A High Specific Energy Output Free Piston Engine-Generator (HISEN-FPEG) for Hybrid Electric Vehicles and Electric Utility Power Generation

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Abstract:

Various alternative power sources offer unique benefits, each with advantages and disadvantages in power, weight, size, fuel economy, emissions and cost. This project concerns the development of a high speed Reciprocating Rapid Compression Machine (high speed free-piston engine) for the generation of alternating current (AC) and direct current (DC) electricity. The mechanism consists of a straight cylindrical connecting rod with outwardly facing pistons fixed to each end, whereby the piston-rod assembly shuttles back and forth in a linear manner, from combustion in directly opposed cylinders, and employs a linear alternator incorporated in the system to generate electricity.

The engine-generator design offers a simple small, lightweight, low cost powerplant with a very long overall life. This Gen-Set concept, under development, may utilize a variety of combustion processes and result in very low fuel consumption and very low emissions that shall meet CARB and EPA requirements well into the forseeable future.

This paper is meant to help further the understanding by interested parties of this technology, and examines the free piston engine-generator mechanisms. Various designs of free piston engines are presented along with explanations on the combustion process, friction, and pumping loss characteristics that enable the Galileo EnGen free-piston engine-generator to become the powerplant of choice for hybrid electric vehicles and for the production of electricity for the national electric utility grid.

I. Introduction

A great deal of interest has been expressed recently in hybrid electric vehicles (HEV) both for their potential of pollution reduction and their increased range over electric-only vehicles (EV). Such a concept is useful as an alternative in the near term, before high specific energy batteries are developed and commercially available for the electric vehicle.

The ultimate goals are to minimize annual emissions, minimize vehicle operating costs, maintain or exceed the performance (such as power-to-weight ratio, acceleration, gradeability, and fuel economy) of the current engine design. Hybrid vehicles are seen as an approach to accelerate the introduction of cleaner electric vehicle technologies by combining electric vehicle battery technologies with fossil fueled propulsion systems. HEV can also provide energy security for this nation, since they displace some petroleum with electricity which may be generated from a number of abundant and indigenous sources.

In a HEV, a small engine and generator (genset) is added to a basic electric vehicle design. This genset will sustain vehicle operation beyond the range provided by the batteries. The additional weight of the genset and fuel is balanced by the removal of some of the vehicle's batteries. In the parallel hybrid design a small engine is used to provide additional mechanical power to supplement battery power when desired such as under heavy acceleration or to provide alternative driving modes. This configuration may provide a greater flexibility but it will add significant weight along with the creation of space constraints and will be difficult in contriving a suitable drivetrain and control strategies for the optimal operations of the parallel design [1,2,3].

In the serial hybrid design (Range Extender Vehicle, REV) the driveline is dictated by the electric motor. The electricity that powers the electric motor is either from the batteries or the batteries and a genset working in unison. The REV begins its day on battery-only operation, and then at a predetermined point the genset is turned on by the vehicles's system controller. The genset and the batteries could be utilized during a certain portion of travel in order to prevent the batteries' deep cycling.

A two-phase study on the serial HEV, or REV was commissioned by the Electric and Hybrid Propulsion Division of the Department of Energy [3]. A number of engine types were selected for evaluation for this program These engines included Orbital 2-stroke SI, GM Quad4, Nomac Turbine, NASA S-70 rotary and MTT MOD-II Stirling engines. Only the GM Quad4 engine could provide a adequate power to meet all test criterions such as acceleration, gradeability and fuel economy. But its power output is overrated for HEV and it is quite expensive. In addition it may not be able to fulfill the compactness required for HEV applications.

The schedule and charts below show developing technologies and how other current high tech generator sets measure up against each other. The Power/Weight Ratio comparison chart is important to the Hybrid Electric auto, as its power plant must be as small and lightweight as possible while possesing good power output. The Power/Fuel Consumption comparison chart tells fuel economy which is important to both the hybrid electric auto and the utility industry, as this tells the cost of electricity (power). These graphs show that the Galileo EnGen is small and light weight and obtains more power per gallon of fuel than any other type of high tech power plant in development today.

