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Existing state of art of free-piston engines

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Abstract. Free-piston engines (FPE), as power generators for electricity and hydropower solutions, have come under intensive research and development during the last decade. The rapid development of information technology provides an opportunity to return to FPE technology development due to better levels of control and management in terms of the engine's work. What is more, changed environmental requirements are imposing stricter conditions upon the development of internal combustion engines. More effective solutions which ensure lower exhaust emissions, which are able to consume a variety of conventional and renewable fuels without any engine modification or rebuild taking place, and which work well with a very wide variety of ambient temperature conditions. However, commercially available or production-ready compact and stable free-piston engine solution are still absent. The objectives of this article are the innovative and novel features of FPE and their influence on engine operations and power production. The article maps the FPE technology and conducts a fact analysis. Various technical solutions, experiments, and mathematical calculations are discussed and are presented critically, along with potential pros and cons. This paper will epitomise the discussions outlined above with one possible theoretical technical solution for FPE, this being the electrical power generator.

Key words: internal combustion engine, free-piston linear alternator, engine generator.

INTRODUCTION

The world's growing electricity deficit forces us to evaluate other options when it comes to energy resources and technology. Over the next two decades, oil will remain the world's main energy source but it will not cover the growing demand for energy. This perspective compels us to develop combustion technology and to find energy alternatives. Fuel converted to electrical power via 'engine generators' (GENSET) is a relatively quick process. Mobile power generation is under constant development (Lund, 2008) and solutions are sought in many sectors. The US Land Forces stated that, in 2020, new technology will produce 75% of operation electricity (Defence Update, 2003), and the EU will replace conventional fuels with 20% renewable energy. These objectives determine the development directions in all energy areas including the automotive industry.

Environmentally-friendly combustion technology will be progressively introduced and engine production will evolve in the direction of hybrid engines. In terms of the automobile industry, significant technological developments focus primarily on electric and hybrid cars which have the potential to consume less energy and reduce emissions. Developments influence and determine mobile electricity production with renewable fuels as being key to progress. One internal combustion engine research area is the free-piston engine (FPE), which was abandoned in the middle of the previous century but which is currently making something of a comeback in terms of low levels of power production. The return of FPE technology is significantly influenced by IT developments which provide faster processors and more sensitive sensors to control the way engines work. Technology compactness and improved capacity parameters make FPE an attractive and promising technology. More deeply FPE-related concepts are being studied by Achten and Aichlamyr (Achten, 1994; Aichlmayr, 2002) but technology has evolved and improved in the meantime.

In this article, FPE studies are provided with an overview and are cited in association with the developments of the previous decade. Chapters are divided based upon problems and in highlighting the pros and cons of the technology. According to the analysis which has been carried out, (1) FPE concepts are mapped out and the list of usable technology developments is improved by the addition of the latest inventions (Table 1); (2) the engine mechanics are debated in connection with simulations and engine control; (3) the principles behind starting-up an engine are critically reviewed, along with the provision of technical examples; and (4) focuses on engine combustion stability and starting an analysis which was carried out in particularly changing load conditions. Finally, an overview is presented and discussed along with the provision of an FPE solution for the mobile GENSET.

ENGINE CONCEPTS

The FPE can be divided into three groups by its actions and extractions (Mikalsen & Roskilly, 2007), and by more complex configurations using three cylinders and four pistons (Hung et al., 2015). The configurations mentioned use piston motion in order to achieve any useful work. For example, the technology implements and supercharges power turbine rotational movement. The single piston FPE consists of only a few parts: (1) the cylinder; (2) the load device; and (3) the rebound device which stores energy for the next compression. The surplus energy is directed towards hydraulic, pneumatic, or electrical power production. The dual FPE configuration skips the rebound chamber since combustion provides compression for the next stroke. This omission increases the overall power to weight ratio. Dual technology is the area which sees the most research and development, so a number of patented designs are available. The patents are found in all three types of hydraulic, pneumatic, and electrical power production. The challenge in terms of FPE is in achieving control of: (1) the piston motion; (2) the stroke length; and (3) compression due to sensitivity to load and cycle-to-cycle variations (Aichlmayr, 2002). The most common designs are illustrated and general pros, cons, and loads are described in Table 1.

