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A review of free-piston linear engines

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HIGHLIGHTS

- FPLEs are classified in different designs.
- Piston dynamics, combustion, and electric power generation of FPLEs are reviewed.
- Experimental systems of FPLEs are reviewed.
- Application of FPLEs for hybrid electric vehicles is discussed.

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ABSTRACT

Unlike conventional internal combustion engines, a free-piston linear engine has no a crankshaft, and thus the pistons move freely in the cylinder. This allows a free-piston linear engine to easily adjust the compression ratio and optimize the combustion process. Free-piston linear engines include two main parts: a free-piston engine and a linear alternator. The free-piston engine is classified into three main types: single piston, dual piston, and opposed piston. The linear alternator is generally categorized as flat-type or tubular-type. Free-piston linear engines can operate with multi-fuel and HCCI combustion because of their variable compression ratios. Furthermore, they are used to generate the electric power applied in hybrid electric vehicles. To promote understanding of the unique features of free-piston linear engines, this paper presents a review of their different designs and operating characteristics. We also discuss the varied experimental systems and applications of free-piston linear engines.

Contents

Abbreviations: FPLE, free piston linear engine; SI, spark ignition; CI, compression ignition; HCCI, homogenous charge compression ignition; CFD, computational fluid dynamics; TDC, top dead center; P–V, pressure–volume; HC, hydrocarbon; NO_x, oxides of nitrogen; DAQ, data acquisition; NI, national instrument; PXI, PCI (peripheral component interconnect) extensions for instrumentation; CNG, compressed natural gas; HEVs, hybrid electric vehicles.

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1. Introduction

In general, in an internal combustion engine with a crankshaft mechanism, the combustion process occurs near its top dead center (TDC) position; thus the highest temperature and pressure are maintained for a relatively long time. Consequently, the heat loss is relatively high, which degrades the engine efficiency. In addition, friction loss is also a problem for internal combustion engines with a crankshaft mechanism because of the complicated engine structure. The friction loss includes the friction among the piston rings, cylinder wall, and piston skirt; friction in the crankshaft and camshaft bearings; and friction in the valves. The crankshaft mechanism contributes significantly to the friction loss through the formation of piston side forces that cause friction between the piston and the cylinder liner [1]. To overcome those drawbacks, researchers have developed a newer design called the free-piston engine. In a free-piston engine, the piston motion is free in the cylinder, without any constraint between the piston position and the rotating motion of a crankshaft. Pescara [2] first proposed the modern free-piston engine, and the original application was a single piston air compressor. Pescara started his work on free-piston engines around 1922 and he developed prototypes with spark ignition in 1925 and diesel combustion in 1928. The latter led to the development of the Pescara free-piston air compressor [3]. Pescara continued his work on free-piston machinery and also patented a multi-stage free-piston air compressor engine in 1941 [4]. Since then, many researchers have published studies of modern applications of the free-piston engine concept, mainly hydraulic engines and free-piston linear engines. The hydraulic engines are usually intended for off-highway vehicles, whereas the free-piston linear engines are usually intended for hybrid electric vehicles. In this paper, we review free-piston linear engine (FPLE) research because of its great potential for development and commercialization. The first FPLE was patented in 1944 [5]. Since then, many kinds of FPLE have been investigated and developed by researchers around the world. In terms of structure, FPLEs include two main components: a free-piston engine and a linear alternator. The linear alternator consists of permanent magnets and windings, in which the permanent magnets can be attached in a rotor or stator [6–11]. When the engine starts, the linear alternator receives alternating current to drive the free-piston engine through a connecting system in the motoring mode. After certain frequencies, spark plugs are activated in a spark ignition (SI) engine, or fuel is injected into the cylinder in a compression ignition (CI) engine to initiate the combustion process in the cylinder and cause a reciprocating motion of the piston. The piston movement and the connecting system then generate current in the windings of the linear alternator as the magnetic flux linked with the winding changes in the firing mode or electrical power generating mode. Electric power output depends on various specifications of the linear alternator, which we will present in the next section.

Unlike conventional internal combustion engines with a crankshaft mechanism, FPLE pistons move freely in the cylinder, which allows the FPLE to change the compression ratio and optimize the combustion process. By changing the compression ratio, an FPLE can operate with homogeneous charge compression ignition (HCCI) combustion, which allows the engine to increase its thermal efficiency and reduce NO_x and HC emissions [12]. An FPLE is also mechanically simple, and the integrated linear alternator allows a compact design, which reduces the manufacturing costs, compared with crankshaft engines. The lack of a crankshaft significantly reduces frictional losses, and the free-piston motion makes the acceleration much larger than in a traditional internal combustion engine. According to findings from the literature [13], predicted peak piston acceleration in a free-piston engine was about 60% higher than in a conventional engine, and the free-piston engine spent less time around TDC, where the gas pressure and temperature are highest, because of its faster expansion. Therefore, the heat transfer loss in the cylinder of a free-piston engine is less than that in a conventional engine. However, free-piston motion in the cylinder does lead to variation in combustion pressure at each engine cycle [14,15]. Also, in FPLE operation, which is mainly controlled by an electronic system, the piston crown can hit the cylinder head if the piston motion is not controlled correctly [16,17], though that possibility can be eliminated by installing a damping device in the cylinder [18].

Many researchers around the world are interested in using FPLEs as advanced power sources that offer reduced emissions and increased performance over existing engines. Such research has been conducted by institutes and universities such as the Korea Advanced Institute of Science and Technology [19], Beijing Institute of Technology [20,21], University of Ulsan [22], National Taiwan University of Science and Technology [23], Shanghai Jiao Tong University [24], Nanjing University [25], Tongji University [26], Stanford University [27], West Virginia University [28], Newcastle University [29], and Sandia National Laboratories [30]. To easily classify and summarize FPLE research results, we here present a review of FPLEs with different designations and operating characteristics. We also summarize some experimental systems and varied applications of FPLEs.

2. Classification of FPLEs

2.1. Number of strokes

Similar to traditional internal combustion engines, FPLEs are classified into four-stroke and two-stroke engines. The strokes of a four-stroke FPLE are intake, compression, combustion, and exhaust. In a traditional internal combustion engine with a crankshaft mechanism, the four strokes happen in two revolutions of the crankshaft, and the combustion stroke is called the power stroke. For FPLEs, the four strokes occur in the linear motion of the piston, and the intake and exhaust valves are controlled by an electronic system. Xu and Chang [31] studied the motion control of a four-stroke FPLE developed for electric power generation. The piston strokes combined with the open/close timing of the intake and exhaust valves were electronically controlled.

Even though the four-stroke principle can be applied to FPLEs, it presents greater technical challenges for motion control than two-stroke engines [31]. The technical challenges for motion control of the four-stroke FPLE include the complex control of the opening/closing times of the intake and exhaust valves vis-à-vis the linear motion of the piston. The opening/closing times of the intake and exhaust valves must be controlled correctly to prevent a collision between them and the piston crown. Therefore,