Within both of the observed charts, and in other combined areas such as size, weight, emissions, cost to manufacture and maintenance, the Galileo EnGen far outdistances any other leading technology. Reasons for this amazing capability stem from the reduced number of moving components and combustion dynamics.

Power Plant Comparison Chart *

Item #	Power Plant Type	Weight w/o Generator	Weight w/Generator	Fuel Consumption Gallons/hr.	Power Output Max HP	Power/Weight w/o Generator	Power/Weight w/Generator	Power/Fuel Consumption HP-hr / gallon
1*	GM Quad 4 4-Stroke Engine	300.	350.	10.9	118.0	0.39	0.34	10.82
2*	Stirling Engine	400.	450.	5.1	64.4	0.16	0.14	12.63
3*	Fuel Cell	500.	500.	2.2	33.5	0.007	0.007	15.23
4*	Rotary Engine	90.	145.	4.4	37.6	0.42	0.26	8.54
5*	Orbital 2-Stroke Engine	90.	145.	7.0	70.0	0.78	0.48	10.00
6*	Gas Turbine Engine (Turbo Alternator)	85.	135.	2.4	32.2	0.38	0.24	13.42
7	Free Piston Engine	n/a.	125.	3.5	67.0	n./a.	0.53	19.14

Source: SAE

* source: data compiled from Society of Automotive Engineers technical papers.

It was shown that traditional engines (GM Quad 4, Rotary, Orbital 2-Stroke) used in the DOE's program have numerous drawbacks [3,4] that might hinder these engines from being used as a genset for HEV. After all, these engines were not designed for making electricity in the first place. They are primarily designed for producing torque for the powertrain mechanism. Other powerplants such as the Stirling engine and Fuel Cell produce electricity directly and are efficient in doing so, but they are very heavy and large. One example recently shown was a proton exchange fuel cell powered vehicle. The vehicle was like a small pickup with the fuel cell filling the entire bed of the truck, which makes it impractical for HEV use. The Gas Turbine engine is relatively small and efficient, but is very expensive to build, requires frequent costly maintenance, has a large intake and exhaust system, and a constant high pitch whine, due to operating speeds of 90,000 rpm presents a noise nuisance.
Some of these engines may meet the specified driving requirements, but they may not meet the other constraints such as low emission, compactness, better fuel economy and serviceability requirements for the HEV [3].

One of the keys to the success of the HEV is to have an engine that can produce electricity more efficiently, with less emissions and a compact size to accommodate the space for batteries and accessories (e.g., heating and air conditioning). An engine to be used in the HEV has to fulfill several criterions. First, the power rating of engines for hybrid vehicles is relatively low (20 - 70 kWe); because the engine will not have to provide alone the peak power during vehicle accelerations. The engine will be road-leveled during accelerations by the electric driveline and its energy storage units (batteries or capacitors). [3] Engines of these small sizes (displacement, number of cylinders, air and fuel flows, etc.) that are currently available have not been designed, built and tested. Second, the engines in hybrid electric vehicles will be operated in a relatively narrow range of torque and speed and in on-off modes which are much different than in conventional vehicles. None of the currently available engines have been optimized with this regard. Third, little work has been done to minimize emissions for any of the engines in the hybrid operating modes. Therefore, it is quite uncertain which of the engine types are best suited for the HEV application and the use of new emission control technologies (such as electrically heated catalysts and reducing NOx catalysts) to reduce the hybrid vehicle emissions to very low levels.

It is here to propose the free-piston engine-generator that is specifically designed for HEV application. With a significant reduction in the moving parts such as multiple crankshaft journal bearings, this engine can obtain a better mechanical efficiency. The massive crank shaft, counter-weights and fly wheel as appear in conventional engines will be replaced by a generator mechanism (magnets and coils) and result in an overall reduced weight. The electricity inducting mechanisms (magnets and coils) are integrated within the engine itself to form a very compact genset unit. It is compact (approximately 2.5 ft in length) and light weight (air or liquid cooled, less than 90 lbs with generator) which can meet the spatial and weight constraints of HEV. Refer to Figures 4a-4c on page 8. By adopting advanced fuel managing strategies and homogenous charge compression ignition (HCCI), intake design, and engine-out treatment, it is able to meet current and future emission and fuel economy standards . This experimental unit will produce a moderate rated power (20 - 30 kWe) on a continuous basis which is suitable for a HEV under development. In addition to the HEV application, the free-piston genset can be used as a mobile generator, compressor or vacuum pump.

