EVS26
Los Angeles, California, May 6 - 9, 2012

Development of a Free-Piston Linear Generator for use in an Extended-Range Electric Vehicle

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Abstract

This paper presents the development methodology of the Free-Piston Linear Generator (FPLG). The FPLG is a free-piston combustion engine with an integrated linear generator. The engine can be used as a range-extending device in an electric vehicle. A systematic development approach for the FPLG is presented consisting of three basic steps. The fully variable experimental apparatus being used for testing the single FPLG-subsystems and the FPLG-system is described. In order to achieve robust operation of the FPLG-system during experimental testing, a hydraulic actuator is implemented to simulate the motion of the free piston. Despite the use of such an hydraulic actuator, it is shown, that the system can be run in a quasi-autarkic operating mode. Experimental results using this quasi-autarkic operating mode are presented. Based on the results obtained, the further development of the FPLG towards a fully-autarkic operating mode without a hydraulic actuator can be tackled.

Keywords: EREV, ICE, generator, on-board, powertrain

1 Introduction

A Free-Piston Linear Generator (FPLG) is being developed at the German Aerospace Center (Deutsches Zentrum fuer Luft- und Raumfahrt, DLR). The FPLG can convert chemical energy of a fuel into electrical energy efficiently. Therefore, it can be used as a range-extending device in electric vehicles. The FPLG consists of three main subsystems (Figure 1):

- An Internal Combustion Engine converting chemical energy into kinetic energy (ICE).
- A Linear Generator converting kinetic energy into electric energy (LG).
- A Gas Spring storing energy and inverting the piston movement (GS).

The piston of the internal combustion engine, the generator rotor and the piston of the gas spring are rigidly coupled and perform a transversal oscillation between bottom dead center and top dead center. Compared to conventional combustion engines this engine concept leads to fully

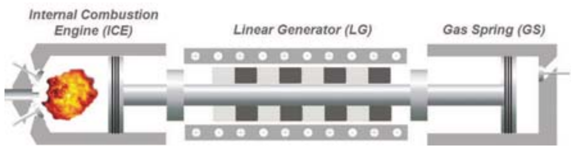

Figure 1: FPLG-system with the three subsystems internal combustion engine, linear generator and gas spring.

flexible operating parameters such as variable stroke and variable compression ratio. Moreover, the trajectory of the piston motion is variable and in general different from the kinematically determined trajectory of a crank drive. More information about the project is available in [3]. The FPLG has the potential to achieve a high efficiency over a wide range of loads, which allows for a direct supply of electric energy to the electric motors without having to use the battery. Additionally, the vibration levels are low, since two systems can be oppositely synchronised. Moreover, due to the highly integrated system the gravimetric and volumetric power densities achieve high values. The FPLG is a free-piston concept with one combustion chamber and electrical power output. Similar concepts have also been presented in [2], [8] and [7].

2 FPLG-Subsystems

The FPLG consists of the three subsystems 'internal combustion engine', 'linear generator' and 'gas spring'. The subsystems have been developed over the last years and have now reached a stage of development allowing them to be used in a complete FPLG-system. The subsystems have been tested up to frequencies of 30 Hz. The specifications of the subsystems are summarized in Tables 1 to 3. Theoretical and experimental investigations have been performed in [4] and [5]. In [6], the development of the linear generator has been presented.

Table 1: Specifications of the internal combustion engine

Parameter	Value	Unit
Bore	82.5	mm
Stroke	40-95	mm
No. Inlet Valves	2	-
No. Outlet Valves	2	-
Inlet Pressure	0-3	bar
Fuel Pressure	100	bar
Valvetrain	electromagnetic	-
Injection	direct injection	-
Injector	swirl injector	-

The internal combustion engine is based on a two-stroke concept. The cylinder head is equipped with two inlet and two outlet valves. The valves are actuated by means of an electromagnetic valve train, which allows for individual valve timing. In order to achieve low HC emissions, fuel is injected directly after the exhaust valves close. The cylinder dead volume at TDC has been minimized in order to achieve a sufficient compression ratio at low strokes.

Table 2: Specifications of the linear generator

Parameter	Value	Unit
Design Force	3620	N
Design Current	113	A
Maximum Force	6120	N
Maximum Current	235	A
Force Density	54	kN/m^2
Motor Parameter	32	N/A
Time Constant (0-90)	6.6	ms

The linear generator has been designed for maximum force density and at the same time minimum time constant. Since the linear generator will be used for controlling the fully-autarkic FPLG-system, a highly dynamic behaviour of the generator is essential. The design force of the generator is sufficient to extract the energy brought into the system by the combustion. In order to minimize costs and the weight of the piston rotor, the energy is extracted during the compression and expansion stroke of the system.

