

Experimental Investigation and Analysis of Homogeneous Charge Compression Ignition in a Two-Stroke Free-Piston Engine

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ABSTRACT

The present paper deals with the experimental investigation of homogeneous charge compression ignition in a free-oscillating two-stroke free-piston engine. The Free Piston Linear Generator (FPLG), which is being developed at the German Aerospace Center (DLR), is an innovative internal combustion engine for the generation of electrical power. This concept can for example be used in hybrid electric vehicles, as an auxiliary power unit or in combined heat and power units. The FPLG consists of three main components. In the two-stroke combustion unit, heat is released by burning a fuel-air mixture and a piston is accelerated. This energy is then converted into electric energy in the second component, the linear generator. This subsystem consists of electromagnetic coils as a stator and permanent magnets as a mover. The mover is rigidly coupled to the combustion piston. The third component, the gas spring, serves as an intermediate energy storage and reverses the piston motion by decelerating it. With this arrangement, the piston oscillates freely between the compression chamber of the combustion unit and the gas spring with no mechanical coupling like a crank shaft. Due to the free piston movement, the top and bottom dead centers and consequently for example the compression ratio are no longer fixed. This freedom and the use of a fully variable valve train provide the opportunity for a fundamental optimization of the internal combustion process.

The homogeneous charge compression ignition (HCCI) is one advantageous combustion process which leads to low raw emissions and high efficiencies. As a basis to utilize a HCCI process, the paper firstly presents a strategy for the transition between the spark ignition mode and HCCI-mode in the FPLG using the high variability of the engine concept. The auto ignition of the lean fuel-air mixture is enabled by the adaption of the compression ratio and an internal exhaust gas recirculation. The latter is accomplished by an early intake valve opening and intermediate storage of combustion gases in the intake manifold. Additionally, the challenges that come with a freely oscillating piston will be discussed here. In the analysis of the experimental results, the pressure curve and free piston movement will be discussed in detail. Due to the free piston movement stochastic variations in the ignition can be equalized by the system without external control. This effect and the measured efficiencies show the promising potential for the HCCI process in free-piston engines.

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INTRODUCTION

All motorized vehicles in Europe and worldwide such as cars, trucks and motorbikes are subjected to directives and regulations for the emission of air pollutants. These restrictions are tightened stepwise with the introduction of the European Directive 91/441/EEC (Euro 1). In order to fulfill these, the vehicle manufacturers investigate several approaches to reduce the CO₂ and pollutant emissions. Besides improvements in aerodynamics, lighter cars and an electrification of the powertrain one key topic is the enhancement of the engine efficiency, for example by novel combustion processes. One promising combustion process, which has the potential of high efficiencies, and low NO_x, CO₂ and particle matter emissions, is the homogeneous charge compression ignition (HCCI) [1].

In order to control this complex combustion process free-piston engines have additional degrees of freedom compared to conventional internal combustion engines due to the missing crank mechanism. Particularly as a result of the variable compression ratio, free-piston engines show a high potential for the control of the HCCI process [2].

One recent free-piston concept is the Free Piston Linear Generator (FPLG), which is being developed at the German Aerospace Center (DLR). In [3] Haag et. al. describe a development approach for the investigation of a HCCI process in the FPLG. Thereby 3D-CFD and chemical kinetics simulations are used to develop a cylinder head and operating strategy for the HCCI combustion. Furthermore, the publication shows measurement results on a hydraulically assisted FPLG system. In contrast to a freely oscillating FPLG this test bench defines the piston trajectory and its frequency by a control system. Consequently the interaction between the combustion process and the piston motion cannot be investigated here. However, different

publications state system inherent advantages of free-piston engines for the operation with a HCCI process since the piston movement is not defined by a crank mechanism and consequently the compression ratio and the top dead center (TDC) is variable [4, 5, 6].

Therefore the objective of the present paper is the experimental investigation of the HCCI operation in a freely oscillating FPLG system. In the examined free-piston system the control allows interactions between the pressure rise in the combustion chamber and the piston trajectory. Through this, improved combustion stability is expected compared to conventional internal combustion engines.

In the next chapter the function principle of the FPLG is explained. After this the freely oscillating functional demonstrator on the test rig at the German Aerospace Center will be described. Especially the internal combustion subsystem is presented in detail here. As a basis the fourth chapter summarizes the development of the HCCI operation and the transition strategy between spark ignition (SI) and the controlled auto ignition as shown in [3]. Before the experimental results are discussed the challenges of HCCI operation with a freely oscillating piston are shown.

THE FUNCTION PRINCIPLE OF THE FREE PISTON LINEAR GENERATOR

The free-piston engine concept as designed by DLR converts chemically stored energy in liquid or gaseous fuels into electric energy by means of an internal combustion process. The structure of the FPLG consists of three different subsystems: combustion unit, linear generator and gas spring. The schematic sketch in [Figure 1](#) presents a single piston design.