II. Concept of the Free-Piston

Within the internal combustion engine, whether it be spark ignition (SI) or compression ignition (CI), combustion of a fuel is the driving force. The reciprocating linear motion of a piston is converted into a rotating motion via a connecting rod and crankshaft by which the mechanical energy in reciprocating motion is transmitted to the other drive-train mechanisms (transmission, water pump, alternator, ... etc.).

Each stroke within a power cycle, a piston has to travel a fixed distance before commencing the next stroke. These types of engines have to be fine tuned in order to prevent knocking (spark knock or end gas knock). In addition to the loss of power, knocking in either types of engines is detrimental to the mechanical parts. Energy produced by knock can not be relaxed because the piston is designed to travel a fixed distance.

At least two variations of free-piston engines have been thought and built. The engine, which was built by the Jarret brothers [5] (shown in Figure 1), constitutes one centrally located combustion chamber and two opposing pistons. A piston guide-fluid chamber assembly is linked to the non-firing face of each piston. Magnetic-ring inductors ride on the assembly and produce electricity when moved back and forth. The fluid chamber serves as a hydraulic spring that will store energy (from combustion) for the piston's return travel during the compression stroke. It has been demonstrated that Jarrets' engine is very compact and light weight. With proper optimization, this engine also could achieve an output of 1.3 hp per cubic inch of displacement. However, the fluid chamber design of Jarrets' engine may suffer from a significant amount of energy loss and requiring proper tightness in seals.

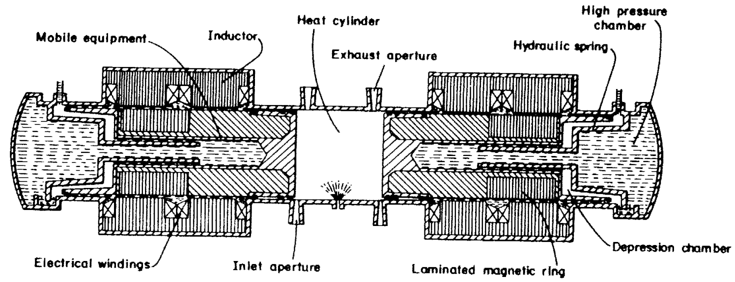

Figure 1 Jarret Free Piston Engine

The free-piston engine of Stelzer [6], shown in Figure 2, is comprised of centered pre-compression chambers and two opposing piston-combustion chambers which are connected by a common rod. A piston-like disk is located in the prechamber and seated on the connected rod. The fuel-air mixture after being inducted into one side of the pre-chamber is then transferred into the combustion chamber via a number of transfer passages built within the engine block. The fuel-air is then compressed and ignited. Part of the power generated from combustion is consumed to facilitate the fuel-air induction, transfer and compression processes of the other side of the assembly, and due to porting, emissions may be a problem. The Stelzer engine was claimed to operate at a high speed of 30,000 cycles per minute. However, there is no technical data available to substantiate his claim.

