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Design and simulation of a two- or four-stroke free-piston engine generator for range extender applications

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ABSTRACT

Free-piston engines (FPEs) are known to have a greater thermal efficiency (40–50%) than an equivalent and more conventional four-stroke reciprocating engines (30–40%). Modern FPEs are proposed for the generation of electric and hydraulic power, with a potential application in hybrid electric vehicles. The numerous FPE configurations considered to date have almost exclusively operated using a two-stroke thermodynamic cycle to improve the thermal efficiency, however it is well known that the application of two-stoke cycles can be limited by noise and exhaust gas emissions constraints. In this article, a numerical model is used to investigate the techno-feasibility of operating Newcastle University's FPE prototype using a two- or four-stroke thermodynamic cycle. If operated as a four-stroke cycle, the linear generator must be used as both a motor and a generator resulting in a more irregular piston motion compared to corresponding operating in a two-stroke cycle. In four-stroke cycles, almost half the indicated power is consumed in overcoming the pumping losses of the motoring process. Whilst the heat release process is appears to be closer to a constant volume process when operated on two-stroke engine cycle, the peak cylinder pressure and compression ratio proved lower. In addition, a narrower power range is reported for a four-stroke cycle despite a corresponding higher thermal efficiency.

1. Introduction

The free-piston engine (FPE) is a linear engine in which the requirement for a crankshaft system is eliminated and the piston assembly has a free and linear motion [1]. After initial investigations and development of free-piston related technologies during the early to mid-20th century, recent advances in control and real-time actuation systems have enabled the technology to become a viable alternative to their reciprocating equivalents, and research is now being carried out by a number of groups worldwide [2–7]. Modern applications of the FPE concept have been proposed for a new generation of electric and hydraulic power solutions, typically in hybrid electric vehicles. A more comprehensive background introduction on the history and categorization of the FPEs has been presented by Mikalsen and Roskilly [8]. In this work, several FPE concepts are reported and they can be categorized according to the following categories: fuel type, combustion mode, load type, cylinder number, or piston type, engine size, etc.

During the operation of FPEs, combustion takes place in the internal combustion chamber, and the high pressure exhaust gas pushes the piston assembly backwards. Due to the linear characteristic, a FPE requires a linear load to convert this movement into electrical energy for the usage of the target application. Reported load devices for the FPEs include air compressors, electric generators and hydraulic pumps [9–13].

In this paper, the FPE is connected with a linear electric generator (free-piston engine generator, FPEG) and is investigated for application within electric and hybrid electric automotive vehicle power systems. Reported FPEG prototypes are classified into four concepts based on the number of combustion chambers and the engine operating cycle. These four concepts are single-piston two-stroke engines, single-piston four-stroke engines, dual-piston two-stroke engines, and opposed-piston two-stroke engines. The basic working principles are similar for each concept: combustion occurs in the closed chamber, the exhaust gas expands causing the piston to move backwards, the linear generator utilises this energy to convert the mechanical work on the piston into electricity.

There have been successful implementations of single piston FPEG concept, coupled with a gas spring rebound chamber. The German Aerospace Centre (DLR) developed a prototype [14–17]

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Nomenclature

A	piston surface area (m^2)	m	moving mass of the piston assembly (kg)
A_d	reference area of the flow (m^2)	m_{air}	mass of gas in the cylinder (kg)
B	cylinder bore (m)	m_{air0}	initial gas mass in the cylinder (kg)
c	load constant of the generator (–)	$\dot{m}_{flow}$	mass flow rate through a poppet valve (kg s^{-1})
C_d	discharge coefficient (–)	m_i	air mass flows into or out of the cylinder (kg)
D_v	valve diameter (m)	m_{in}	inlet air–fuel mass through the intake valve (kg)
F_{const}	thrust force of the mover (N)	m_{out}	burnt gas mass through the exhaust valve (kg)
F_e	load force of the linear electric generator (N)	m_l	gas leakage mass through the piston rings (kg)
F_f	mechanical friction force (N)	p_d	downstream air pressure (pa)
F_l	gas forces from the left cylinder (N)	p_u	upstream air pressure (pa)
F_r	gas forces from the right cylinder (N)	T_u	temperature of the inlet gas (K)
h_i	specific enthalpy of the mass flow (J kg^{-1})	U	internal energy of the in-cylinder gas (J)
Q_c	heat released from combustion process (J)	V	cylinder volume (m^3)
Q_{ht}	heat transferred to cylinder wall (J)	x	mover's displacement (m)
L_v	valve lift (m)		

which operated at 21 Hz, realising a power (electric) output of approximately 10 kW. Increasing the frequency up to 50 Hz should lead to a power output of 25 kW of a single piston FPEG system [16,17]. A prototype was also developed by Toyota Central R&D Labs Inc., these researchers reported stable operation for extended periods of time albeit with abnormal combustion (pre-ignition) [18,19].

