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The Free Piston Power Pack: Sustainable Power for Hybrid Electric Vehicles

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ABSTRACT

The Free Piston Power Pack (FP3) represents a new concept in the design of free piston engines. The FP3 is a free piston engine with an integral generator for electrical power output. Its novel features are an integral compressor and a passive intake valve located in the head of the piston. These improvements eliminate undesirable problems that affect conventional free piston engine designs, such as piston ring wear and the need for an external compressor, and allow a significant increase in power density. The FP3 is designed to meet the highest levels of fuel efficiency and exhaust emissions performance in a compact size for use in hybrid electric vehicles (HEVs). This paper describes the design of the FP3 and gives details of the operation and construction of a prototype.

INTRODUCTION

The inherent advantages of the free piston engine concept have prompted much research investment by major automotive and government organizations [1, 2, 3]. The benefits arise from the elimination of the crankshaft and connecting rod, and the simple linear motion of the piston:

- Mechanical simplicity gives efficient, compact and direct conversion of piston motion to electrical energy (hydraulic output free piston engines are also being developed by others).
- Virtual elimination of piston side-load forces improves performance of and simplifies design of the piston ring seal.
- Operating speed is approximately constant over the load range. This enables gas exchange systems and timing requirements to be highly optimized for the narrow speed range.
- Choice of length of stroke is independent of crankshaft considerations. Similarly, compression ratio is freely adjustable during engine operation.

However, conventional implementations of the free piston engine have limitations that will prevent their widespread use:

- Accelerated piston ring wear caused by the use of intake and/or exhaust port slots. The wear over time leads to degraded engine and emissions performance. This is a disadvantage associated with two-stroke engines in general.
- The need for an external compressor which increases the space requirements of the engine.
- The layouts of conventional free piston engines are constrained by the arrangement of the engine components. As a result, they tend to be physically long and unsuited to the requirements of the engine bays in existing passenger vehicles.

FREE PISTON POWER PACK

The FP3 retains the fundamental advantages of the free piston engine concept while addressing the problems listed above. The new features of the FP3 are:

- High power density of two-stroke cycle combined with high fuel efficiency and low exhaust emissions.
- Long life, high performance piston seal and mover bearing.
- Many space saving features that more than double the power density of the FP3 compared to the best existing free piston engines.
- Dimensions that enable it to fit easily into the engine bay of existing passenger vehicles.
- Dynamic balance for reduced NVH.

Figure 1 shows the layout of the FP3. The general specifications are:

- 100 kW peak power
- Displacement 2.82 liters
- 8 cylinders (consisting of 4 free piston modules, each with 2 cylinders)
- 30 Hz operation – equivalent to 1800 cycles per minute

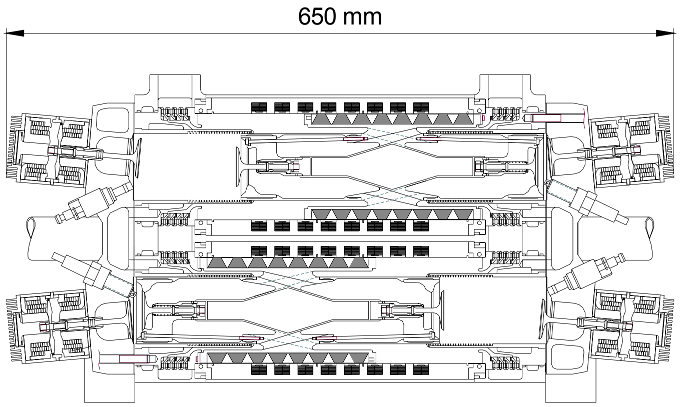

Figure 1: Layout of the Free Piston Power Pack.

Pempek Systems is currently developing a prototype of the FP3 based on a single piston module. Testing of the electro-pneumatic exhaust valve is complete. Fabrication of the engine and generator hardware has been completed and testing is in progress.

On a point of nomenclature, in this paper the main moving component is referred to as the mover. Due to the highly integrated nature of the FP3, the mover has several sub-features (e.g. combustion pistons, compressor chambers, generator magnet assembly) which are referred to individually.