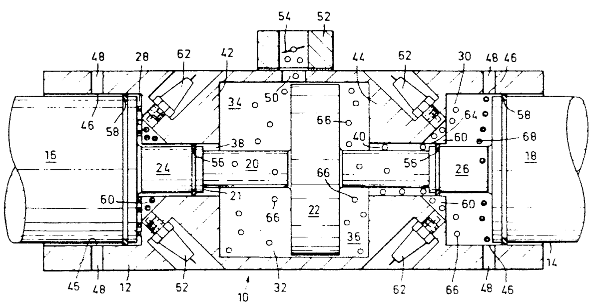

Figure 2 Stelzer Free Piston Engine

Another configuration of the free-piston engine by Galitello [7], shown in Figure 3, is that two combustion chambers are placed in the opposite direction. Their pistons are linked by a straight connecting rod. The pistons are shuttled back and forth as the result of the combustion taking place in the cylinders alternatively. By mounting the electricity inducting mechanism onto the connecting rod, the mechanical energy in a linear motion can be converted into electrical energy. The stroke that the piston travels can vary within its maximum allowed distance and is dictated by the autoigniton characteristics of the fuel and air-to-fuel ratio. This free piston mechanism allows greater flexibility to relax the energy (pressure) created by knock. The quality (frequency and voltage) of the electricity generated can be manipulated by fine tuning the engine to run at a specified cycle.

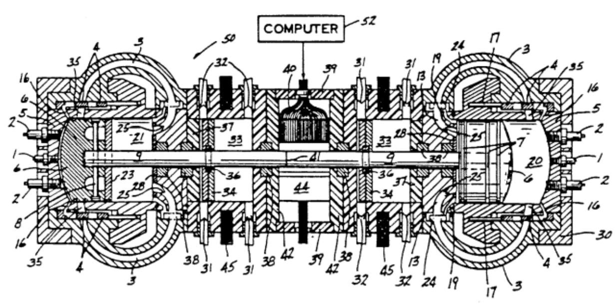

Figure 3 Conceptual Galileo Free Piston Engine

A judgement is that the free-piston engine has lesser moving parts (such as crankshaft journal bearings) compared against traditional reciprocating engines. The thrust and anti-thrust forces (piston slap) exerted between the rings and cylinder are eliminated since the plain of a piston is always normal to the connecting rod. The friction between the piston rings and the cylinder wall can be greatly reduced. Because of its simplicity and less frictional loss, this engine is able to achieve a power-to-weight ratio and brake specific fuel consumption far better than conventional designs. In addition, it allows tighter piston-cylinder wall clearance. This will lead to reduced blowby and less unburned hydrocarbons trapped in the top land and ring grooves which will result in cleaner engine-out emission.

III. Concept of Homogenous Charge Compression Ignited (HCCI) Combustion:

Achieving a homogeneous, ignitable fuel-air mixture is the key to ensure a quick and thermo-chemically allowed complete premixed combustion. The mixing processes of the fuel and air is dictated by the fluid motion (turbulence, air entrainment and dispersion) and by the volatility of the fuel. For a gaseous fuel such as CNG and LPG the homogeneous fuel-air mixing and relatively complete premixed combustion can be easily achieved. Engines that are fed with these fuels can be operated with a leaner mixture and at a higher compression ratio.

For most SI engines, the homogeneity of the fuel-air mixture and good quality of premixed combustion can be achieved at a steady operating mode after the engine has been warmed up. The air-to-fuel ratio is usually tuned in at stoichiometry in order to obtain a better performance (no knocks) and reduced levels of emissions. However, for conventional intake design (carburetor type or throttle body injection type) the gasoline engine mostly likely will suffer momentarily acceleration lean-out, deceleration and cold-start enrichment which are caused by the incomplete vaporization of the fuel (heavy ends) and mixing of the fuel and air. These problems are well known to cause high levels of emission.

Extensive research (such as swirl induced shrouded valve lip, tumbling assisted vane in the intake manifold, heated impingement plate, and direct fuel injection, ... etc.) has been explored to enhance the fuel and air mixing process. By facilitating the electronic fuel injection the air-fuel mixture can be more accurately prepared which results in a significant reduction in engine-out emission.

For conventional diesel engines, a homogenous fuel-air mixture is difficult to achieve. It is because the fuels used in diesel engines are less volatile than gasoline. The fuel is directly injected into the cylinder near the end of the compression stroke. The combustion is initiated at spots where the ignitable mixture of vaporized fuel and air is formed. A short duration of the premixed combustion precede the diffusion combustion. The overall air-fuel mixture is quite lean with diesel engines. With the higher polytropic compression heating, finely atomized fuel spray and properly configured injection and piston crown design, a better fuel-air mixing and vaporization can be achieved. This will result in a better quality of pro-premix combustion and a better emission.

