A high efficient energy converter for a hybrid vehicle concept

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Abstract

This publication deals with the concept, the explanation, the development and the actual measurement results of a free-piston linear generator (FPLG). The free-piston linear generator is able to convert chemical energy into electrical energy by using a combustion process. In this publication the function and the characteristics of the free-piston linear generator will be explained first. Then the surrounding system and its effects on the FPLG are explained. This is important to understand the effect of every subsystem to the FPLG. In the next step the development based of the three base components, the gas spring [7], the linear generator [4] and the combustion [6] will be explained. Each chapter includes actual measurement results generated on a purpose-built test bench. At the end of the publication the current situation of the FPLG development and the further steps are presented.

Keywords: Alternators, free-piston linear generator, linear generators, gas spring, combustion.

1. Introduction

Efficiency improvements in order to reduce the production of CO2 are required in all technical areas of life to limit the anticipated climate changes [1] to an extent sustainable for humanity. Current approaches in the field of transportation cover both the increase of efficiency of conventional drives and the development of hybrid, battery, fuel cell and range extender concepts, and combinations of these. The aim of every alternative power train design is to transform the stored energy into a kinetic energy with the greatest possible efficiency. In many concepts electrical energy is necessary in order to drive electric motors.

This requirement is met particularly well by a free piston linear generator. It is capable of transforming chemical energy into electrical energy by means of a combustion process. As explained in [2], the high degree of efficiency and its independence of the load level are inherent in the design of the free-piston linear generator. This is achieved by keeping the system frequency constant and adapting to the power demand by variation of the stroke and compression ratio. Furthermore, these system characteristics give the free-piston linear generator the possibility to be operated with

both conventional fuels such as petrol, diesel and gas and with alternative fuels such as biofuel, synthetic fuel, hydrogen etc. In the development of scenarios for the introduction of alternative power train concepts the free-piston linear generator can be seen as a bridging technology, between conventional power train technology and fuel cell technology. Particularly since both of these technologies provide electric energy at their energy interface.

2. Free-piston linear generator system

In order to create an understanding of the boundary conditions affecting the base components the concept of the free-piston linear generator is described in this section.

valves | top dead center | combustion chamber | bottom dead center | stator | mover | gas spring
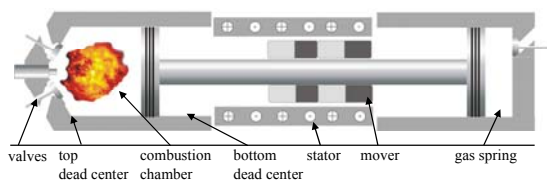
Figure 1: Illustration of the principle of the free-piston linear generator

2.1 Construction

The free-piston linear generator in Figure 1 is based on a double piston system (hatched) built into a cylinder. At one end there is the combustion chamber for the combustion of a liquid or gaseous energy carrier. The opposite end consists of an adjustable gas spring. The spring rate of the gas spring can be adjusted by means of regulating the gas volume or the gas mass. The gas exchange of the combustion chamber is controlled by electrically actuated valves in the cylinder head.

The mover is mounted between the piston of the combustion chamber and the piston of the gas spring. Permanent magnets are glued to the mover and additionally secured by a fiber-glass reinforced bandage. The mover with the permanent magnets is enclosed by a stator with integrated generator winding and a cooling system. The mover and the stator together compose the linear generator.

2.2 Operation

At the start of the load cycle the double piston is at the top dead center (TDC) and a flammable mixture previously introduced into the combustion chamber is ignited by a spark plug. The double piston with its integrated mover begins to move towards the gas spring (bottom dead center BDC). The movement of the magnets induces a voltage in the coils of the stator which drives a corresponding electric current. Half of the energy released in the combustion is captured between top dead center and bottom dead center in this way. The other half is stored in the gas spring and extracted by the linear generator on the return stroke of the double piston (BDC-TDC). The gas in the combustion chamber is actively flushed out between bottom and top dead center while fresh gas is introduced. When the fresh gas is compressed and the double piston has arrived at TDC, the next load cycle can begin. The variation of the output power is achieved by adjustment of the stroke, which is determined by the gas volume in the gas spring. The mechanical frequency of the double piston system is kept constant.

