variations of the prototype, the coefficient of variation (COV) of the compression ratio is found to be higher than 27%. While the peak in-cylinder gas pressure and pressure rising ratio cyclical variation can maintain a stable operation (similar to the conventional diesel engines), higher COVs of the compression ratio can always complicates the engine combustion. Therefore proper control strategies are necessary for the FPDLG.

1. Introduction

Under the background of the requirements for low fuel consumption and stringent emissions standards in the whole world, researchers not only focus on the technological improvements and performance optimizations for the current energy conversion device, but also explore new efficient power devices. Free-piston engine linear generator (FPLG) is a typical representative of the new efficient power devices [1–5]. The FPLG combines free-piston engines and a linear generator. The general working principle is that the high-temperature and high-pressure gas is produced after the combustion process in the engine cylinder, which pushes the piston assembly and the moving magnet of the generator reciprocate, then the generator converts parts of the kinetic energy of the moving magnet into electricity [2–4]. Therefore, the FPLG offer the potential to generate and deliver power without the need to convert linear piston motion to rotary crankshaft motion. This concept is proposed in the 1920s by Pescara [6,7]. Its potential advantages include low frictional loss [7], multi-fuel possibilities [8], low NOx emission [9,10], which all have been reported over the conventional internal combustion engines (ICEs). However, there are some disadvantages of the FPDLG, compared with the conventional ICEs, such as the prototype is unable to operate smoothly during the generating process because its special dead center movements are lack of mechanical restraint, the working process of the FPLDG is very sensitive to the combustion fluctuations occurring in the engine. Although the FPDLG has these disadvantages, it could operation stably and generation electric power if the combustion characteristics of the engine are clearly and the suitable control strategies are applied. Then the FPDLG, as a power source, is used to the vehicles and the power-plants in the world.

According to the combustion mode, the FPLG can be mainly divided into two categories: compression ignition engines FPLG (such as free-piston diesel engine linear generator, FPDLG) and spark ignition engines FPLG (such as gasoline FPLG). Most of research institutes such as West Virginia University [11,12], Toyota Central R&D Labs [13,14], they focus on the gasoline FPLG and the diesel FPLG. And then multiple FPLG prototypes are developed by these institutes. As the experimental data shown, the thermal efficiency was estimated to be up to 46% (including friction and compressor losses) at the power of 23 kW [15,16]. Although the FPDLG has high thermal efficiency which is more suitable for high-power machinery, it is more difficult to run continuously and stably. Therefore, researchers also make great efforts to solve the problem of the starting process and carry out theoretical

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Nomenclature

COV	coefficients of variation	m	the combustion quality factor
DAQ	data acquisition	n	the number of the stages of calculating
EFS	electronic fuel injection system	n_i	combustion quality factor of the i stage
EMF	back electromotive force	p	means the premix combustion process
FPDLG	free-piston diesel engine linear generator	Q	the fuel mass fraction
FPE	free-piston engine	R	the equivalent length of crank
FPLG	free-piston engine linear generator	t	time
HCCI	homogeneous charge compression ignition	t_{0i}	starting timing of heat release
ICEs	internal combustion engines	v	the piston velocity
SNL	Sandia National Laboratories	x	the piston displacement
TDC	top dead center	X_1	the premix combustion percentage
C_i	combustion coefficient of the i stage of the Wiebe function	X_2	the diffusive combustion percentage
d	means the diffusive combustion process	ω	the equivalent speed
dX/dt	rate of combustion heat release by the Wiebe function fitting	θ	the equivalent crank-angle
$(dp/dt)_{peak}$	the peak pressure rising ratio	λ	the equivalent ratio of crank-to-rod
		Δt_{0i}	the combustion duration of the i stage
		β_i	combustion quality percentage of the i stage

analysis.

In the early stage, Clark and Atkinson [17] proposed a numerical model of the FPLG, which contained a dynamic model, a thermodynamic model, a scavenging process model, a combustion process model and a heat transfer model. To obtain test results, they improved the common-rail injection system of the fuel supply system [17]. Finally, it was found that stable operating upon cranking was the most difficult to overcome in the compression ignition case [12].

