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DEVELOPMENT OF A TWO-STROKE FREE PISTON ENGINE FOR THEAPPLICATION OF A LINEAR GENERATOR

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ABSTRACT

A free-piston engine (FPE) for the application of linear generator (LG) is developed. The development involved extensive modeling and simulation works before the actual prototype is built. Several testing are conducted for each subsystems of the LG-FPE. The first testing is aim to provide a benchmarking with regards to the injection current into the linear generator coil when different amount of voltage (with different amount of 12V battery quantity). Next, the tests progressively venture into the in-cylinder behavior while varying the voltage. From the experiments, it was found that the 5- battery configurations of LG-FPE resulted in compression pressure of around 5 bar in both cylinders while the translator speed achieved is around 300 cycle per minute. These parameters achieved its threshold values which will successfully start the engine.

Keywords: Free-piston engine, linear generator, two-stroke, starting

INTRODUCTION

The coupling of internal combustion engine with electrical power generator is not a new concept. However, the introduction of free-piston electrical generator brings about an alternative method of power generation, especially for series-hybrid electric vehicles application and portable power generators. The free-piston engine technology itself has been known for other applications such as hydraulic pump, gasifier and air compressor. Successful operations of these machines have been reported (Aichlmayr, 2002). As for the linear generator free-piston engine combination, it is still at a relatively early development stage. The attractiveness of a linear generator free-piston engine lies in the promising advantages such as high power to weight ratio, multi-fuel capability, and low manufacturing cost and low maintenance due to less components plus its mechanical simplicity (Aichlmayr 2002; Blarigan 2002; Hansson and Leksell. 2006; Mikalsen and Roskilly 2007). (Vasanthy and Jeganathan 2007, Vasanthy et.al., 2008, Raajasubramanian et.al., 2011, Jeganathan et.al., 2012, 2014, 2020, Sridhar et.al., 2012, Gunaselvi et.al., 2014, Premalatha et.al., 2015, Seshadri et.al., 2015, Shakila et.al., 2015, Ashok et.al., 2016, Satheesh Kumar et.al., 2016).

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Free-Piston Engine Technology

In a conventional engine (referred to as crank-slider engine), the engine transforms the linearly oscillating movement of the piston into the rotating movement of the crankshaft. Free-piston engine on the other hand, is an engine where its piston moves freely without any constrain of neither a crank nor rotating crankshaft. The motion of the piston in a crank-slider engine is restricted by kinematics of the crank-slider mechanism and dynamics of the combustion gases in the combustion chamber. Whereas, the motion of the piston in free-piston engine is determined by the dynamic balance of forces (gas dynamics and frictional forces) acting upon it. In addition, a single cylinder crank-slider engine contains about 50 components, of which 28 undergo linear motion and 22 undergo rotating motion (Tóth-Nagy 2004). A flywheel mechanism is usually employed to regulate the kinetic energy obtained from the engine based on the load and operating conditions. The engine is driven by the gas pressure due to combustion in the combustion chamber. This pressure, which acts on the piston surface, then produces the gas force to move the piston downwards thus rotating the crankshaft at the end of the connecting rod.

The single component of the engine to perform rotating motion is the crank pin, while the piston performs oscillating motion and the connecting rod performs both rotating and oscillating motion. The masses of these components produce rotating and oscillating imbalance which must be counterbalanced, at least partially, to ensure the smooth operation of the engine (Merker et al., 2006). Due to the kinematics constraint on the piston, there are two positions where the piston momentarily stops to reverse its direction, known as Top-Dead-Center (TDC) and Bottom-Dead-Center (BDC). These are the positions during which the piston’s velocity is zero and its acceleration is at maximum. (Manikandan et.al., 2016, Sethuraman et.al., 2016, Senthil Thambi et.al., 2016, Ashok et.al., 2018, Senthilkumar et.al., 2018.