2.3 Integration in a vehicle

The FPLG is planned to be integrated as energy converter in the vehicle structure as shown in **Figure 2**.
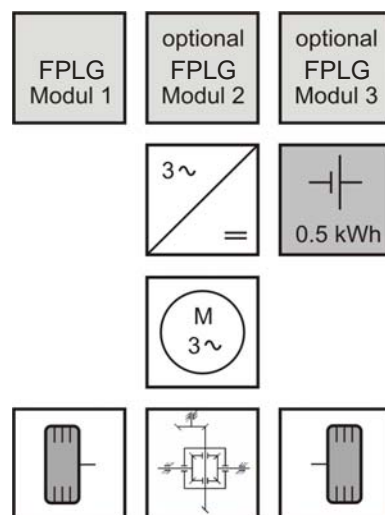

Figure 2: FPLG integrated in a hybrid vehicle

Since the FPLG produces electrical energy, it is possible to combine multiple FPLG modules in a vehicle. Having multiple smaller modules provides the possibility to adapt the numbers of active modules to the momentarily requested electrical power for the electric drive. By using

this operation strategy it is possible to reduce the system losses and the fuel consumption of the vehicle in comparison to a conventional hybrid vehicle. Using multiple FPLG modules in vehicles which need more power and only one in vehicles with smaller power consumption, also allows the research to be concentrated on a single engine size.

3. Boundary conditions

The design of the output to be provided from the FPLG is based on the speed profile in the New European Driving Cycle. A mid-range car with the values listed in **Table 1** is assumed as the vehicle. This class of car was selected as it represents a great share of the cars used in Europe.

Table 1: Basic data for the vehicle used as a basis for the design

parameter	value	unit
c_w	0.325	-
A	2.2	m²
c_r	0.0115	-
m	1750	kg

Taking into consideration the acceleration processes resulting from the New European Driving Cycle, the electrical outputs required as illustrated in **Figure 3** were determined with the help of a simulation. Both the parameters listed in **Table 1** and an 80 kW electric traction motor contributed to the simulation model.
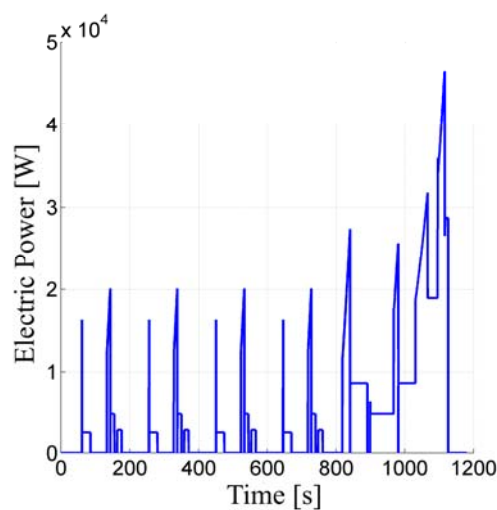

Figure 3: Illustration of the electrical power required in the New European Driving Cycle

The outcome of the simulation is that a maximum electrical output of 50 kW is assumed for the design of the FPLG. As the FPLG engine will have two FPLG systems running in opposition to one another to balance the masses in motion, the targeted electrical output per system is 25 kW.

In the following, the three subsystems of the FPLG – gas spring, linear generator and combustion section – are described.

4. Combustion

4.1 Basics

The combustion section of the FPLG converts the chemical energy stored in a fuel into kinetic energy by accelerating a piston. Its basic layout consisting of piston, cylinder and cylinder head is the same as the layout used in any reciprocating piston engine. However in contrary to most known engines, the FPLG uses neither connecting rods nor a crankshaft (see Figure 1).

Also, the four stroke process commonly used in automotive applications is not applicable to the FPLG. The reversion of the piston motion at the end of the exhaust stroke would require a large force which can only be provided efficiently by a crankshaft. For this reason, a loop scavenged two stroke process is implemented. The piston motion is reversed by the gas force of the combustion section at each top dead center. An electro-magnetic valve train (EMVT) allows for the abdication of a camshaft and further increases the variability of the combustion process.

Another important component of the combustion section is the fuel injection system. The gasoline is injected directly into the combustion chamber using a common rail injection system.

4.2 Combustion test rig

The development of the free piston engine requires an approach, where every component is tested separately at first. Bringing all three components into service at the same time is an impossible task, because each of them is characterized by a large set of parameters which influence each other. In order to be able to test every single component, it is necessary to use an actuator, which replaces the missing components and, therefore drives the piston. The actuator moves each component along a predefined, desired trajectory so that it can be operated independently from the other two components. A

hydraulic linear actuator is chosen for this application as it is able to generate high forces and it allows adapting the trajectories without any mechanical changes [9].