Table 1. Common free-piston engine designs

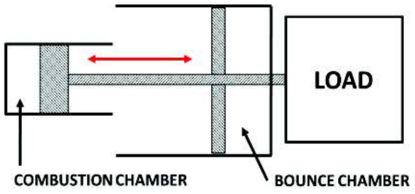
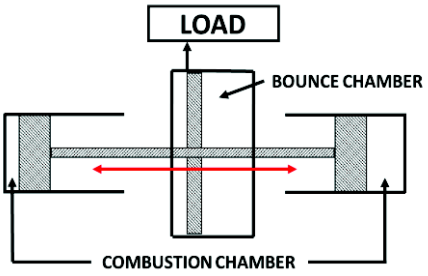
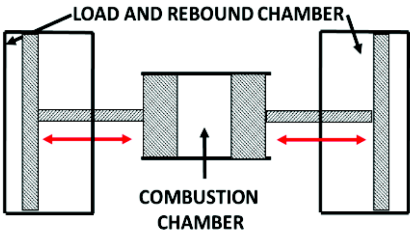
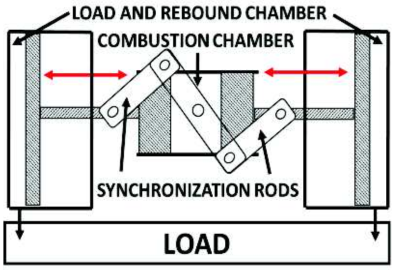
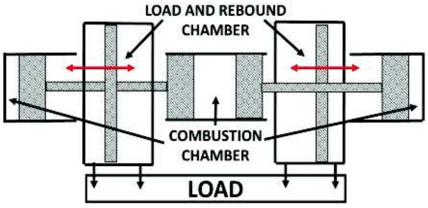
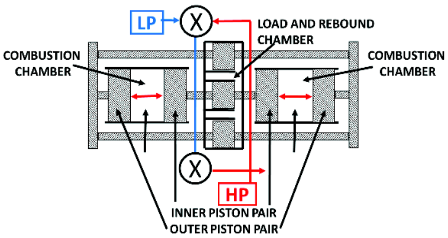
Configuration	Representation	Pros / Cons/General description/ Load
a) Single piston and one cylinder solution (Achten et al., 2000; Zhang et al., 2015a; Zhang et al., 2015b Zhao et al., 2010; Zhao et al., 2013; Zhao et al., 2014; Brunner et al., 2005; Hibi&Ito, 2004; Kock et al., 2013)		Simple design, compact, unbalanced, counterweights may be needed, allows long stroke, scavenging or injection fuelling, exhaust ports or valves for the outlet.
b) Single piston rod, two piston and two cylinder solution (Mikalsen et al., 2010; Jia et al., 2014a; Jia et al., 2015a; Jia et al., 2015b, Mikalsen & Roskilly, Part 1, 2010; Xiao et al., 2010; Tikkanen et al., 2000; Clark et al., 1998; Blarigan et al., 1998; Fredriksson & Denbratt, 2004; Xu & Chang, 2010; Robinson & Clark, 2016)		Every revolution two power strokes, better power output, massive piston causes unbalance, long stroke, challenge to control, great power output, loading hydraulic or electric generator, scavenging or injection fuelling, exhaust ports or valves for outlet.
c) Two opposed piston, two piston rods and one cylinder solution (Wu et al., 2014; Xu et al., 2011; Zhou et al., 2005)		Concurrent combustion, separate bounce, and load chambers, challenge to control, loading hydraulic or producing high pressure for the turbine, scavenging or injection fuelling, exhaust ports or valves for the outlet.
d) Two opposed piston, two piston rods and one cylinder with synchronisation rods (Achten, 1994; Hanipah et al.,2015; Mikalsen & Roskilly, 2007a; Aichlmayr, 2002)		Concurrent combustion, piston synchronization, minimal vibration, separate bounce and load chambers, loading hydraulic or producing high pressure for turbine, scavenging or injection fuelling, exhaust ports or valves for the outlet.

Table 1 (continued)

e) Four piston, opposed – dual, two piston rods and three cylinders solution (Nguyen et al., 2015)		Four pistons, three combustion chambers, two separate bounce and load chambers, loading hydraulic, injection fuelling, exhaust ports.
f) Four piston, opposed, two cylinder solution (Li et al., 2015; Zhang et al., 2015)		Four pistons, two combustion chambers, concurrent combustion, compression ignition, three interconnected hydraulic chambers, intake and exhaust ports.

The FPE is a reciprocating engine, one which is frequently termed a linear piston engine, in which the steady piston moves and transforms thermal energy into power. Unlimited piston motion and the variable clearance volume V_c between the 'top dead centre' (TDC) and the 'bottom dead centre' (BDC) is missing from the rod and crank mechanism. The FPE configurations differ but at least have: (1) a combustion chamber; (2) rebound or bounce-storing energy; (3) load absorbing or consuming energy. Fewer moving parts decrease friction and increase system efficiency as piston rings, bearings, bounce, and rebound result in minimal kinematic constraints (Aichlmayr, 2002). The FPE compression and expansion (power) stroke is similar to the revolution of a two-stroke engine. The compression stroke starts at BDC, after the charge is sucked in to the cylinder and it ends when the charge is compressed until the pressures equalise. The compression stroke uses released rebound storage energy. The compression or spark initiates combustion in TDC and thermal energy converts into kinetic energy through rapidly expanding gasses. The expansion lasts until blow-down is achieved, in BDC, since the exhaust port or valve opens and releases exhaust gasses. The inlet port or valve opens and scavenges (compresses) a charge into the cylinder and then the cycle repeats. The FPE designs may vary but operational principles are the same (Mikalsen & Roskilly, 2007a).

The FPE is exploited by electric generators, and by hydraulic and pneumatic systems. In hydraulic systems, pressures are achieved via a small piston mass and the efficiency rate is relatively high. The hydraulic control system keeps the discharge pressure constant. Linear electric generators are compact power packs due to the use of ferromagnetic materials or permanent magnets in pistons mechanisms. In linear electric generators, the oscillation frequency is set in accordance with the load. The FPE advantages and challenges are as follows:

The FPE advantages:

- A structurally simple machine;
- A variable compression ratio during operation;
- Variable compression allows high compression ratios;

- Allows for multi-fuel operation;
- Each stroke generates power;
- Piston movement is not limited by crankshaft radius;
- The missing crankshaft reduces the geometry significantly;
- A significant kW to kg ratio;
- Allows a long piston stroke to be implemented;
- Small frictional losses;
- Good volumetric efficiency;
- Lower temperature release due to a rapid burning process;
- Lower fuel consumption due to lower frictional losses;
- Reduced emissions;
- Able to work in very low temperature conditions;
- Low vibrations due to the crankshaft being absent.