The operational principal of a stratified gasoline engine is very close to that of diesel engines. This type of engine has shown a better improvement in fuel economy and performance over the conventional design of SI engine [8,9], but it was notorious for its exhaust emission. What might have caused this problem was ascribed to the insufficient fuel and air mixing which resulted in incomplete combustion and high levels of unburned hydrocarbons.

The concept of the homogeneous charge compression ignition (HCCI) engine is to facilitate the combined merits of premixed combustion of a SI engine and the lean-burn and non-soot low emission of a diesel engine. In a HCCI engine the combustion takes place uniformly in the combustion chamber. Unlike the conventional SI engine where the flame propagation is clearly discernable, the ignition occurs at numerous hot spots and then high temperature region spreads out in all directions. The overall combustion duration is much shorter than that of traditional SI engines because the average path for flame propagation is comparatively shorter.

The quality of combustion is determined by how the mixture is prepared and how the burning is influenced by the reaction kinetics and in-cylinder flow field. The high pressure and temperature as a result of a higher compression ratio can extend the lean limit and sustain flamelets within the turbulent eddies in a HCCI engine. An equivalent fuel economy of diesel engines can be obtained in this engine and particulate emission will be less than that of the diesel engine. This concept has been successfully tested on 2-cycle [10] and 4-cycle [11] gasoline engines where the combustion process is initiated by the autoignition of the mixture instead of a spark plug. It has been shown from experimental results [10,11] that there was little cycle-to-cycle variation in the peak cylinder pressure and the thermal efficiency was improved by such smooth combustion. The stabilized lean combustion improved fuel economy and produced low emissions compared to conventional SI and diesel engines. The HCCI concept was also successfully applied to operate a 4-stroke CFR engine [12]. The KIVA code was used to model and analyze the combustion process based on the data acquired from an engine that was operated with HCCI concept [13]. The experimental result of C.D. Wood [14] on a modified two-stroke cycle engine illustrated that if an engine with a homogeneous charge is brought to spontaneous combustion, the desired features of low NOx along with insensitivity to fuel-air ratio and the ability to run lean would be obtained.

Homogeneous Charge Compression Ignite combustion when operating at lean conditions and a higher compression ratio will result in a higher fuel economy and higher brake efficiency. Uniform distribution of fuel-air mixture in this system will result in a better quality of combustion and less unburned hydrocarbons, CO and NOx in the exhaust. HCCI's higher compression capability and fast combustion will also result in faster operating speeds, less blowby and less cyclic variation. By adopting exhaust gas recirculation (EGR) the peak flame temperature can be lowered and hence the NOx kinetics can be limited.

IV. The GALILEO Engine Concept and Issues for Investigation

The conceptual design of a Galileo Engine, as shown in Figure 3, is a symmetrically designed, variable compression, free-piston 2-cycle or 4-cycle engine run by energy generated from spontaneous combustion of a homogeneous fuel charge (HCCI combustion). It is comprised of a straight, rigid connecting rod #9, two power pistons #6 (one affixed to each end of rod #9), at least one power transfer piston #34 affixed to rod #9 (used for energy extraction from the piston-rod assembly) and a timing mechanism #41 (to monitor position and velocity). The free floating rod-assembly shuttles back and forth between two opposed cylinder heads #5, from compression-ignition in one cylinder to compression-ignition in the opposed cylinder. Power transfer pistons #34 extract the kinetic energy the rod assembly has through its use as a compressor, a vacuum pump, or a linear motor/generator to produce electricity and start the engine. There are numbers of bearing-seal assemblies #38 to bear the weight loaded on the rod and to maintain pressures and vacuums within the engine.

The top or outwardly facing side of each power piston #6 is used for compression and combustion in area #20, while the bottom, or inward facing side of the piston, is used for inducting an air-fuel mixture into space #21. As piston #6 rises from relative bottom to relative top (relative to compression ratios achieved), it inducts an air-fuel mixture below it. As the piston reverses direction and descends from combustion, an intake/transfer valve #24 is switched from intake (intake open/transfer closed), to transfer (transfer open/intake closed) and the piston proceeds to precompress the inducted air-fuel mixture while transferring it into accumulators #3. At the opposite end of each accumulator, near the combustion chamber, there is an injector valve #4 that doesn't open until the piston starts its rise. At that point, the high pressure homogenous fuel charge in the accumulator is injected into the cylinder and the piston compresses it to autoignition. The exhaust ports which are not shown in Figure 3 are located in such a position that will minimize or eliminate the overlapping of the intake valve and exhaust port openings.