PASSIVE INTAKE VALVE

The intake port in the FP3 is a seated poppet valve located in the head of each piston [4], as shown in Figure 2. The intake valve operates in a completely passive manner, that is, there are no external controls. The motion of the intake valve is governed by the difference in pressures of the cylinder and compressor acting across the valve, the force of a gas return spring and the dynamics of the mover.

In the operation of the FP3, opening of the intake valve is synchronized to the opening of the exhaust valve. During the compression, combustion and initial expansion of the cylinder volume, the high pressure in the cylinder keeps the intake valve tightly shut. On approach of the mover to BDC the exhaust valve is opened to commence the gas exchange process. This causes the cylinder pressure to drop below the compressor pressure and the intake valve is forced open. The intake valve remains open as long as there is sufficient flow pressure to work against the return spring force. The intake valve eventually closes under the action of the return spring and the reversal in direction of the mover at BDC.

The gas exchange process in the two-stroke cycle should be completed in the fastest time possible – to allow the longest possible expansion of the combusted gases, and the longest stroke for compression of the fresh air. This requires a short actuation time and large flow cross-sectional area. The valve has a seat diameter of 36 mm and the maximum stroke is 10 mm. Since the opening force on the intake valve is fixed, the actuation speed can only be increased by reducing the moving mass, i.e. the valve and stem, and the return spring. The valve and stem are manufactured from titanium. The return spring is a gas spring on the stem of the valve and is sealed with piston rings. It is charged via a small port when the valve is in the closed position. A weak coil spring provides a closing force to ensure that the gas return spring is charged when the engine is started.

The passive intake valve provides three significant benefits for the design and performance of the FP3.

UNIFLOW GAS EXCHANGE

The intake and exhaust valve arrangement of the FP3 provides uniflow scavenging of the cylinder.

ELIMINATION OF CYLINDER SLOTS

The cylinder wall of the FP3 is completely free from gas exchange slots, and the piston rings run on an uninterrupted, cylindrical surface. It is therefore possible to apply to the FP3 the piston sealing technology that has been developed for modern four-stroke engines. However, even better long-life performance is expected for the piston ring seal in the FP3 because the pistons and cylinder walls of free piston engines are subject to substantially lower wear-inducing lateral forces than those of crankshaft driven engines. Further aspects of piston sealing are discussed later.

AXIAL LENGTH REDUCTION

In a conventional free piston engine, access must be provided to the outside of the cylinder for ducting of fresh air to the intake cylinder slots. This disallows any other major components, the generator in particular, from being mounted around the cylinder, as shown by the hatched regions in Figure 3a. Therefore, the cylinders and generator must each occupy their own axial section in the engine. The length of the generator section, and hence the distance between the cylinders, is at least as long as the length of the moving section of the generator, L, plus the stroke, S. Since the dimension L determines the rating of the generator, it can be expected to contribute significantly to the length of a conventional free piston engine.

Using the passive intake valve in the FP3, the supply of fresh air to the cylinder is in an axial direction through the rear of the piston. This leaves the outside of the cylinder free from any external ducting and enables the generator to be overlapped with both cylinders. In this case the distance between the cylinders is limited only by the axial length of the support for the generator magnets, W, plus the stroke, S, as shown in Figure 3b.