Challenges to overcome are these:

- The starting process;
- Piston movement control;
- Variable piston stroke which leads to poor volumetric efficiency;
- Precise load control;
- An accurate fuel mixture;

In conclusion, normally the crankshaft controls and stores energy for the next stroke. The FPE employs a two-stroke principle as it needs a power stroke in every cycle. The one-piston FPE reciprocates in terms of combustion and for the necessary rebound force in balance with the controlled load. The proper combustion characteristics ensure that the engine works as expected and the residue is diverted for power production. The FPE needs enough computing power, accurate algorithms, quick reaction sensors, and powerful enforcement mechanisms to control the piston, scavenging, ignition, and exhaust release. Otherwise, the engine management process fails.

ENGINE MECHANICS

The FPE is missing a crankshaft, and instead the load force is directly coupled to the piston. The calculations and simulations based on the balance of piston motion on the engine power mode. The compression ratio r_c (r_c = total cylinder volume V_t / cylinder clearance volume V_c) and cylinder volume V (m^3) calculates in a similar way to calculations for crankshaft engines, but volume V at any crank angle φ (degrees) is problematic. The piston location calculations for crankshaft engines are take into account the connecting rod length l (cm), crank radius α (cm), and time- change rate dependent on crank angle φ. In terms of FPE, piston motion is derived from free-body motion and, therefore, excludes crankshaft radius and piston friction by side forces. The main piston motion characteristics in the FPE are shown in Fig. 1 (Aichlmayr, 2002; Mikalsen & Roskilly, 2007a).

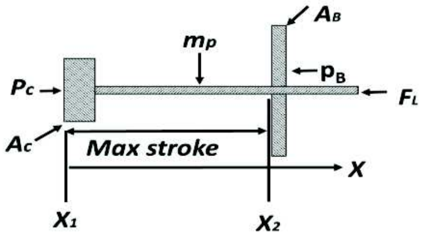


Figure 1. FPE body diagram and generalised loads and friction acting on a piston (Aichlmayr, 2002; Mikalsen & Roskilly, 2007a).

Determining the location of the piston requires variables; piston mass m_p (kg); and combustion chamber pressure P_c (bar); and combustion chamber area A_c (m^2); and load force F_L (N). The load force F_L (N) consists of the bounce chamber area A_B (m^2), and rebound or bounce pressure p_B (bar). The combustion force acts in the x-direction, and in applying Newton's second law a force balance (Mikalsen & Roskilly, 2007b) can be described:

$$\sum F_x = m_p \frac{d^2x}{dt^2} = P_c A_c - F_L \tag{1}$$

The piston velocity (v) can be calculated from the FPE work function. Velocity can be calculated between the set points x_1 and x_2 (Fig. 1) and, after integration, the equation is expressed as follows: (Mikalsen & Roskilly, 2007b):

$$\underset{1\rightarrow 2}{\mathrm{W}} = m_p \left(\frac{\bar{V}_2^2-\bar{V}_1^2}{2}\right) = A_c \int_{x_1}^{x_2} P_c dx - \int_{x_1}^{x_2} F_L dx \tag{21}$$

The x_1 and x_2 are the piston dead points, and velocities v_1 and v_2 are set at zero, so the equation can be reducing as follows (Mikalsen & Roskilly, 2007b):

$$A_c \int_{x_1}^{x_2} P_c dx = \int_{x_1}^{x_2} F_L dx \tag{3}$$

The assumption that piston position determines as a function of combustion pressure $P_c = P_c(x)$, and x_1 is known (Eq. 3), in which case more variables should be available for precise control. One important variable is preparation of air-fuel mixture. The air-fuel mixture preparation consists of: (1) the exact calorific value of the fuel; (2) the air-fuel ratio; (3) the air-fuel mixture quality; and (4) the temperatures (Aichlmayr, 2002). In order to be able to control all of the aforementioned parameters, the control unit has been designed to analyse the information it receives from sensors and processes according to the algorithms that have been set for just this purpose. The FPE needs proactive intervention to be able to manage the piston as any failure to do so causes a collision in dead centres. The management system senses and calculates piston movement and load force F_l by the prescribed function. The location x_2 computation starts after combustion, in fairly quick time, and it is impossible to conduct this without controlling F_L. So it excludes sudden load changes.

ENGINE START UP PRINCIPLES

The absence of a flywheel concludes any remaining problems which need to be overcome. The FPE piston's missing connection with any mechanical parts directly influences the start-up process. The start-up problems occurred regardless of configuration, and researchers report that the start for a dual-piston engine is the real problem (Noren & Erwin, 1958; Aichlmayr, 2002; Nemecek & Vysoky, 2006; Mikalsen & Roskilly, 2007a; Zulkifli et al., 2008; Xu & Chang, 2010). The FPE must start the combustion on the first stroke (Braun & Schweitzer, 1973) and the start-up requires additional technical equipment. The cylinder is fuelled, the piston is positioned on the maximum value, and required pulse energy is released (Farmer, 1947; Noren & Erwin, 1958; Aichlmayr, 2002). The FPE is started with a spring or a hydraulic system that can generate the piston movements in the cylinder (bounce or rebound), (Farmer, 1947; Aichlmayr, 2002), with this being the most widely-used practical method (London & Oppenheim, 1952).

The latest General Motors patent is similar to the Sigma GS-34 gas generator and differs in terms of its physical synchronisation mechanism which controls the piston movement with levers (Durrett et al., 2012; Nait et al., 2012). The piston synchronises with bounce chambers and the permanent magnets generate electricity in coils. Magnets are added in the piston and the coil windings are enveloped around the cylinder. (Hanipah et al., 2015). The solution need piston cooling when the *Fe* magnet works on the temperature 770 °C and more. When using other alloys in the magnets, the temperature is even lower. The temperature decreased the ability of the magnet and the power producing of the FPE linear generator is inhibited. (Kittel, 1995). The two stroke FPE design by General Motors is shown in Fig. 2.