The free-piston engine is restricted to the two-stroke operating principle, as a power stroke is required on every cycle. Although a four-stroke version is conceptually possible, it requires additional components and cumbersome design (Petreanu 2001). Generally, free-piston engine posses the following features:

1. A combustion chamber.

2. A rebound or energy storage device.

3. A load or energy absorbing device.

There are several configurations of a free-piston engine all of which will have the typical features listed above. The elimination of the rotating crankshaft mechanism in a free-piston engine implies a series of advantages over the conventional engine (Nandkumar 1998; Achtenei al., 2000; Petreanu 2001; Aichlmayr 2002; Carter and

a) Reduce friction losses that lead to a better overall engine thermal efficiency.

b) Compact construction offers high power density.

c) Variable compression ratio operation, higher thermal efficiency can be achieved and offer multi-fuel operation capability.

These advantages characterize free-piston engine unique features which also represent challenges which must be overcome to enhance its potential over conventional technology.

Free-piston linear generator

The most recent development on free-piston engine involves free-piston linear generator configurations. The configuration has several advantages compared to conventional generator engine such as reduced size, weight and moving parts. The transient response is good with the absence of crankshaft and flywheel, resulting in fast power delivery. In addition, low mechanical losses and high efficiency are expected. The free-piston linear generator applications will be in the portable electrical generator and hybrid-electric vehicles. Most researchers focus on employing the free-piston generator concept for the series hybrid electric vehicles application (Blarigan et al., 1998; Goertz and Peng 2000; Tóth-Nagy 2004; Xia et al., 2006; Hansson and Leksell. 2006; SaifulAzrin 2007). The simplicity of the linear generator free-piston engine design can be observed in Figure 1. The prototype's components consist of two sets of the same parts symmetrically located about the stator assembly centerline. There are two sets of piston assemblies (each consist of a piston, piston pin and two piston rings), cylinder blocks, cylinder heads, scavenging chambers and reed valves. The cylinder heads are custom made for direct injection system. The direct injectors are designed for CNG with dedicated injector driver. Due to the absence of the crank-slider mechanism and flywheel components, the power-to-weight ratio of the engine is increased substantially.

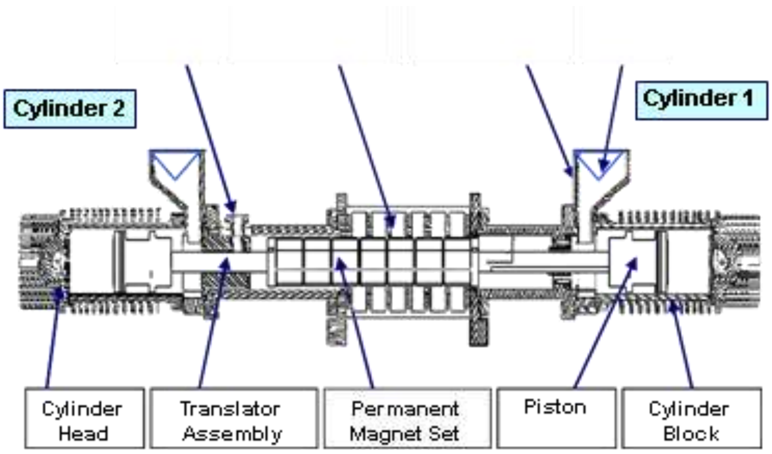

Figure 1: Linear generator free piston engine prototype components

The experimental setup consists of hardware and software developments. Besides the prototype itself, the hardware involves the sensors and actuators for the engine and battery banks and inverter driver of the linear generator. While for the software, hundreds of virtual instrument (VI) for the control and data acquisition's computer programs were developed on the LabVIEW and LabVIEW Real-Time software platform.

Hardware

The hardware used in this experimental setup consists of electrical and mechanical components. The electrical hardware can be classified into sensors, actuators, driver & amplifier and controller & data acquisitions. The layout of these components is shown in Figure 2.