In order to develop the combustion section, prototypes of all combustion components are attached to the hydraulic actuator. If possible, mass production components are used. In many cases some modifications have to be made, for example the cylinder head is based upon a mass production design and modified to fit the electromagnetic valve train and fulfill other special requirements of the FPLG.

As a result, an extremely flexible internal combustion engine test stand has been realized [6]. Valve timing and valve lift can easily be varied as well as piston stroke, compression ratio and charging pressure. Of course, the standard actuating variables such as ignition timing and fuel mass can be set via software as well. Both two stroke and four stroke operation are possible at the test rig. All relevant data is recorded, including piston position, all valve positions, in-cylinder pressure, inlet pressure, outlet pressure, several temperatures and many more.

4.3   First Measurement results

The test rig and the first prototype engine (combustion section) have been put into operation in two stroke mode. Frequencies up to 20 Hz were successfully tested. The test stand with the hydraulic actuator allows for frequencies up to 30 Hz, but with the current cylinder head, combustion becomes unsteady at higher operating frequencies due to an inefficient scavenging. A dedicated two stroke cylinder head design will help mitigate this problem. Still there is a long road ahead to the targeted value of 50 Hz.

The results at 20 Hz are good. Combustion works steadily at frequencies between 5 Hz and 20 Hz and at strokes between 50 and 90 mm. In-cylinder peak pressures up to 107 Pa were measured, resulting in an indicated power between 5 and 15 kW. In Figure 4 the indicated power is plotted over inlet pressure with the piston stroke as a parameter. The variable stroke can be used to regulate the power in a comparatively small range. The reason that a reduction of the stroke does not lead to a more significant reduction of the indicated power is found in the inefficient scavenging, which gets worse with larger strokes. Nevertheless the experiments show that the FPLG introduces the

variable stroke as an additional option for regulating the power of a combustion process.
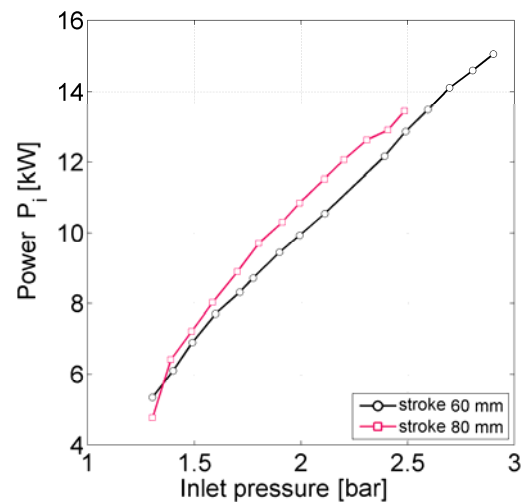

Figure 4: indicated power in dependence of inlet pressure and piston stroke

5.   Gas Spring

5.1   Basics

The gas spring is the element that distinguishes the FPLG of most other free-piston engine concepts. Its most obvious task is to invert the piston motion at bottom dead center. To do so, the gas spring works as energy storage. When compressing the medium in the gas spring, the kinetic energy of the piston is converted to potential energy, which is returned when the gas spring expands. Thus, the medium in the combustion section can be compressed for the next cycle and the linear generator can generate electrical energy in both the expansion phase and the compression phase.

Moreover, the gas spring is used to adjust the system to different operating points. By varying the stiffness of the gas spring, the bottom dead center and the stroke can be controlled. The amount of energy being stored in the gas spring is modified by changing the stiffness.

Based on the basic equations describing the gas spring it is found that two values can be used practically for changing the stiffness of the gas spring during operation: Either the mass of the medium or its volume. In the following, both alternatives are examined and compared.

In order to vary the mass during operation, a valve is installed in the cylinder head of the mass-variable gas spring. It is opened for a short

time around the top dead center of the engine (which is the bottom dead center of the gas spring), just when the pressure in the gas spring cylinder is at its minimum. Once the valve is open, the pressure in the cylinder will adapt to the reservoir pressure. The reservoir is assumed to be big enough to keep the reservoir pressure almost constant. To set the pressure in the reservoir an electro-pneumatic valve is used.