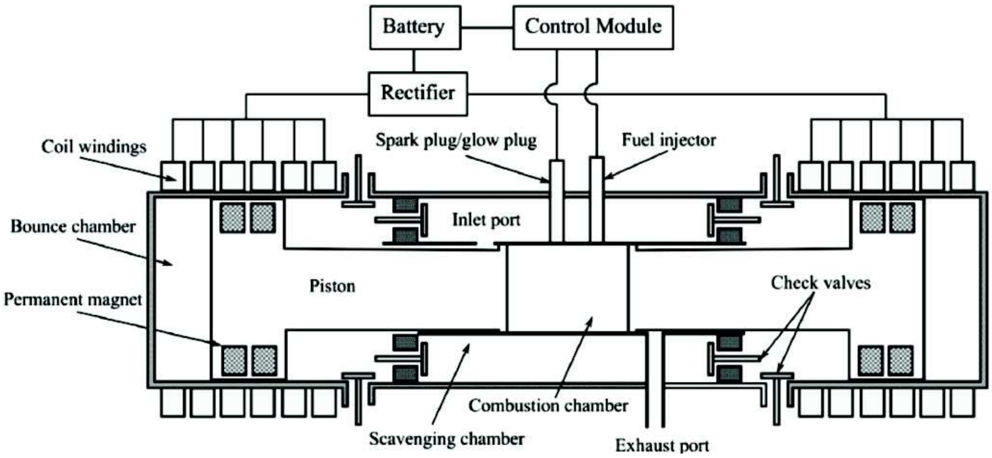


Figure 2. GM's opposed piston two stroke design FPE linear alternator (FPLA) (Xu et al., 2011).

In terms of FPLA, Patent No US 20110012367A1 (2011), Holmes resolves the engine starting conundrum by using an electrical flywheel. The opposed piston simplified linear alternator is shown in Fig. 3. The engine driving system (1) which includes a linear machine (2) with a linearly-moving piston (3). With that in mind, (3) moves along a path between the first end (4) with a first combustion chamber (5) which has a first fuel source and spark plug (6), and a second end (7) with a second combustion chamber (8) with a second fuel source and spark plug (9). A first coil (10) has windings around the path of the linearly-moving piston. It can be seen that (3) is positioned towards the first end (4). Similarly, a second coil (11) is also wound around the path and is positioned towards the second end (7) (12). Other items are a third coil (13) rotary machine, (14) fourth coil, (15) transmission, (16) variable speed motor, (17) rotor, (15) transmission of speed. The FPLA connects electrically via two sets of coils to a rotary machine (middle) and a battery source via a converter. In addition, a variable-speed motor connects mechanically via a gear box to the rotary machine as well as being electrically connected to the whole system via two sets of coils. This FPLA uses stored energy from batteries to create a starting electrical current in the first and second coils. The starting magnetic field moves the piston and creates the magnetic field in the cylinder coils. The converter starts the engine and converts electricity. The external coils and rotating bodies are kept limited in size and mass. The alternative solution is a programmable controller which generates the needed current and oscillation directly in the engine coils (Holmes, 2011).

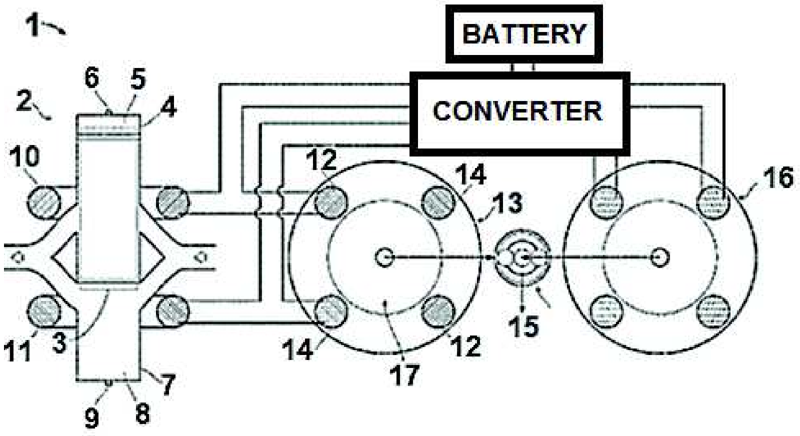


Figure 3. FPE starting system principle (Holmes, 2011).

The turbo charged energy converter, Patent No EP 1540155B1 (Max et al., 2005), is shown in Fig. 4. The energy converter system (1) consist of, comprising piston (2 & 3), combustion chamber (4 & 5), inlet (6 & 7), and outlet (8 & 9) manifold, inlet and outlet valves (10, 11, 12, & 13). One inlet and one outlet valve are controllable separately by control unit in order to regulate the beginning of suction and compression stroke. When piston starts moving, the magnets in the generator affect electromagnetically the coil windings. Differences compare to solution in Fig. 2 is, that magnets are added in to the piston rod. This solution is less sensitive to temperatures but load of generator has impact for piston velocity.