A computer operating system #51 regulates the engine. It monitors the piston-rod assembly to detect its position and speed, it regulates fuel mixtures, fuel volume, EGR, injection start time and duration, energy extraction from the piston-rod assembly, it energizes the coils to move the piston-rod assembly in starting, and energizes the spark or glow plugs as the engine is starting. When the engine starts to run, the coils are converted to generating electricity. When the engine starts running in its compression-ignition mode, the spark or glow plugs are shut off.

It is important to realize that the drawing and mechanisms presented in Figure 3 is, by no means, of the final design. Before building a prototype, it is necessary to determine the power output, bore, maximum stroke and physical dimension of the this engine that can meet the requirements as a Genset for a serial configured Hybrid Electric Vehicle. The operating speed, speed staging and transient response will be also defined. The power output for a HEV application is most likely within 20 to 70 kWe. Operating speed will be 3600 cycle per minute or multiple of 60 Hz within this proposal, for the first generation prototype. Subsequently, future development shall incrcrease the operating speed to produce a smaller genset with regard to kWe output.

The originally targeted operating speed range was from 3,000 to 20,000 cpm. The upper speed might well be over stated, however, our goal is still to reach as high a speed as possible. With the current racing engine technologies, the engine can be readily reaching speeding exceeding 10,000 rpm. Multi-valve 4-stroke SI engines made by Alpha-Romeo, Lamborghini and DFS Cosworth are able to achieve engine speeds exceeding 11,000 rpm. High speed 2-stroke SI engines such as Husquavarna MK4 engine, URM 500 Moto-Cross Engine, Yamaha 250cc engine can operate at speeds exceeding 8,000 rpm with conventional 2-stroke transfer porting design.

A prototype free-piston engine/generator (U.S. Patent #41542000) designed and built by the Jarret brothers was able to run over 9,000 cpm again with conventional 2-stroke transfer porting design. Jarrets' engine can operate at 25:1 compression ratio and achieve 90% combustion efficiency. The free-piston engine (U.S. Patent #4385597) designed and built by Stelzer has been stated to achieve over 30,000 cpm without significant vibration.

The porting of Jarrets' or Stelzer's free-piston engines are not unusual. Timings of the ports opening and closing and port locations are typical to those of the current 2-stroke engine design. However, there are numbers of well known constraints on the gas exchange process associated with the conventional 2-stroke porting. The evaluation of porting and gas exchange process that shall be done in this program.

Most of the commercial automotive engines such as GM Lumina 3.1 V6 engine have the high speed operating capability (as high as 9,000 rpm) but this engine speed is limited by ECM so that the effective maximal operating speed is 4,400 rpm at wide open throttle. The condition corresponds to the optimal bsfc and the plateau on the torque curve. The Galileo free piston engine does not produce any torque to a drivetrain mechanism. The linear motion is converted into AC directly. The frequency, voltage and amperage are determined by the engine speed and stroke. The engine map of this free piston engine shall be determined in this program. The Galileo free piston engine is designed to have a high speed operating capability but it does not really have to operate at this speed.

Galileo Research Inc. is designing a proprietary scavenging and valve-train mechanism which will alleviate the disadvantages of the conventional 2-stroke scavenging method and will be suitable for a high speed operation and reduction in unburnt hydrocarbons. For the Range Extender hybrid vehicle application, this free piston engine will be running only at several set speeds that are determined by the electric motor's specifications. If the generated electricity is to be loaded to the common grid net, the engine speed will also be determined such that the electricity has the close quality required, i.e., within ±0.3 Hz variations. For a steady state condition, the electricity generated by a free piston engine should have a wave form close to sine wave with a minimum distortion.