The volume-variable gas spring includes a second piston in addition to its working piston. The control piston is located opposite the working piston. Compared to the working piston, the control piston moves slowly and only when a change of the operating point is required.

5.2 Modelling

In order to describe the processes within the gas spring, a scope of energy balance is defined around the gas in the cylinder. According to the first law of thermodynamics, the energy balance for this system is found and combined with the mass balance. Moreover, the thermal caloric equations of state are used to model the medium as ideal or real gas.

The differential equation system is completed by a material model, which describes the variable R_i, Z and u as a function of pressure and temperature. Ideal gas models can be used as well as more complex models like the one by Zacharias [8].

5.3 Measurement Results and Efficiency

To evaluate the two gas spring alternatives, both of them are built and their characteristics are analyzed at the hydraulic test stand. To improve comparability, they are constructed in a very similar manner and with identical dimensions.

As more than 50% of the nominal power of the FPLG is stored in the gas spring, the efficiency of the gas spring is a very important factor on overall system efficiency. In the following, the thermodynamic efficiency is regarded, which means that all energy losses in the gas volume affect the efficiency, but piston friction does not. The thermodynamic efficiency is defined as the ratio of the mechanical work that the piston applies to the gas during compression, and the mechanical work that the gas applies to the piston during expansion.

The two alternatives are compared at three different operating points at a constant frequency and strokes of 45, 65 and 85 mm. In each case,

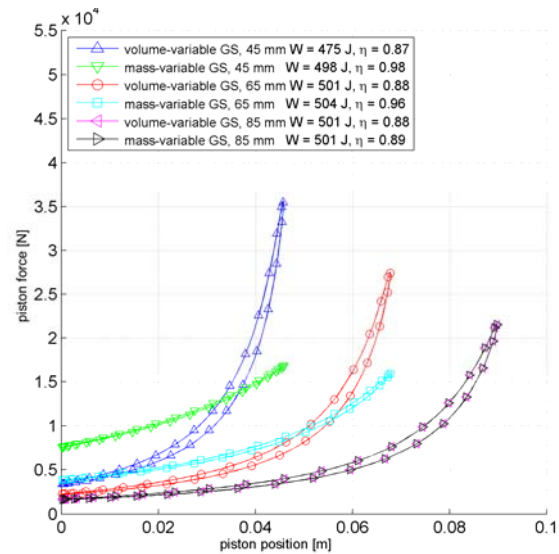the reservoir pressure or the control piston position are set such that Wcomp is about 500 J.

Figure 5: Force diagrams of mass-variable and volume-variable gas spring at different strokes [7]

The area enclosed by the graphs in Figure 5 is a measure for the energy losses in one cycle. It is obvious, that the volume variable gas spring performs worse than the mass variable gas spring. The efficiency at a stroke of 65 mm is only 88 per cent with the volume variable gas spring, compared to 96 per cent with the mass variable alternative. At the largest stroke, both plots are almost identical, because the cylinder geometry and thermodynamic processes are the same for both gas springs.

Two reasons were found for the differences in efficiency of both gas spring types, especially at reduced strokes.

Firstly, due to the large dead volume in the mass variable gas spring at small strokes, the maximum peak pressure is at a relatively low level (see Figure 5). This reduces temperature peaks, too. As wall heat dissipation happens particularly at high gas temperatures, the losses are reduced by this mechanism. In order to store the same amount of energy in the gas spring, the start pressure (pressure at BDC of the gas spring) has to be increased. This means that the heat transfer from the wall back to the medium is reduced as well, but this effect does not compensate increase of losses around TDC.

Secondly, the trunk piston entering the cylinder increases the effective wall area. With the control piston positioned in the cylinder, the surface being in contact with the gas consists not only of the cylinder inner surface and the two

piston roof surfaces, but also of the piston outer surface. This again increases wall heat losses, especially around the TDC of the gas spring.

6. Linear Generator

6.1 Basics

The linear generator is the component that converts the mechanical energy into electrical energy. Due to the Faraday's Law the mover, consisting of permanent magnets, induces an electrical current in coils of the stator.

The boundary conditions mentioned above require the linear generator to have an electrical output of 25 kW. This corresponds to a force around 5000 N assuming a frequency of 50 strokes per second and a stroke of 90 mm.