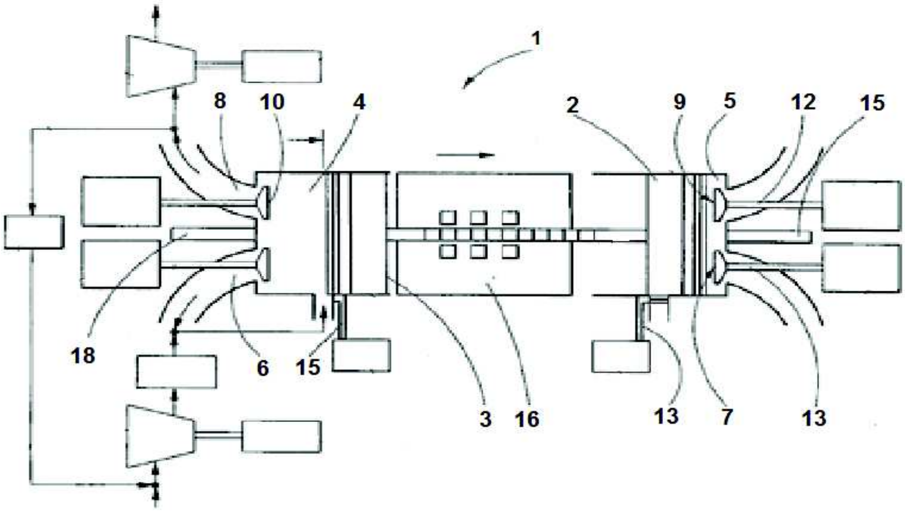


Figure 4. FPE linear alternator (Max et al., 2005).

The batteries operate the linear alternator as a linear motor. The piston is oscillated in the cylinder, building to a higher compression each cycle until sufficient compression is developed for auto-ignition. The fuel which is introduced into the engine ensures self-powered operation. A cold starting process is a special case since a considerable amount of compression is required to achieve the automatic ignition temperature (Max et al., 2005).

The linear alternator allows the FPE to be started without the need for any additional systems and this restrains FPE to compact dimensions. An engine which starts up by means of a battery or supercapacitor is a reasonable prospect when it comes to smoothing out load peaks which can cause malfunctions in engine operation. Any FPE starting without external aids ensures system compactness. When using the spring, hydro or pneumatic systems as engine starters, additional developments in FPE construction are necessary. What's more, when using pneumatic pumps or electrical engines as FPE starters, the mass of the FPE increases. This is problematic in terms of the transportation of FPE.

ENGINE START-UP COMBUSTION STABILITY

The opposed piston FPE generator (FPEG) consists of mechanical resonance starting (Atkinson et al., 1999; Li et al., 2008; Jia et al., 2014a; Jia et al., 2015b). The spring theoretical model was researched and the start-up experiment was conducted on a prototype engine. They investigated engine control, input parameters and misfire reasons. The FPEG (a) simplified scheme and (b) prototype is shown in Fig. 5. The stoichiometric mixture takes place in the intake manifold. The ignition system consists of a 2V battery, ignition coil, and spark plug, which is activated automatically after the required compression has been achieved. The generator motors the start-up process and switches the generator mode after the starting-up process has been completed. The magnets are placed in the centre of the piston and the stator coil is connected to an electrical load absorber. All three starting phases: 1) starting; 2) the electrical motor phase; and 3) the generator switch phase is to be coupled up to a proper control system in order to ensure transition and stable running. All of the processes are measured by system sensors and data is sent to electrical controllers: 1) starting; 2) ignition; 3) electrics; and 4) the external load control system (Jia et al., 2015b).

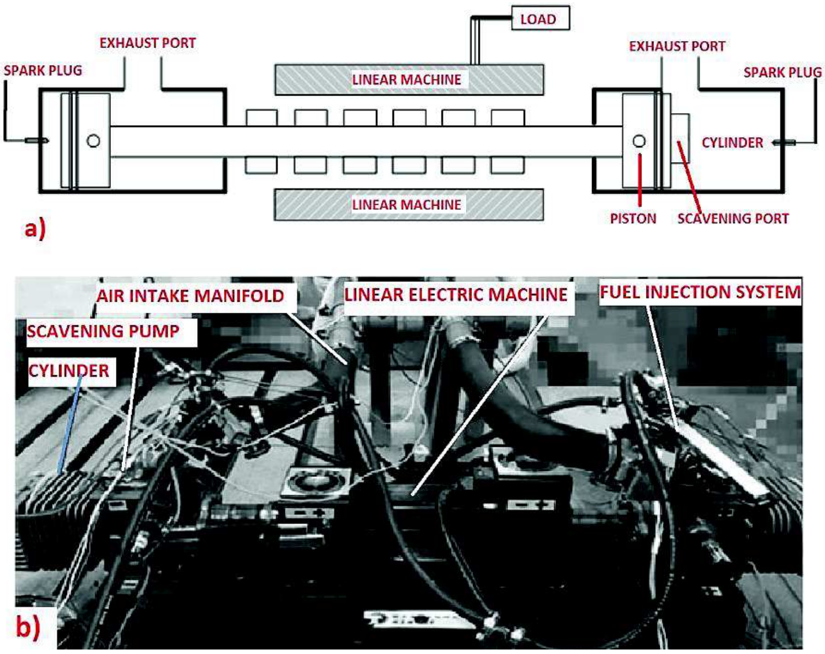


Figure 5. FPE generator simplified design (a) (Jia et al., 2014a) and the prototype (b) (Jia et al., 2015b).

Practical tests of FPE starting are carried out. Testing theory based on the factor that the FPEG is free of side forces, and system friction is low in proportion to electrical force within the start-up. In the practical tests, the theoretical starting force of FPE was 60*N* and in this case, it illustrates the crossing of the friction forces. The practical experimental results are illustrated in Fig. 6. Piston displacement extends step-by-step, until it reaches to maximum value. Gas pressure in the cylinder and maximum velocity of the piston increases with each stroke. Suitable compression value in FPE cylinder was reached in less than a second (Jia et al., 2014). The amplitude of piston movements and velocity increased in respect to the completion of the stroke time (Fig. 6). Fig. 6 shows that, in addition to friction, air leakage, heat transfer, and vibration all exist as additional drains on energy production. Piston movement amplitude, maximum piston velocity, and cylinder pressure peak which increases gradually by resonance and also increases rapidly (at *0.8* fractions of a second) all serve to achieve the target for ignition. Later research will need to focus on new targets, these being achieving the compression ratio (8:1) and the cylinder pressure (*10 bar*). The crossing of the friction forces, the static friction force (*60N*), was set as a maximum theoretical force. In practical experiments it emerged that it was twice as much as *60N*. In FPE tests, forces were applied which were between *80N* to *125N* at a *15N* interval. At *80N* (*8.5Hz~510 cycle per min*), the maximum cylinder pressure of *5 bar* after four cycles was achieved and remained at the same level.