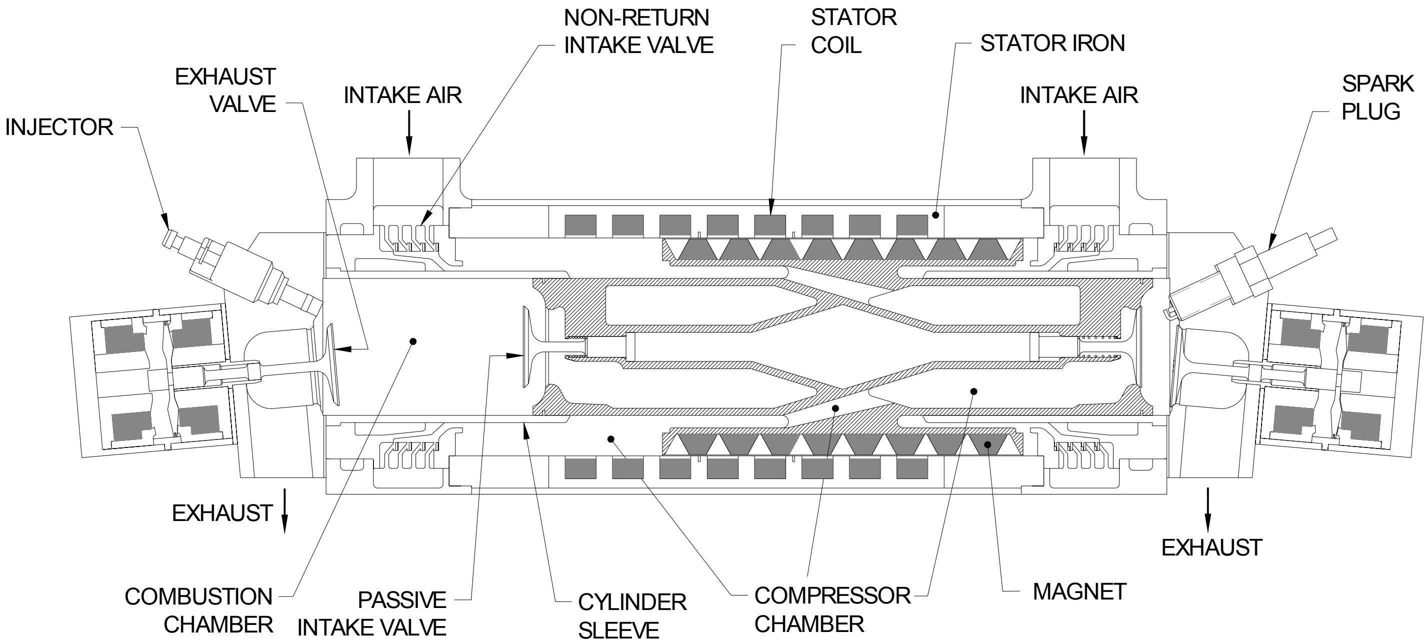

Figure 2: Simplified cross-section of a single FP3 free piston module.

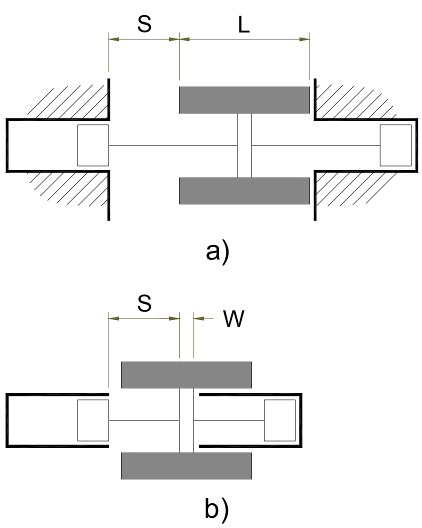

Figure 3: Conceptual diagram showing axial length constraints for a) conventional free piston engine, and b) FP3. Cylinders are shown by heavy lines on the left and right. Dark areas represent the generator magnet assembly. See text for explanation.

COMPRESSOR

Two stroke engines require a compressor to drive the gas exchange process. All free piston engine designs published to date make use of an external compressor which adds significantly to the volume of the overall engine. The FP3 eliminates the extra space required for an external compressor by incorporating this function into the existing outline of the engine [4] – see Figure 2.

There are two compressors in the FP3, one for each combustion cylinder. Each compressor is identical, and is comprised of a compressor chamber, a non-return intake valve and a piston. The intake valves are annular in shape and are located co-axially on the outside of each combustion cylinder sleeve. The compressor chamber comprises the volume around the outside of the combustion cylinder sleeve, and a volume inside the opposing combustion piston that feeds air to the combustion chamber through the passive intake valve. These two volumes are connected by linking cavities in the central section of the mover. The linking cavities for both compressors must pass through the same region and must be arranged so that they pass by each other without connecting the two compressors. Two piston rings seal the outer surface of the mover to prevent air leaking from one compressor to the other.