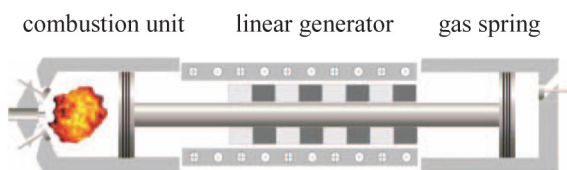


Figure 1. Function principle of the FPLG

The piston of the combustion unit, the mover of the linear generator and the piston of the gas spring build one rigid piston unit. In the combustion unit the energy stored in fuels is released by a two-stroke internal combustion cycle. The pressure raise due to the heat release moves the piston unit towards the TDC of the gas spring. The gas spring serves as a temporary energy storage. The compressed air reverses the piston movement and accelerates the piston towards its initial position. The linear generator performs the extraction of the energy which is released in the subsystem of the combustion unit. Thereby, the energy is extracted during both the expansion and compression phases. The linear generator consists of a mover with permanent magnets and windings fixed in the housing, which form the stator.

With the subsystem of the gas spring, the free-piston system selected by DLR distinguishes itself from most free-piston projects in the past. An overview of historical and current free-piston engines can be found in [7] and [8]. Due to the predictable forces it creates, this

subsystem simplifies the piston motion control. Furthermore, the top and bottom dead center of the combustion can be varied within the mechanical and combustion-technical limits. This enables a variation of the stroke and the compression ratio. With these degrees of freedom, advantages in efficiency at full and especially at part load are expected as well as the possibility to use diverse fuels. In combination with a compact design, the FPLG qualifies for the use in hybrid cars.

Due to the mass forces which result from the oscillating movement of the piston unit within free-piston engines, the development at DLR aims for a system with two opposite pistons. With an appropriate synchronization of the piston units, this setup allows a complete compensation of all mass forces. This can be achieved e.g. by the arrangements which are shown in [Figure 2](#).

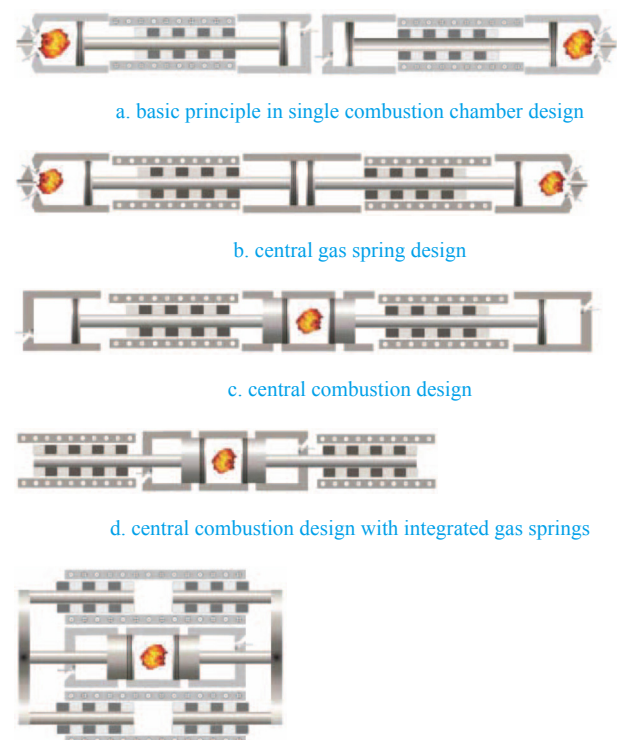


Figure 2. Design variants of FPLG modules

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The first arrangement in [Figure 2](#) consists of two separate combustion units, linear generators and gas springs. It is built of two symmetrically arranged single piston units of [Figure 1](#). The combination of two subsystems provides the possibility to reduce the length and the weight of the FPLG. Thereby, either the gas spring or the combustion chambers can be merged. With the integration of the gas spring on the rear side of the combustion piston, a further decrease in length can be achieved (designs d and e). Due to a higher thermal efficiency and advantages at the synchronization of the two piston units, the DLR is aiming for a FPLG-system with a central combustion chamber.

FPLG TEST RIG SYSTEM

The investigated free-piston system which was build up on the test rig of the DLR in Stuttgart is based on a single piston design according to Figure 1. As a functional demonstrator for a free-piston engine concept consisting of the subsystems combustion unit, linear generator and gas spring, the set-up of a single piston unit without mass balancing is sufficient. The structure of the FPLG system is presented in the form of a 3D model and a picture of the test bench in Figure 3 and Figure 4. It operates in a frequency range of 16 to 21 Hz and generates up to 10 kW electric power. Detailed information of the test rig system and its control can be found in [9], [10] and [11].

