A high efficient energy converter for a hybrid vehicle concept – gas spring focused

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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) with the focus on the gas spring. 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 represented.*

Keywords: Alternators, free-piston linear generator, linear motors, linear alternators, linear generators, permanent magnet generators, synchronous generators, gas spring, combustion.

1. Introduction

Efficiency improvements in order to reduce the production of CO_2 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 increasing the 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 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 of the free-piston linear generator at all load levels is inherent in its design. This is achieved by keeping the system frequency constant and adapting to the power demand by variation of stroke and compression. Furthermore, these system characteristics mean that the free-piston linear generator can be operated with both conventional fuels such as petrol, diesel and gas and with alternative fuels such as sun fuel, 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

The principle of the free-piston linear generator will be described in this section in order to assist in the understanding of the boundary conditions acting on the linear generator.

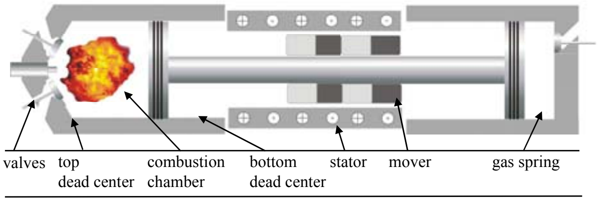

Figure 1: Illustration of the principle of the free-piston linear generator

A Construction

The free-piston linear generator in Figure 1 is based on a double piston system (hatched) built into a cylinder. At one end of it is the combustion chamber for the combustion of a liquid or gaseous energy carrier. An adjustable gas spring is built into the end opposite of the combustion chamber. The volume of gas in the gas spring can be adjusted by means of a control valve which allows the spring rate of the gas spring to be regulated. The flue gas is scavenged out and the fresh gas brought in by electrically actuated valves in the cylinder head of the combustion chamber.

The mover is mounted between the two pistons of the double piston. Permanent magnets are glued to the mover and additionally secured by a fibre-glass reinforced bandage. The mover with the permanent magnets is enclosed by a stator with integrated generator winding and the necessary cooling system. The mover and the stator together compose the linear generator.

B Operation

At the start of the load cycle the double piston is at the top dead centre (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 centre 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 centre and bottom dead centre 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 remaining in the combustion chamber is scavenged around bottom dead centre and 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 in the power to be output is achieved by adjustment of the stroke, which is determined by the volume of gas in the gas spring. The mechanical frequency of the double piston system is kept constant.

C Integration in a vehicle

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

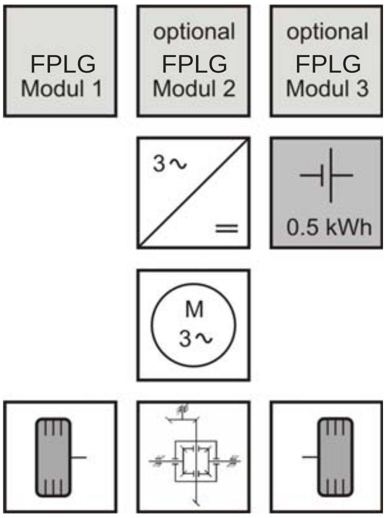

Figure 2: FPLG integrated in a hybrid vehicle

It is possible to combine multiple FPLG modules. The effect of this combination is the possibility to adapt the numbers of used modules to the requested electrical power for the traction. 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. It is also possible to manufacture small vehicles with one integrated module or large ones with more than one FPLG module. In both vehicles the same module size can be used.

3. Boundary conditions

The design of the output to be provided from the linear generator 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,

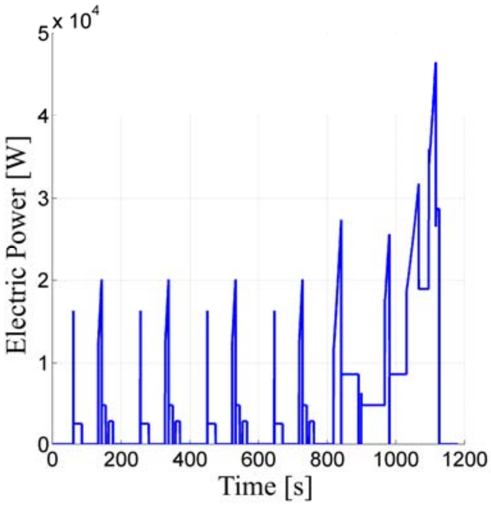

Figure 3: Illustration of the electrical power required in the New European Driving Cycle

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 a 80 kW electric traction motor contributed to the simulation model.