The mover functions as the compressor piston. As the mover traverses from one end to the other, air is drawn into the expanding compressor chamber through the non-return intake valve. When the mover reverses direction, the non-return valve closes and the air in the chamber is compressed. The compression ratio can be chosen by design. Near BDC, the passive intake valve opens to allow the compressed air into the combustion chamber and flushes out the exhaust gases.

Any gases that blow-by the combustion piston seal appear in the compressor chamber that feeds the opposing combustion chamber. This provides an in-built mechanism for the recirculation of exhaust gases and hydrocarbons. The small, extra volume of gases introduced into the compressor is not expected to affect the dynamic behavior of the FP3.

GENERATOR

Design of the generator is focused on providing a high level of integration into the FP3, because it is central to the energy conversion process. As has been previously discussed, the generator overlaps the combustion chamber. The generator uses a permanent magnet topology for the highest possible power density and efficiency. The AC output of the generator is converted to DC by an external power conversion block. Refer to Figure 2 for details of the generator design.

The magnets are high energy-product NeFeB magnets, which can be manufactured with the desired trapezoidal section. The iron pieces are made from SM2 powdered iron from MII Technologies, which has high saturation flux density, low losses at operating frequencies up to 250 Hz and good shaping properties.

In order to maintain the small radial dimensions of the FP3, it is important that the generator has a low radial profile. By using magnets that are axially magnetized, the need for back-iron (magnetic steel underneath the magnets) is removed and the mass of the mover can be reduced. Eight rings of magnets are used in a multi-pole arrangement in order to reduce the length of the flux paths. This also reduces the flux per pole and, hence, the radial thickness of the back-iron in the stator side of the generator.

The magnets are situated on the mover, which minimizes the heat generation on the mover. Adjacent magnets have like-poles facing each other and have an iron pole piece between them which acts as the magnetic pole on the surface of the mover. The magnets and pole pieces are manufactured as half-circle segments which are glued to the mover.

The generator mover is encased in a 0.5 mm thick steel sleeve which acts as the bearing surface for the mover. The sleeve is thick enough to contain the forces between the magnets, but thin enough to be insignificant as a short-circuit path for flux between adjacent magnetic poles.

Copper strip is used for the stator coils to achieve a high slot fill factor. The coils are pre-assembled and stacked with the axially-sectioned stator iron. The pitch of the stator teeth is different to the pitch of the mover magnetic poles to minimize cogging forces. Water cooling is provided for the stator.

The stator coils are connected to inverters which control the flow of energy between the coils and the battery system. The inverters are controlled by digital signal processors which maximize the efficiency of the power extraction and coordinate with the engine control unit. The generator is also used as a motor to start the engine by providing an initial, electrically-powered stroke to create the compression required for the first combustion-driven stroke.

ELECTRO-PNEUMATIC EXHAUST VALVE

The exhaust poppet valve is driven by a high-speed electronically controlled actuator [5]. Figure 4 shows the physical layout of the valve and actuator. The actuator has two opposing solenoids that share a common armature. The armature is connected to the valve stem and the solenoids apply forces to open and close the valve. Each solenoid incorporates a gas spring formed by the space between its pole face and the armature. The edge of the armature is sealed with a piston ring to prevent air leaking between the two opposing gas springs.

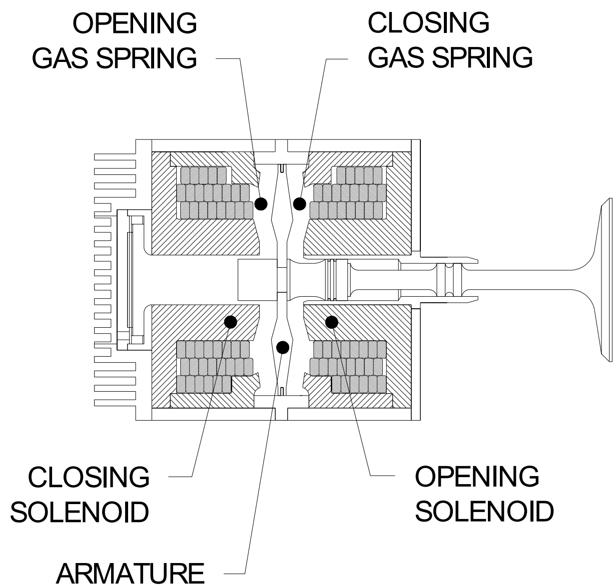

Figure 4: Simplified diagram of electro-pneumatic exhaust valve.