Schematic illustrations of a pre-prototype model of the Galileo free piston engine are given in Figures 4a to 4c. This model is originally based on a 30 in^3 displacement, 2-stroke Bourke engine, Figure 4a. This engine, without a generator, weighs 50 pounds and produces about 30 horse power. The crank shaft-piston assembly and a pair of integrated cylinder-head assemblies are shown in Figure 4b. This figure clearly shows that most of weight is coming from the mid section of the Bourke engine. The combined weight of two cylinder-head assemblies, piston and piston rods is a small portion of the total weight. Figure 4c shows when the crankshaft and rotary generator are replaced with a linear generator. It is important to understand that the linear generator shown in Figure 4c is not the actual size for the comparable engine (25-30 kWe). Also, the OBD (on board diagnostic) computer and various sensors are not shown in this figure. It is believed that these items will only take up small space and weight. The purpose of these illustrations is to demonstrate the concept of Galileo free piston engine and its advantages, as a gen-set, over the conventional engines

Figure 4a Bourke Engine Coupled with a Generator

Figure 4b Cylinder-Head and Crank Shaft-Generator Assemblies of a Bourke engine

Figure 4c Preprototype Model of a Galileo Free Piston Engine

Friction of a Galileo free piston engine is significantly reduced due to a lack of moving parts. In a conventional engine the combustion force imparting to the connecting rod can be broken up into two component forces exerting on the connecting rod.. The parallel component force is the force to drive the crankshaft. The normal component force is the force that causes friction between piton-ring assembly and cylinder wall. It is this reason that there is audible piston slap and severe cylinder wear between crank angle 360 (TDC) and 405 (45 after TDC) because combustion is most rigorous taking place between these two phases.

Theoretically, within the Galileo engine, there is no normal component force exerting between the piston rings and the cylinder. The sliding force between rings and the cylinder are mainly caused by ring expansion due to the pressure gradient between the opposite sides of the piston and caused by the weight of rings. The piston itself (without any rings) is suspended in the cylinder without any surface-to-surface contact. While the piston-rod assembly may not be precisely right on the center of the cylinder, there may be some surface contact between the piston and the cylinder, but, by all means , this contact surface and the normal component forces exerting between these surfaces should be much less than those in the conventional engines.

The friction force exerting between the rod and the linear bearings is proportional to the gross weight that the rod carries. This gross weight includes the piston-rod assembly and the magnets of linear generator. If these moving parts are lubricated by a force feed lubricating system, the gross weight for a 25 kWe unit is less than 10 kg (22 lb) which is lighter than the combined weight of the piston, connecting rod and crankshaft of the comparable size of a conventional engine. Therefore, the friction reduction should be substantial. The seals on each of its two ends do not bear any significant load. It should not give rise to significant friction losses. The PV (loading) characteristics of these moving parts will be evaluated in this program.

Pumping loss has been characterized in the past as the sum of the admission and discharge losses. These losses are the result of the inability of achieving a smooth and fast gas exchange process such that the in cylinder pressure is still above the atmospheric pressure at the end the blow-down phase and the in cylinder pressure is below the atmospheric pressure during the induction phase. The pumping loss varies with the engine speed and load. Since the free piston engine will operate only at several discrete engine speeds at a fixed load the porting for achieving the best gas exchange shall be designed in this program.

Because conventional 2-stroke engines run with a stoichiometric fuel/air mixture, the typical scavenging process results in a high HC and CO emission. The gas exchange process and scavenging method given in Galitello's patent is not quite the same as the conventional 2-stroke engine scavenging process. When the blow-down phase is complete, the piston is traveling from its relative BDC toward the engine head. The fuel/air mixture that was compressed and stored in the accumulator will be admitted into the cylinder by opening the accumulator's gate (valve) soon after the exhaust ports are covered by the piston. The trapped burnt gas will be served as internal EGR for emission control. The admitted fuel/air mixture will be adjusted accordingly.