Based on the conclusions, there are four main research directions for compression ignition free-piston engines: hydraulic free piston engine, control strategies, application of HCCI combustion mode, prototype designation and experimental discussion. For the first direction,

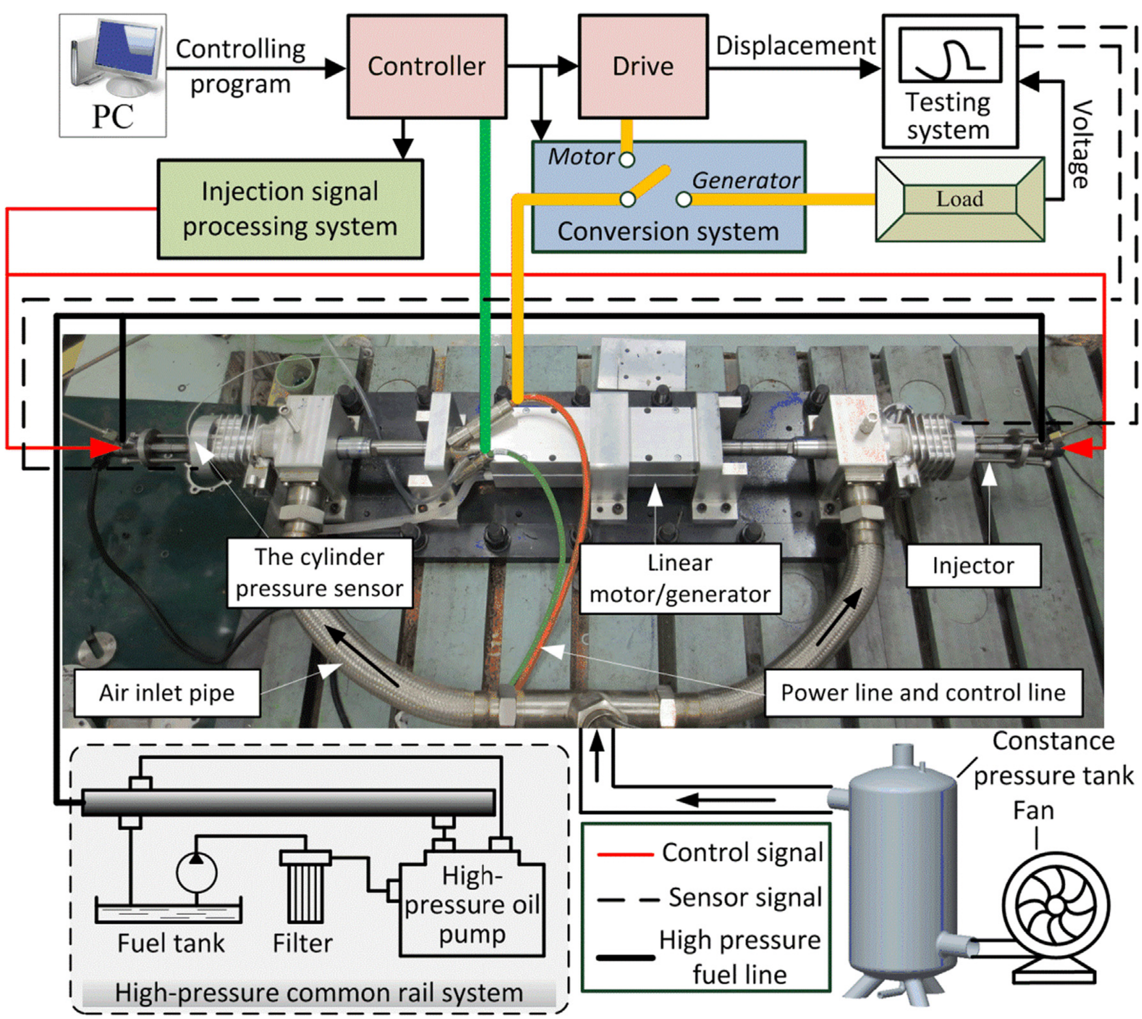

Fig. 1. The FPDLG prototype system and test rig.