As with the passive intake valve, the exhaust valve must operate as fast as possible. Due to the long air gap in the magnetic circuit, the solenoids by themselves are not able to achieve the required forces without being excessively large. The use of a spring provides stored energy to assist the acceleration of the valve [6]. We have opted for gas springs primarily because of their low mass.

The valve and stem are fabricated from titanium and the steel armature has been sculpted to remove unnecessary material. The total moving mass is 92 g. The valve has a seat diameter of 36 mm and the maximum stroke is 8 mm. The prototype exhaust valve unit has a measured actuation time of 6.0 ms for a stroke of 7.1 mm which meets the requirements of the gas exchange process, though tests show that there is the possibility for further reduction of actuation times.

In the closed state, the exhaust valve is held shut by the closing solenoid against the force of the compressed opening gas spring. The air in the closing gas spring is at atmospheric pressure.

Opening of the exhaust valve commences with the de-energization of the closing solenoid. The opening gas spring is then able to force the exhaust valve open. As the valve opens, the pressure in the opening gas spring decreases and the pressure in the closing gas spring increases. The increasing force exerted by the closing gas spring causes the armature to reverse direction and closes the exhaust valve. When the exhaust valve returns to the closed position the closing solenoid is re-energized to hold the valve shut.

During actual operation, losses in the system mean that the exhaust valve does not fully return to the closed position. Suitable energization of the solenoids while the armature is moving compensates for these losses. Such energization is also used to reduce the lift of the exhaust valve.

MOVER BEARING

In the FP3, the primary bearing surface of the mover is the interface between the generator stator and the mover. The ultimate intention for the FP3 is that this bearing be service-free for the life of the engine. The bearing normal forces are predominantly due to the weight of the mover and the unbalanced magnetic pull of the generator. By design, the maximum bearing contact pressure is 0.02 MPa, and the mover speed is less than 10 m/s. This allows much scope for the selection of long-life bearing materials and lubrication techniques, including dry lubrication. In the current design of the FP3, the bearing surface of the mover is a steel sleeve that runs on aramid composite bearings which are installed between the stator iron poles.

PISTON SEALING

The simplified diagram of Figure 2 shows a standard piston ring seal. Such an arrangement has been shown to be effective over the life of modern two-stroke engines [7], and the performance will improve when used in a free piston engine. It does, however, rely on the use of a suitable low emission lubricant.

While the above technique is proven, we have chosen to trial a potentially superior sealing method for the prototype FP3 that uses a piston ring and labyrinth seal on the cylinder. The labyrinth seal reduces the cylinder pressure seen at the piston ring, which can be designed for much lower friction and wear rate than is possible in a conventional engine. The piston ring is installed into the bottom of the cylinder and a series of labyrinth seal grooves are cut into the wall above it. The piston is a plain cylinder. This method is not possible in a conventional crankshaft engine because the short length of the piston relative to the stroke does not provide the necessary overlap.

The materials for the cylinder and piston were chosen to give a good running fit over temperature to control the crevice volume. The cylinder is a water-cooled cast iron sleeve. The piston is a titanium sleeve, which has a low friction, low wear surface treatment applied.

Once this piston sealing technique has been verified, there are possibilities for further improvement. Instead of the piston ring, other low pressure seals, such as a carbon or composite polymer rod seal, could be used with the intention of achieving a lubrication-free piston seal. Reduction of the crevice volume can be achieved using metals and/or ceramic composites that are currently being investigated for ring-less pistons in conventional four-stroke engines [8].

OPERATING FREQUENCY

The motion of the mover is largely controlled by the second-order mass-spring system comprised of the mover mass and the spring effect of the combustion chamber gases. For a given stroke, the operating frequency of a free piston engine is therefore affected by the mass of the mover [1]. As with all cyclic energy conversion devices, a higher operating frequency leads to higher power density (so long as the increased frequency does not have a detrimental effect on other aspects of the system). This consideration also applies to the generator. In light of the above, the design of the FP3 was geared to achieving the highest operating frequency.