6.2 Axial force calculation

There are two aims to be achieved by the calculation of the linear generator (LG). The first aim is to get a maximum electrical power. To reach a maximum of electric output power it is necessary to develop a LG with maximum axial force. So it is important to find a geometric structure which guarantees a maximum of axial force.

The second aim is the efficiency of the linear generator. The efficiency of every electrical motor or generator is a function of several variables including the magnetic force. With a higher magnetic force it is possible to gather a higher mechanical power. The higher mechanical power Pmech leads to a higher efficiency η as shown in (1) by constant losses. To get an optimal efficiency it is also possible to reduce the losses Pv. In [5] the main focus is on finding the optimum by increasing the magnetic force.

$$\eta = \frac{P_{el}}{P_{mech}} = \frac{P_{mech} - P_v}{P_{mech}} = 1 - \frac{P_v}{P_{mech}} \quad (1)$$

The base for the calculations is the FEA-tool Ansys. By using this tool it is possible to calculate 2-D results for different types of the LG. As illustrated in Figure 6 every important geometry parameter can be varied by changing the coordinates x(1)..x(n) and y(1)..y(n). Additionally the width of the slot and the magnets can be varied.
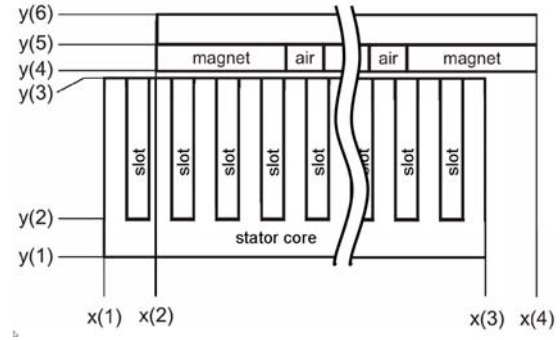
Figure 6: 2-D FEA Model

The base parameters for the calculation are represented in Table 2.

Table 2: Base parameters

Parameter	value	unit
air gap radius	100	mm
active length mover	270	mm

The results of calculations with many variations in [5] lead to the optimal geometry and system assembly. The calculated average force by using a current density of 10 A/mm2 is 5260N.

6.3 Efficiency of the linear generator

One of the FPLG boundary conditions is the variability of the mover's stroke. Because of this additional dimension it isn't possible to use the traditional efficiency graphs in which the force is plotted against the rotation speed. The solution is one graph for every stroke.
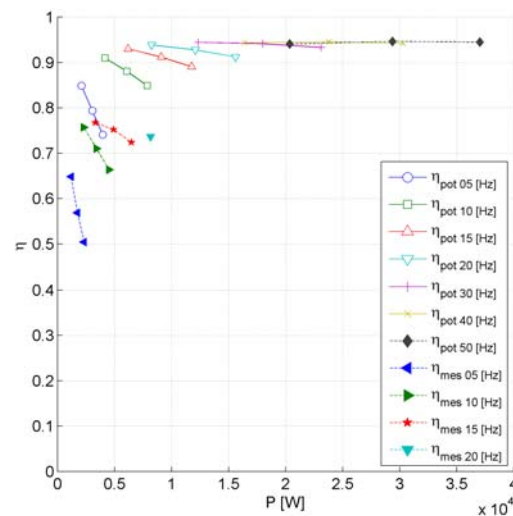
Figure 7: Efficiency LG stroke 80 mm

In Figure 7 the measured efficiency and the calculated efficiency of an optimized linear generator (pot) are presented at different frequencies. The operation point has a stroke of 80 mm.

7. Conclusion

The concept of the free piston linear generator was explained and its application as a range extender for electric vehicles was presented. The three subsystems linear generator, gas spring and combustion section and their basic characteristics were shown. Based on the basic equations for all three components, experiment setups were shown and a selection of measurement results was presented.

The most recent hardware realizations of the subsystems are intended to be used in a first FPLG demonstrator in near future.

The FPLG has the potential to be a key component in future drivetrain concepts. Several advantages including improved efficiency are possible. Today's measurement results indicate that the realization of the FPLG within a car will become possible.

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Florian Kock received his Diploma degree from Technical University of Darmstadt in 2010. Since then, he has been a research asociate and project manager at German Aerospace Center, Institute of Vehicle Concepts. He has been working in the fields of alternative energy converters and control theory, in particular on the free piston linear generator.