A motoring force of *95N* (*10Hz ~600 cycle per min*) achieved *7 bar* in six cycles and remained stable afterwards (Jia et al., 2015b).

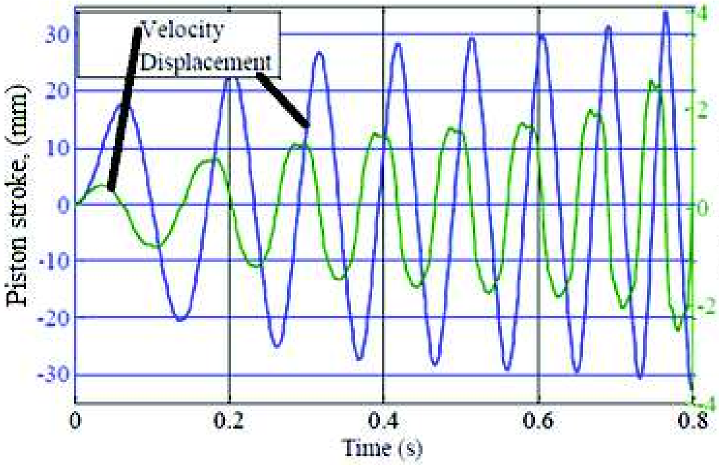


Figure 6. The experimental results of piston stroke and velocity (Jia et al., 2015b).

The starting force needs to exceed *103N* to be able to start the engine smoothly. After several cycles a motor force over *103N* (650 cycles per min) provides conditions which ensure that ignition can take place. The fixed motoring force of *125N* with ignition timing set 27mm from the central position was implemented for the start-up process. The prototype runs using the stoichiometric air-fuel ratio ($\lambda = 1.0$). The velocity profile is close to symmetrical before and after BDC/TDC as the difference in acceleration is small. The maximum piston velocity is achieved in the middle of the stroke. With a higher starting force having been achieved, the piston velocity and compression is higher. The piston moves at a high and relative constant speed at the middle portion of the stroke. The slowdown of the piston takes place at the bottom dead centre (BDC) and top dead centre (TDC). The FPEG prototype output maximum force reaches *232N* and a piston velocity of 3.1 m s^{-1}. The higher figures result in overheating of the stator coil and, after starting, the piston velocity declined. The piston decline increased gas flow through the piston rings and the heat transfer. Limiting of the piston movement velocity caused misfires in the combustion process. For this reason, the FPE control unit is adjusted as follows: when the electrical generator is being used as a motor, continuous ignition and combustion were both achieved. After a period of 1.2 seconds, the system obtains the stability it requires (Jia et al., 2015b).

Considerably more complex starting-up operations are being researched by Carlson. The ports are closed and the trapped air is compressed by the piston towards the TDC point. The trapped compressed air behaves like a mechanical spring and supports the next stroke. The pistons are cyclically reciprocated to suit the air charge pressure rise and combustion pressure rise. Finally, a spark plug initiates combustion in the first cylinder and then in the second cylinder. The spark plugs are used until maximum cylinder pressure achieves the required compression ignition level and, after the HCCI mode is working, the SI is disabled (Carlson, 2005). The FPE linear generator (FPLA) start-up and mechanical problems are being researched by Zulkifli et al., 2008.

The spark ignited dual FPE uses a brushless linear motor to produce the required start-up force. The research focuses on the FPLA mechanical model and provides simulations for different motoring force values. The start-up strategy proposes the presence of air compression in the engine cylinders prior to combustion (Zulkifli et al., 2008).

The generator coils will be loaded with a fixed DC voltage, and an open-loop, rectangular commutation of the input current and a high motoring force reciprocates the translator at small amplitudes until the amplitude and speed of the mechanical resonance reach the required parameters for combustion (Zulkifli et al., 2008). A starting method which uses the resonance in a diesel free-piston linear alternator with a commercial permanent magnet tubes has shown that: (1) the FPLA can be started by using the air-spring characteristics and with a comparatively small thrust force, but a greater thrust force will engage the start-up in a few less cranking cycles; (2) the load on the linear alternator is associated with the cylinder bore measure and the maximum electromagnetic force is approximately proportional to the bore square measure; (3) with the same fuel/air equivalence ratio and external load resistance, a longer effective stroke length helps to increase the compression ratio and also served to indicate the efficiency of the free-piston engine; (4) with the same fuel/air equivalence ratio and external load resistance, it can generally be seen that a longer effective stroke length leads to a higher power output level (Mao et al., 2011). Researches of the diesel FPE start-up and working parametric analysis (Mikalsen & Roskilly, 2010), and detailed engine control strategies (Mikalsen & Roskilly, Part 1, 2010; Mikalsen & Roskilly, Part 2, 2010; Mikalsen et al., 2010) reached on the similar results.