A single-piston four-stroke FPEG prototype was developed by Xu and Chang [20]. The engine was designed and manufactured based around an existing reciprocating four-stroke engine, and was modified to operate as four-stroke FPE connected to a linear electric machine. In this prototype, a mechanical spring was connected to the piston assembly, operating as a "kickback" device to return the piston during the non-power stroke. A reversible energy storage device was integrated to accumulate the energy from the electric power output. Stable running of the prototype was reported, and a 2.2 kW average output (electric) power with a generating efficiency of 32% was reported [20].

The dual-piston configuration is the most common layout due to the elimination of the rebound device [21–25]. The only significant moving part is the mover of the generator coupled with piston at each end, and located in the middle of two opposing combustion chambers. Combustion occurs alternatively, the expanding exhaust gases drive the piston thus overcoming the compression pressure force imposed by second cylinder. The effective efficiency of dual piston FPEG was estimated to be up to 46% (including friction and compressor losses) at a power level of 23 kW [26]. Successful engine starting and ignition processes by the linear electric machine with mechanical resonance have also been reported [27,28].

The opposed-piston FPEG concept consists of two pistons with a common combustion chamber. Each piston is connected to a rebound device and a linear electric generator is coupled to both pistons. The main advantage of this configuration lies in the balanced and vibration-free characteristics [8]. However, synchronizing the opposed free pistons is a significant technical challenge [8]. Johnson et al. proposed a piston synchronization method through (a) passive coupling of linear alternators and (b) using a common load for both stators, thus providing a stabilizing force [29].

This paper presents the design and simulation of a dual-piston spark-ignited FPEG suitable for operation using either a two-stroke or four-stroke thermodynamic cycle, and investigates the general engine performance of the system operated. For the first time, this work demonstrates the potential advantages and disadvantages of the FPEG using different thermodynamic gas-exchange cycles.

2. Working principle description

2.1. Prototype schematic configuration

The purpose of this paper is to design a FPEG suitable for operation using either a two-stroke or four-stroke cycles and to quantify their corresponding performance characteristics. The conceptual design of a dual-piston FPEG is based on the patent by Mikalsen and Roskilly [30], and is illustrated in Fig. 1. The prototype is comprised of two opposing internal combustion cylinders, each with its corresponding combustion chamber, set of poppet valves (5 & 6), spark electrode (1) and piston (2). A linear electric machine (8) is located between the opposed cylinders/pistons. The two pistons are connected using the mover (7) of the linear electric machine, this component is the only significant moving part of the system.

In general terms, the starting process is initiated by operating the linear electric machine as a motor, however once the system is operating at steady-state the machine will be switched to "generator" mode. Switching between motor/generator is managed using an active controller supports which will drive or brake the piston assembly in real time to ensure a stable operation and meet the target of compression ratio and power output. Without rotational motion and corresponding camshaft timing system, the engine employs an independent intake and exhaust valve systems.

The majority of reported dual-piston FPEG configurations, such as that presented in Fig. 1, use a conventional two-stroke thermodynamic cycle. The power stroke of the two-stroke cycle is controlled to take place alternately in each cylinder, and it drives the compression stroke of the other cylinder. However, the hardware employed in this configuration can be extended to operate four-stroke thermodynamic cycle by simply modifying its control parameters, *i.e.* fuel flow rates, spark timing, intake/exhaust valve timing and working mode of the linear electric machine. Hence, by performing the intake and compression strokes separately from the expansion and exhaust strokes, the FPEG can operate on a four-stroke cycle [30].

2.2. Two-stroke and for-stroke control mode

The two-stroke thermodynamic cycle operation in each cylinder results in a steady but reciprocating motion of the piston assembly. The power stroke takes place alternately by each cylinder and the linear electric machine is operated as a generator throughout the generating process. The two strokes are: (1) Compression stroke: Initiated when both the intake valve and exhaust valve are closed