Another point regarding the efficiency is that the Galileo free piston engine will be operational at a compression ratio higher than the conventional SI's in order to onset compression ignition. The thermal efficiency will certainly increase as compared with the same class of SI engine. Further, the homogeneous charge compression ignition (HCCI) combustion system will allow the engine to run with a lean fuel/air mixture and result in unburnt HC and CO levels far below the conventional 2-stroke engines.

The quality of electricity generated will be adjusted by fine tuning the engine so long as the free piston engine is operational with a constant fuel/air supply. As indicated in this paper, the only purpose of a Galileo free piston engine is to make nothing else but electricity. This engine, like any electricity generating mechanisms such as steam turbine and internal combustion genset, are operated at a specified steady state condition. The voltage and frequency are supposedly produced with a steady state quality. The speed of the pistons will be adjusted so that it will closely follow a sine or cosine wave patterns. Consequently the AC produced will be subject to minimal harmonic distortions.

In regard of cooling and lubrication, they, by all means, are important. However, the tribological study shall be evaluated in an alpha prototype. The thermal loading, cooling duty and configuration will also be evaluated in the alpha prototype. The optimization and FEMA of a manufacturing prototype will be accomplished through the beta prototype in this program.

Combustion and engine technology of this invention is nothing new at all. What has been achieved in current engine technology can be readily implemented to this free piston engine. The new ideal that this engine brings about is that it combines all the current technologies in high speed engine designs, fast response actuators, compact linear generator, high speed lightweight structure materials, and high speed electronic controls which were not available a decade ago into an advanced power generating mechanism that has the combined characteristics of being small, lightweight, with very good fuel economy and very low emissions. The key to the success of this technology is both on the engine itself and the implementation of high speed data acquisition and electronic controls that are now available.

V. Conclusions

A Free Piston Engine similar to a reciprocating rapid compression machine has been initially designed and is under further development. The engine has one major moving part, a piston-rod assembly that shuttles back and forth from compression-ignition to compression-ignition in opposing cylinders. Because this engine has fewer moving parts, less inertia, and less friction, the brake specific fuel consumption (bsfc), thermal and mechanical efficiencies should be far better than those of the conventional engines. Also, this free-piston engine-generator is a lean-burn engine and emissions of unburned HC and CO should be very low and by incorporating an EGR device the NOx emission can substantially be reduced and will meet EPA and CARB's standards well into the forseeable future.

The engine design is symmetrical and allows for simple modular units of cylinder heads and power transfer unit(s). A piston-rod assembly, along with bearings, seals and a timing system are incorporated within the engine heads and power transfer unit(s). Rather than separate and distinct components of engine and pump or generator, this powerplant may combine all three into one compact lightweight integral unit. Applications include generators, compressors and vacuum pumps or combinations thereof, where size, weight, emissions or performance are factors. The engine is expected to be an environmentally clean source of power that generates Alternating Current electricity. It will also be relatively small, lightweight, with high power output, enhanced fuel economy, reduced emissions, with low maintenance and low manufacturing cost.

In this program, it is intended to develop a free-piston engine that is specifically targeted for the HEV application. The engine sizing, fuel-air induction system, turbulent combustion processes, exhaust gas treatment, bearings, seals, lubrication, timings of fuel management and valve trains, electricity induction system, will be investigated. Also, 1st and 2nd generation prototypes shall be constructed and tested, resulting in a manufacturing model and production readiness within a 2 year time frame. Expected prototype development costs are $ 2.25 Million Dollars. This may be lowered if alternative financing may be obtained (state/federal government programs) and facilities with existing equipment that is needed may be utilized (federal government/business).

The Company has an initial prototype 1 - 2 kW free-piston engine-generator it has been working on for the past 2 years. This initial prototype, which may be seen on the following pages, has allowed for hands on experience to perform initial investigation of components and mechanisms. Further, the development of this initial prototype has resulted in several valuable patentable features which will be pursued when financing is obtained.

Galileo Research, Inc. is pursuing continued development of this technology and is seeking cooperative research partners for this project. We have laid out a detailed business plan and prototype development plan to facilitate the development of this technology. Complete spreadsheets and operating expenses may be seen within our business plan. For further contact regarding cooperative reserach, funding, or partnerships, please contact us at

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