Table 3: Specifications of the gas spring

Parameter	Value	Unit
Bore	82.5	mm
Stroke	40-95	mm
Inlet Pressure	0-10	bar
Valve train	electromagnetic	-
Piston	oil lubrication	-
Cooling	water	-

The design of the gas spring is similar to the design of the combustion chamber. Piston, cylinder and cylinder housing can be designed similarly. The cylinder head of the gas spring is less complex. A small electromagnetic valve is mounted on an aluminium plate. The electromagnetic valve is used to control the cylinder pressure of the gas spring. It is also needed to refill the gas spring, since gas is lost through blowby between the piston and the cylinder. Generally, the bore of the gas spring can be different to the bore of the ICE. However, by using the same bore for both subsystems, components are easily exchangeable and can be used for the ICE as well as for the GS. Due to this fact, the bore has been chosen to be the same for the ICE and the GS.

3 Development Methodology

The development of the FPLG requires a new approach. Since the piston can move freely, bringing all three components into service at the same time, while controlling the piston motion, is a difficult task, because each of them is characterized by a large set of parameters which influence each other. Therefore, DLR has set up a new development methodology for the FPLG (Figure 2). The methodology comprises three stages.

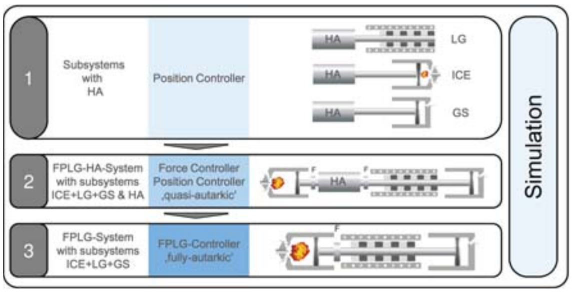

Figure 2: Development methodology for the FPLG

First, the three subsystems ICE, LG, GS are tested separately by means of a hydraulic actuator (HA). The HA-system allows for a variation of the piston motion, while the system is in

service. Dead centers (TDC, BDC), stroke, frequency and trajectory of the piston motion can be adapted. In order to control the hydraulic actuator (HA), a model-based control algorithm has been implemented, which is described in detail in [1]. For the investigation of the single subsystems, the HA is position-controlled. The control algorithm is able to realize arbitrary piston motions in order to investigate the behaviour of the subsystems depending on the above mentioned parameters.
During the second stage of the development process, the three subsystems of the FPLG and the HA are mounted on the test stand. Figure 3 shows the test stand comprising the ICE, HA, LG and GS. This setup allows for the quasi-autarkic operation of the FPLG-system. A quasi-autarkic operating point is defined as an operating point, where the HA eliminates itself in a way that it only drives the weight of its own piston section and overcomes its own friction. Therefore, the HA-system never exerts a net force on the FPLG-subsystems. The FPLG-system runs as if no hydraulic actuator was attached. The advantage of still having the HA implemented in the system is the fact, that the hydraulic actuator can act as a fail-safe unit, which enables the system to run stable despite unknown disturbances or incorrect control algorithms. Therefore, this stage is very important towards the development of control strategies for a fully-autarkic operation of the FPLG. The quasi-autarkic operation will be explained in detail in section 4.
The HA is removed from the FPLG-HA-system at the third stage of the development process. The FPLG can then run in a fully-autarkic mode. In order to be able to control this fully-autarkic mode, explicit control algorithms are necessary in order to achieve a stable operation of the system. The development of these algorithms is temporarily under way.

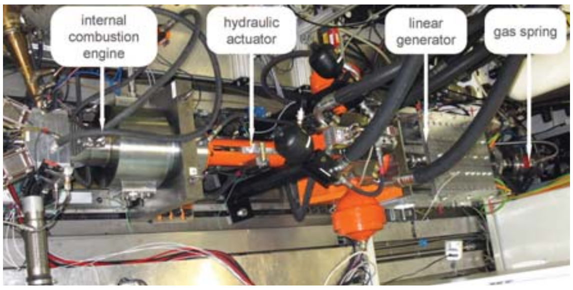

Figure 3: FPLG test stand with subsystems and hydraulic actuator

4 Quasi-autarkic Operation

It was the goal of stage two of the development methodology in Figure 2 to run the three FPLG-subsystems and the hydraulic actuator in a quasi-autarkic operating mode. This mode has been defined as a state, in which the FPLG-system moves 'freely' and the hydraulic actuator does not influence the motion of the piston caused by the three FPLG-subsystems. In order to derive the constraints for a quasi-autarkic operating mode, kinematic and kinetic equations are set up for the hydraulically supported FPLG-system. Figure 4 shows the system with all external forces acting on the piston unit:

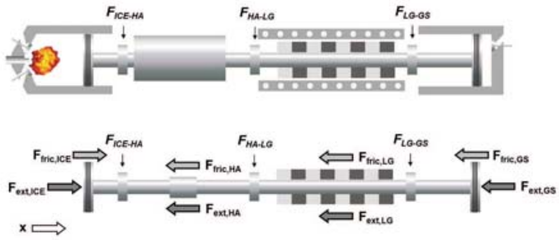

Figure 4: FPLG-HA system with external forces

Newton's second law of motion states that the total external force acting on the piston is equal to the product of its mass and its acceleration:

$$F_{ext_{total}} = m_{pis} \cdot a_{pis} \quad (1)$$

Thus, the acceleration of the piston is dependent on the mass of the piston and the total external force on the piston:

$$a_{pis} = \frac{F_{ext_{total}}}{m_{pis}} \quad (2)$$

The position of the piston can be calculated from the acceleration of the piston by integrating twice over time:

$$v(t) = v_0 + \int_{t_0}^{t} a(t)dt \quad (3)$$

$$x(t) = x_0 + \int_{t_0}^{t} v(t)dt \quad (4)$$

The total external force $F_{ext_{total}}$ consists of all forces acting on the piston. These forces are shown in Figure 4. For every subsystem, the external force consists of a frictional force F_{fric} and an applied force F_{app}. The applied forces of the ICE $F_{app,ICE}$ and the GS $F_{app,GS}$ are due to the cylinder gas pressure acting on the piston. The applied force of the LG $F_{app,LG}$ is the electromagnetic force, while in the HA it is the pressure of the oil acting on the piston $F_{app,HA}$. The total force can be written as follows:

$$\begin{aligned} F_{ext_{total}} =& F_{app,ICE} + F_{fric,ICE} + F_{app,GS} \\ &+ F_{fric,GS} + F_{app,LG} + F_{fric,LG} \\ &+ F_{app,HA} + F_{fric,HA} \end{aligned} \quad (5)$$

Considering the two systems FPLG (consisting of ICE, GS, LG) and HA, the kinetic equation 1 becomes:

$$F_{ext_{ICE,GS,LG}} + F_{ext,HA} = (m_{pis_{ICE,GS,LG}} + m_{pis_{HA}}) \cdot a_{pis} \tag{6}$$

In order to achieve a quasi-autarkic operating mode, where the HA eliminates itself, the external force of the HA must equal its inertia force of the piston section. Therefore, the definition of the quasi-autarkic operating mode yields the following equations:

$$F_{ext,HA} + m_{pis_{HA}} \cdot a_{pis} = 0 \tag{7}$$

$$F_{app,HA} + F_{fric,HA} + m_{pis_{HA}} \cdot a_{pis} = 0 \tag{8}$$

With regards to the section forces of the system, this definition can be translated into the following equation (Figure 4):

$$F_{ICE-HA} - F_{HA-LG} = 0 \tag{9}$$

The difference between the two section forces between the hydraulic actuator and the FPLG-subsystems must equal nought at all piston positions. If this is equation is fulfilled, the system runs in a quasi-autarkic mode.
In order to achieve a quasi-autarkic operating mode, the pressure in the gas spring, the force of the linear generator, the frequency and the trajectory of the piston motion have to be adapted. This adaption is performed by a control algorithm. The controller is fed with the measured applied and section forces. It then calculates the gas spring pressure and the force of the linear generator necessary to reach the stroke and the bottom dead center set arbitrarily by the user. After that, by using the measured forces, the piston motion of a quasi-autarkic mode can be calculated. The frequency and the piston motion can be fed through to the position-based controller of the hydraulic actuator. By iterating this process several times, an operating point can be found, which is quasi-autarkic by the definition set above. The results of such an operating point are presented in the next section.