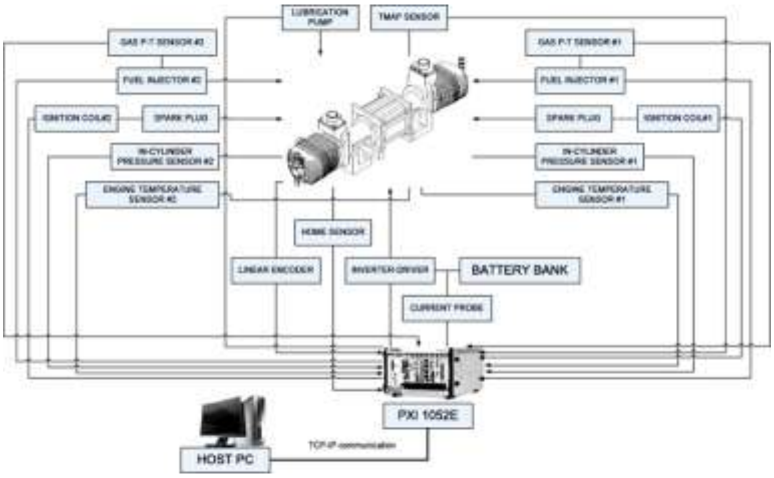

Figure 2: The sensors, actuators and controller for experimental setup.

Controller and Data acquisition: The controller used for the experimental setup is the National Instruments PXI 8186 integrated in PXI 1052E chassis. The data acquisition card installed in the chassis is PXI 6052E, while two counter cards (model PXI 6602) are used for the displacement reading and injector and ignition timing. The controller is connected to a host PC via TCP-IP communication. The user control function is done from the host PC by using LabVIEW Real-Time software platform. The details of the program will be described under software section.

Fuel system: The fuel system of the experimental setup is designed for high pressure gaseous fuel. Two types of fuels were tested namely, CNG and hydrogen. The fuel supply system is shown in Figure 3.

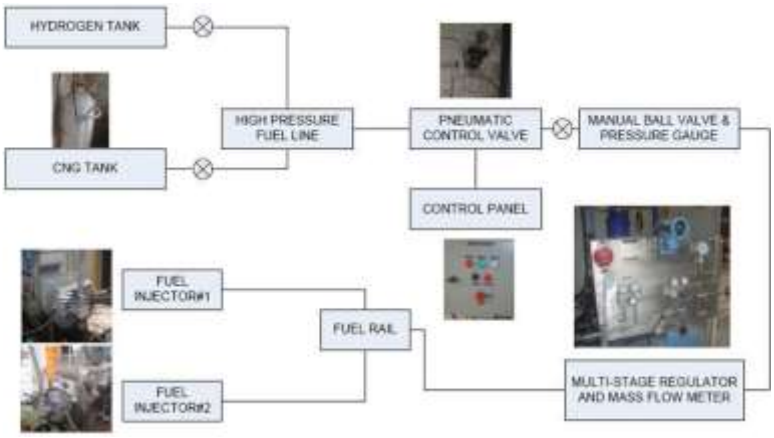

Figure 3: The fuel system for the experimental setup

RESULTS AND DISCUSSIONS

Motoring with 3 and 5 Batteries

In the motoring experiments, the prototype was ran at different battery voltage levels while the in-cylinder pressures, current level and translator speed data will be referred to as the baseline before commencing the combustion experiments. A few benchmarking experiments were done to obtain pressure and displacement profile of the free-piston engine during no combustion. The graphs will be referred for the compression pressure and speed during motoring and to monitor current reduction of the battery bank as the experiments continued. The current reduction will reduce the motoring force, thus affecting the experimental result. The benchmarking current vs. time for 3 and 5 batteries is shown in Figure 4.