The FPE idea is simple and compact power pack technology, which is easily maintained due to a few simple engine parts. The engine's external starting extras include system ballast, which means that linear or rotational electrical generators maintain the preliminary measurements and are used for operation of normal engine. The stable duty-cycle is achieved by controlling the piston stroke and energy storage. After solving the FPE management process satisfactorily, the unique features of this resource can be released onto markets so that they can compete with existing crankshaft engine technology. The scavenging, spark, or compression ignition and exhaust release process represent a major challenge for all types of FPE. The piston dictates consequent processes which include compress control. In order to be able to ensure smooth running, the control systems have to start with the nature of the fuel itself and the fuel preparation process. When it comes to piston motion calculations using different fuels, the algorithms can be developed. FPE control requires precise algorithms and optimised operating software for the 'virtual crankshaft'. The piston speed is high, and data traffic needs to be extremely rapid when it comes to sending and receiving sensor information and executing commands. Control functions can only be carried out by using sensitive sensors and high speed reaction valves.

OUTLOOK

The FPE frequency depends upon P_0 and L loads. Therefore the fuel mixture, the moving piston (of between 4–15 kg), the ignition position, and the loads need advanced combustion control strategies in place to be able to properly manage them. FPE load regulation is one method of controlling the combustion process. Fuel injection and exhaust manipulation have only a limited level of influence on the engine's operation and the methods used for fine tuning. Stroke-to-stroke manipulation is carried out by reducing the external excitation and increasing the damping coefficient. The method prevents engine damage and bounce chamber damping. The piston rod stiffness provides a positive effect on external excitation and ignores the initial state. The pressure peaks and working cycle variations are controlled by the piston motion estimation and by accurate injection timing. When using one piston hydraulic FPE, the process of controlling it is less problematic than when using rigidly connected pistons, because every revolution consists of two power strokes. The first piston's compression is the second piston's, which means that the system management reaction rates must be higher. The timing-based injection method reduces pressure variability and means that the resultant kinetic energy will be used. The aforementioned method has a significant effect on the reliability and simplicity of engine operations. The method allows the pressure in the combustion to be controlled, along with the forming of the air-fuel mixture. Accordingly, the most important controlling principle is the control of the entire fuel system, starting from fuel chemical kinetics and subsequent gas dynamics.

The varied stroke causes fuel injection timing problems. The problem can be solved by limiting of the piston stroke interval. The piston oscillation frequency must be increased step by step, until the piston stroke has reached to the maximum value. The load control must restrained within tight limits otherwise the piston hits the cylinder head and the engine stops. The same problem was revealed in the engine starting process, where valve actuation and timing may cause abnormal combustion. FPE misfiring can be caused by a lack of energy storage and, due to the unstable load, the electrical generator cannot work as a flywheel. The engine stops if any interruption is experienced in compression, combustion, ignition, or injection, or a mistiming occurs.

Geometrically, the FPE allows the maximum stroke of the piston to be used, but the long piston stroke and the rapid piston movement are problems when it comes to controlling the FPE. The piston movement frequency and stroke length are directly related. The piston management in hydro/gas/spring bounce or electrical load systems remains within a very limited range. The FPE can operate on limited conditions, when the precise compression into the cylinder and control of the engine are guaranteed. The aforementioned operation parameters serve to limit the power output range of FPE. The bounce and rebound systems are controlled by the 'pulse with modulation' method. This method needs pre-defined mathematical functions, controllers, highly-sensitive sensors, and fast-acting valves to be able to control the engine operation. The precise piston motion control is complicated, mainly in terms of the engine's full load regime.

When a controllable hydraulic cylinder is used in the engine, the piston can be stopped at the BDC, until combustion energy is released at the top of the parallel piston (Fig. 7). This speciality allows the engine to be operated at very low operational frequencies in terms of piston usage, but efficiency is decreased in the optimum range.

The FPE and reciprocating engine comparison is shown in Fig. 7. The rigid connection FPE and regular reciprocating engine piston stroke and velocities are presented in the Fig. 7. The engines have a similar piston stroke and compression ratio (13.9). The piston motion frequency was 48.8 Hz. The time, when FPE piston velocity is equal to zero ($v = 0$ m s^{-1}) (around to the TDC), is longer, compare to reciprocating engine piston velocity (point A in the Fig. 7). The FPE combustion process is quicker compare to reciprocating engine (after the point B). In a conventional engine, the crank mechanism rotates and continuously changes the geometry of the combustion chamber, thereby disrupting the process of complete oxidation. In the FPE, free body motion allows better fuel oxidation to be developed and rapid combustion is directly related to a peak cylinder temperature and heat release in the cylinder which is significantly lower than in traditional IC engines. The complete combustion and the combustion temperature are ways in which emissions can be reduced to a remarkable degree. In the author's opinion, a unique feature of the FPE is between points A and B, as shown in Fig. 7. Fuel mixture burning is a chemical process, which means that the precise fuel mixture preparation process and the related chemical equations must be known in advance. The rate of expansion for burning hydrogen-oxygen is far better than it is for carbon-oxygen and, thermodynamically, the stoichiometric limitations are different, as is adiabatic efficiency. The FPE is capable of working at very low fuel consumption rates, based on lean (30:1) and super lean (50:1) fuel mixtures. Important is adiabatic efficiency not rich air-fuel mixture. When combustion takes place, the shock wave which passes through the fuel makes it burn differently, which is close to the detonation point and is key when it comes to extracting more energy from each kilogramme of fuel. Lean mixtures release more power because more oxygen is in the combustion process, burning carbons and hydrogen. During the TDC piston's dead time there is enough of an opportunity to create the pressure required for burning a very lean mixture and, in a very short time, the temperature will increase enough to support the hydrogen-oxygen reaction. Due to the fast combustion process in the cylinder, cylinder walls are not affected by flame. In addition, in to the cylinder sucked air-fuel mixture is cooling the cylinder wall. From this it can be seen that noise levels are reduced, exhaust gasses do not consist of any useful heat energy, and polluting carbon monoxides are greatly lessened in quantity.