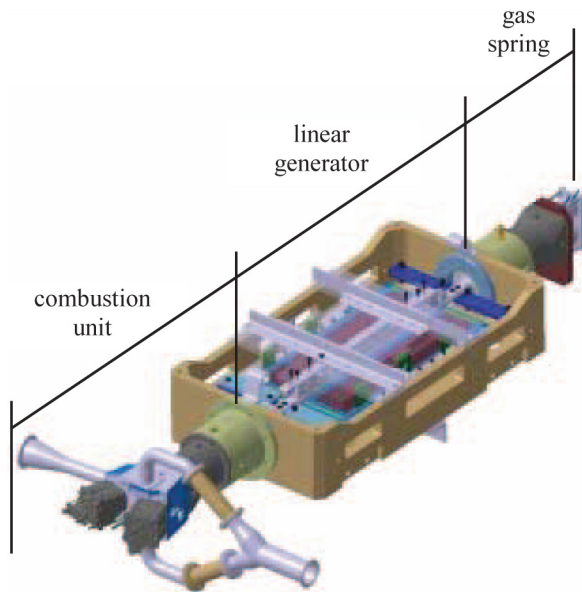


Figure 3. 3D model of the functional demonstrator

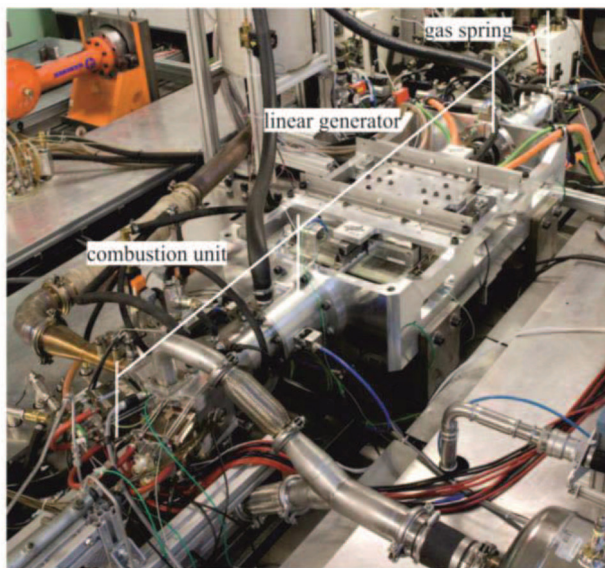


Figure 4. Functional demonstrator on the test bench

Combustion Unit

The combustion unit is designed as a two-stroke spark ignition (SI) engine with direct injection. Although a four-stroke process would be technically feasible, it requires a higher energetic effort. In order to use the inbuilt properties of a free-piston engine as the variable stroke, the gas exchange is accomplished by loop scavenging with two intake and one exhaust valve in the cylinder head. An electromagnetic valve train enables a fully variable valve lift and timing. The bore diameter is 82.5 mm and the stroke can be varied from 60 to 90 mm within its mechanical and physical limits. Consequently the displacement volume is between 321 and 481 cm³. A 6 hole injector is centrally mounted in the cylinder head. It is connected to a common rail injection system, which delivers an injection pressure between 100 and 200 bar. The boost pressure, which is provided by the infrastructure of the test rig, is varied between 1.2 and 2 bar (abs.). With that, the combustion unit provides up to 12 kW indicated power output. For the pressure indication, an absolute and a relative pressure sensor are positioned laterally in the cylinder head. Figure 5 illustrates the geometry of the sensors and actuators. The detailed development of this cylinder head is described in [3]. For the series of measurements presented here the coolant temperature is 60° C.

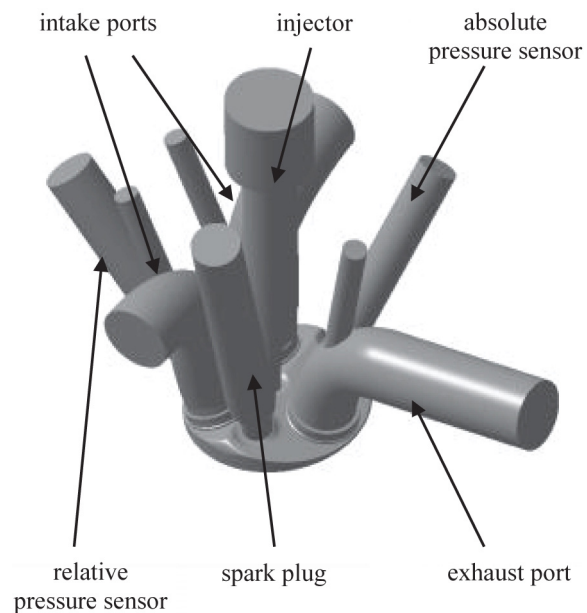


Figure 5. Functional model of the cylinder head

Linear Generator

The mover of the linear generator consists of Neodymium-Iron-Boron magnets, which are cased in glass-fiber reinforced plastics. These two blades are mounted to a central rod, which connects the combustion piston and gas spring piston as one rigid package. On both sides the stator is surrounded by linear motors which were derived from similar setups used in the machine tool manufacturing. With this arrangement, lateral forces on the piston unit can be evened out. The linear generator in the functional demonstrator creates a maximum force of 12,000 N. Although only one third of this force is needed under regular operation conditions, it is chosen as a safety reserve in the early stage of development.