MOVER MASS

By minimizing the mass of the mover, the natural frequency of the mover can be increased. The mover is largely hollow and is fabricated from aluminum. The length reduction afforded by the overlap of the generator and combustion chambers also reduces the length of the mover. The moving mass of the generator is minimized by the removal of the back-iron in the magnet assembly. The total mass of the mover is 5.2 kg. Simulations of the FP3 predict an operating frequency of approximately 30.4 Hz for a compression ratio of 9.8 at peak power.

MODULAR DESIGN

A major design feature of the FP3 is the use of four free piston modules in one engine. An important benefit of using four units in parallel is that the forces and moments of the individual units can be cancelled to achieve dynamic balance. This translates into improvements in noise, vibration and harshness.

Also, a simple, first-order analysis shows that a higher operating frequency can be achieved with multiple smaller modules, rather than one larger unit.

Consider the uniform scaling of the free piston engine in all three linear dimensions by the factor dx. The power generated by the engine is proportional to the capacity and speed (frequency) of the engine. The amount by which the power changes due to scaling, dP, is given by

$$dP = dC \times dF$$

where dC is the change in the capacity of the engine, which is simply dx^3, and dF is the change in operating frequency. By ignoring the effects of combustion and to a first-order approximation, the natural frequency of the mover is proportional to the square root of the spring stiffness divided by the mover mass. Assuming a constant compression ratio, the stiffness of the combustion chamber gas is proportional to the bore area and the inverse of the stroke. It can be shown simply that the change in frequency is given by

$$dF = dx^{-1}$$

and therefore

$$dP = dx^2.$$

The scaling factor for the volume of the whole engine, dV, is equal to dx^3. Hence,

$$dP = dV^{(2/3)}.$$

This shows that as a free piston engine is scaled up the power output increases at a lower rate than the engine size. This analysis ignores the secondary effects of scaling, but indicates the underlying trend.

By using four smaller free piston modules, the FP3 is able to generate more power than a conventional free piston engine with the same capacity. Assume that the power output of a single FP3 free piston module is known to be 25 kW at an operating frequency of 30.4 Hz. Being comprised of four such modules, the FP3 simply has a rating of 100 kW. In contrast, if the single free piston module is uniformly scaled to be four times the volume, this analysis predicts that the operating frequency drops to about 19.2 Hz with a corresponding drop in the output power to approximately 63 kW.

OTHER FEATURES

HIGH PRESSURE DIRECT INJECTION

Direct injection of fuel after the exhaust and passive intake valves have closed eliminates the possibility of cross-flow of fuel from intake to outlet during scavenging.

SPARK IGNITION

Spark ignition enables the compression ratio to be varied by adjusting the instant of the start of combustion. This is in contrast to compression ignition systems.

LONG STROKE

Compared to conventional engines, the FP3 is designed with a relatively long stroke (103 mm) and small bore (66 mm). This aspect ratio promotes higher combustion efficiency and helps to minimize the volume of the FP3. The long stroke aids in the design of the generator.

The small bore does not adversely affect the scavenging performance. Conversely, the scavenging performance is expected to be excellent due to the relatively low and constant operating frequency of free piston engines and the relatively large valves.

MULTI-FUEL CAPABILITY

The FP3 lends itself to operation with many different combustion technologies and fuels, including hydrogen.

CONCLUSION

The Free Piston Power Pack removes all significant impediments of conventional free piston engine designs. The main innovations in the FP3 are the elimination of gas exchange slots in the cylinder, an integral compressor and other space saving features. The FP3 provides the direct generation of electrical power with high fuel efficiency and low exhaust emissions in a very compact volume. The FP3 realizes the well understood potential of the free piston engine concept and is an ideal source of sustainable power for use in HEVs.

Construction of a prototype FP3 free piston module is complete and testing is in progress. Current work is focused on the electronic control of the generator and electronic starting of the engine. The generator control system and electro-magnetic forces show good agreement with our simulation results. The next stage of testing is to investigate the dynamic behavior of the module with combustion and to implement the engine control algorithms. The final phase of testing will investigate the fuel efficiency and exhaust emissions performance.

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