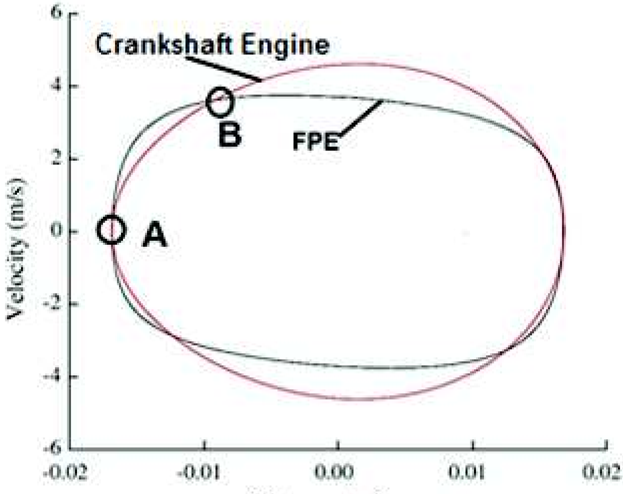


Figure 7. Compared FPE and IC engine velocity and piston stroke (Xiao et al., 2010).

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In conclusion, the piston ridged rod principle should be maintained due to the absence of side forces and lower levels of friction on the piston. According to the engine start-up and operations control problems, useful energy must instantly be withdrawn via the centre of the rigid piston rod and sent to the rotational movement. Not having been subject to cooling, the reciprocating moving magnets or ferromagnets are not stable and cannot produce sufficient current at a stable frequency. It is possible to use an external frequency converter to produce the current at the stable frequency but this is an additional cost and also acts as extra ballast for the system.

The solution which is being proposed by the author is as follows: the rotating flywheel is polyfunctional, and is positioned on top of the two piston one-rod engine, and rotates horizontally as shown in Fig. 8. The flywheel ensures the stability of the generator and stores energy for the next load peak. The rotating flywheel carries magnets which are placed on the outer side of flywheel.

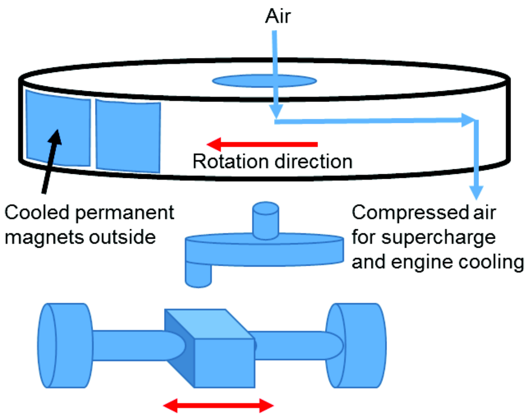

Figure 8. The simplified design of the FPE generator.

The permanent magnets and coil windings are kept outside and are constantly cooled. The normal port scavenging in a lean mixture situation is insufficient, and as a result the engine must be supercharged. The flywheel compresses air for supercharging and engine cooling via inner channels. The air cooled engine is powerful and excludes the outer cooling system. Finally, the flywheel serves to stabilizes the combustion engine and reduces piston movement vibrations. Such a configuration keeps the engine-generator (GENSET) flat, with a very low centre of gravity, and horizontal rotation adds stability. The solution is a two-stroke engine, with two power strokes per revolution. Combustion will be carried out after each 180^{o} degrees stroke. The recommended piston stroke is 1.8 of the piston diameter and should not be variable. The piston rod consists of two parts: (1) a lightweight piston with sleeve; and (2) the reciprocating rigid rod. The sleeve keeps the piston in TDC for a longer period of time as it moves freely on the piston rod. The compression stroke starts and the air-fuel mixture compresses until TDC is reached. The connected flywheel with its piston rod moves towards the BDC and the spark ignites the mixture. From this point forwards, combustion continues towards the BDC. The engine has outlet and inlet ports and charging takes place through electric valves which are located on top of the cylinder. The heat exchanger pre-treats the fuel and uses exhaust gasses for heating and breaking down fuel molecules. The engine lubricates itself from the crankcase, which is a small area of the engine and which uses the piston rod reciprocating motion for pumping oil. Crankcase lubrication allows fuel injection without any oil admixtures. The flywheel with its magnets acts in a contrary fashion and works as the engine starter.

CONCLUSIONS

The different technical solutions which are available in terms of FPE have been reviewed from the point of the system's invention until the present day. The simulations and empirical experiments have all been discussed. Any weaknesses or strong points related to FPE have been mapped out and discussed in a critical fashion. The most important findings are these: 1) there exists a significantly lower kW kg^{-1} ratio in proportion to crankshaft engines; 2) lower fuel consumption rates have been registered against those of crankshaft engines due to the lower friction levels; 3) the missing crankshaft allows the engine dimensions to be significantly reduced and, at the same time, allows the maximum piston stroke to be applied and lower temperature release to be achieved due to the rapid burning process which in turn reduces the levels of emissions.

The most important points to identify in relation to FPE are these: 1) piston movement is too complicated to control; 2) during engine operations, three variables should be precisely controlled at the same time, with these being the following; 3) air-fuel mixture, engine load, and volumetric efficiency.

The technical solution which involves a new power generator is described with the general description of generator operation. The most important advantages in this novel solution are these: a slim motor-generator with the aforementioned planetary moving flywheel/generator rotor which stabilises the system based on the spinner effect; the flywheel is also supercharger; two stroke engine with crankcase lubrication allows to use fuels without oil; internal combustion engine combustion process is controlled by crankshaft, what is connected to ridged rod of piston.

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