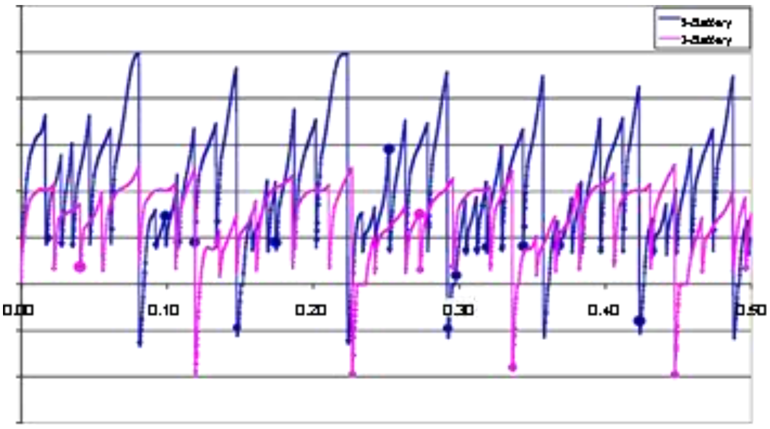

Figure 4: Current vs. time for 3 and 5 battery motoring

There are 2 sets of data; the first set is with the motoring voltage of 36 Volts (3-Battery supply), while the second is with 60 Volts motoring voltage (5-battery supply). The type and capacity of the batteries used are the GP Atlas maintenance-free battery, 12V 45AH.

Compression-Expansion Pressure Profile

Figure 5 shows the pressure vs. displacement for each cylinder with different battery quantities, i.e. 3 and 5 batteries. It was found that for 3-battery motoring, the maximum pressure in cylinder 1 and 2 are approximately 4bar and 3.5bar respectively. Whereas, for 5-battery configuration, the maximum pressure in cylinder 1 and 2 are approximately 6 bar and 5.5 bar respectively. The, pressure in cylinder 2 is less than that in cylinder 1 due to the leakage area on the bushing of cylinder 2. This leakage had resulted in less scavenging pressure during intake, thus reducing the amount of air induced and trapped in the cylinder.

Compression-expansion translator velocity profile

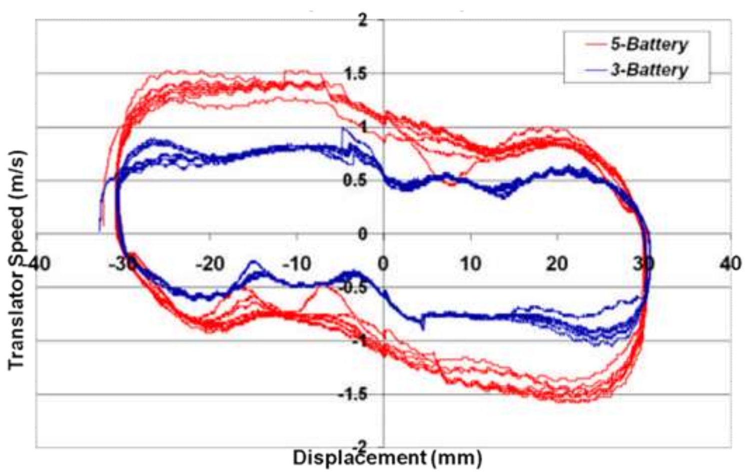

Figure 6: Translator velocity profile vs. displacement (translator position

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The translator velocity is negative when the translator is moving towards cylinder 2 and positive when it is moving towards cylinder 1. Thus, from Figure 6, the negative values of the velocity occur when the translator is moving towards cylinder 2, which is during cylinder 1 expansion stroke and cylinder 2 compression stroke. On the other hand, the positive values of the velocity occur when the translator is moving towards cylinder 1 during compression stroke of cylinder 1 and cylinder 2 expansion stroke. The profile shows faster expansion stroke than compression stroke which can be attributed to the reduced translator's acceleration due to the increment in compression force. In addition, when the battery quantity is increased from 3-battery to 5-battery motoring, the translator velocity is increased by 0.5m/s which resulted in overall vertical expansion of the velocity profile. It was predicted that further increase in battery quantity will eventually result in horizontal expansion of the translator velocity profile (SaifulAzrin 2007).

CONCLUSION

The prototype is successfully tested. Experimental data for the benchmarking are obtained. In summary, the motoring with 5-battery is identified as the best configuration during starting. The resulting compression pressures in both cylinders are above 5 bars while the translator speed of 300 cycle per minute. Although the value still lower than crank-slider engine, it may result in combustion for successful starting.

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