5 Results

The following results were measured at a quasi-autarkic operating point, which was obtained with a certain set of parameters. Depending on the parameters chosen, there are a great number of such operating points. Therefore, an exemplary operating point was chosen.
The external forces of the three FPLG-subsystems in this exemplary quasi-autarkic operating point are shown in Figure 5 over the piston position. Starting at BDC of the ICE, the pressure in the combustion chamber increases during the compression phase. At around TDC, fuel is ignited and the cylinder pressure rises sharply. At the same time, the gas spring is expanded and the cylinder pressure of the gas spring drops. The compression ratio of the gas spring is low resulting in a small pressure difference between TDC and BDC. The external forces of the ICE and the GS always act on the opposite direction, whereas the external force of the LG changes its direction at the dead centers. The linear generator decelerates the piston motion in both directions. This is due to the operating strategy, which uses the linear generator to extract energy out of the system during the compression and expansion stroke.

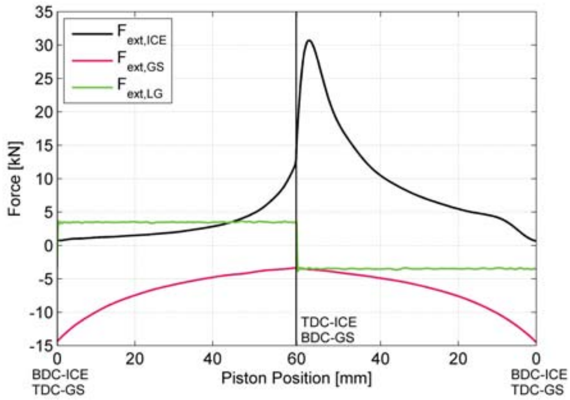

Figure 5: External Forces of the three FPLG-subsystems at a quasi-autarkic operating point. Frequency: 21 Hz

Two trajectories of the piston motion are plotted in Figure 6. One trajectory has been measured on the test stand while the other trajectory has been calculated from external and section forces measured. The small deviation of the two trajectories shows that quasi-autarkic operating modes can be achieved using the method described above.

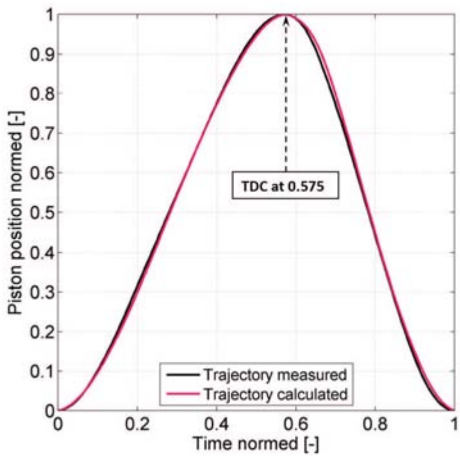

Figure 6: Trajectory of the piston motion, measured and calculated. Frequency: 21 Hz

It can be noted, that the shape of the trajectory is unsymmetric. TDC of the combustion process is found to be at 57.5 % of the periodic time.

The frequency was found to be 21 Hz at this particular operating point. However, the operating frequency of the system mainly depends on the mass of the piston. The frequency of the system can only be partly altered by changing setup parameters of the ICE, LG or GS. The mass of the piston used in this experiment was 25 kg, which can be reduced sharply. Future concepts aim towards a piston mass of 4 kg, which will then result in higher frequencies of about 50 Hz and an increase in power density. At 21 Hz, a power output of roughly 10 kW has been measured. Increasing the frequency up to 50 Hz should lead to a power output of 25 kW of a single FPLG-system. A full FPLG-module consisting of two single FPLG-systems oppositely synchronised in order to eliminate oscillations will reach a power output of 50 kW.

6 Conclusion

The German Aerospace Center (DLR) is developing a free-piston combustion engine with an integrated linear generator. Based on a three-stage developing process, DLR has developed the three FPLG-subsystems 'internal combustion engine', 'linear generator' and 'gas spring' during first stage. A unique hydraulically supported FPLG-system has been set up to be able to test the subsystems separately. The experimental apparatus used is fully variable and therefore allows for detailed investigations of the subsystems. At stage two, the FPLG-subsystems in combination with the hydraulic actuator were run in a quasi-autarkic operating mode. It is now possible to test control algorithms safely for the fully-autarkic system in stage three. The work described is the basis for the further development of the FPLG. The last step in the development methodology - the fully-autarkic FPLG - will be achieved soon. At the same time, the FPLG-subsystems are further optimized in order to achieve better performance. The FPLG is an innovative free piston engine, which has the potential to set new standards as a range-extending device in an EREV.

Abbreviations

BDC	bottom dead center
EREV	Extended-Range Electric Vehicle
FPLG	free-piston linear generator
GS	gas spring
HA	hydraulic actuator
ICE	internal combustion engine
LG	linear generator
TDC	top dead center

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