In the following, the three subsystems of the FPLG – gas spring, linear generator and combustion section – are described. First hardware realizations are intended to be used in a first FPLG demonstrator.

4. Gas Spring

A 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 (see next section) 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.

Figure 4 illustrates the functionality of a mass-variable gas spring. In order to vary the mass during operation, a valve is installed in the cylinder head of the 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. When the valve is open, the pressure in the cylinder will adapt to the reservoir pressure. The reservoir is assumed to be large enough to keep the reservoir pressure almost constant. The pressure in the reservoir can be set using an electro-pneumatic valve.

Gas losses are uncritical in the mass-variable gas spring. As the valve is opened in every cycle, gas losses are compensated automatically. Nevertheless, larger gas losses should be avoided as they correspond with energy losses and therefore affect the efficiency of the system.

Contrary to the mass-variable gas spring, the volume-variable gas spring is shown in Figure 5. In addition to its working piston, it integrates a second piston, the control piston. Compared to the working piston, the control piston moves slowly and only when a change of the operating point is required.

Here, gas losses cannot be compensated by refilling the gas spring. As a result, the cylinder-piston unit has to be hermetically sealed. For this reason, a trunk piston (plunger) is used as working piston in the volume-variable gas spring. This inevitable constructive detail massively influences the efficiency of the gas spring, see section D.

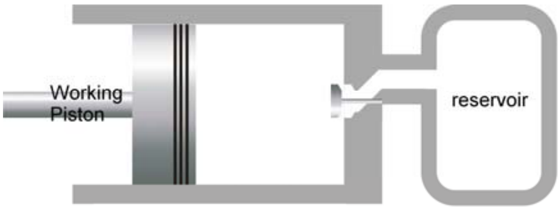

Figure 4: Mass-variable gas spring

Figure 5: Volume-variable gas spring

B Model equations

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 given as follows:

$$\frac{dU}{dt} = \frac{dQ_W}{dt} + \frac{dH_{V,in}}{dt} + \frac{dH_{V,out}}{dt} + \frac{dH_B}{dt} - p\frac{dV}{dt} \tag{1}$$

In the equation, $H_{V,in}$ and $H_{V,out}$ are the enthalpy flows through the inlet and outlet valves respectively, H_B is the enthalpy flow caused by blow-by-effects and Q_W is the heat transferred across the cylinder wall.

Similarly, the mass balance for the same scope is given as

$$\frac{dm}{dt} = \frac{dm_{V,in}}{dt} + \frac{dm_{V,out}}{dt} + \frac{dm_B}{dt} \tag{2}$$

Moreover, the thermal caloric equations of state are used to model the medium as ideal or real gas:

$$v(T,p) = \frac{R_i \cdot T \cdot Z}{p} \tag{3}$$

$$u = u(T,p) \tag{4}$$

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].

The gas spring affects the FPLG system by applying a force on the piston. As the geometry of the piston is known, this force can easily be calculated from the gas pressure. On the other hand, the thermodynamic state in the gas spring depends on its volume. Again, if the constructive geometry is known, this volume can be calculated from the piston position, which is a variable that is known in the FPLG system.

C Measurement Environment

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 to adapt the trajectories without any mechanical changes [9].

For some earlier experiments, especially for the ones at frequencies above 30 Hz, a crankshaft based test stand can be used, too. But greater flexibility and operating conditions closer to the ones at the final FPLG system make the hydraulic test stand preferable in most cases.

D 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 effect 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:

$$\eta_{th} = \frac{W_{\exp}}{W_{comp}} = \frac{\int_{TDC}^{BDC} pdV}{\int_{BDC}^{TDC} pdV} \tag{5}$$

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 W_{comp} is about 500 J.

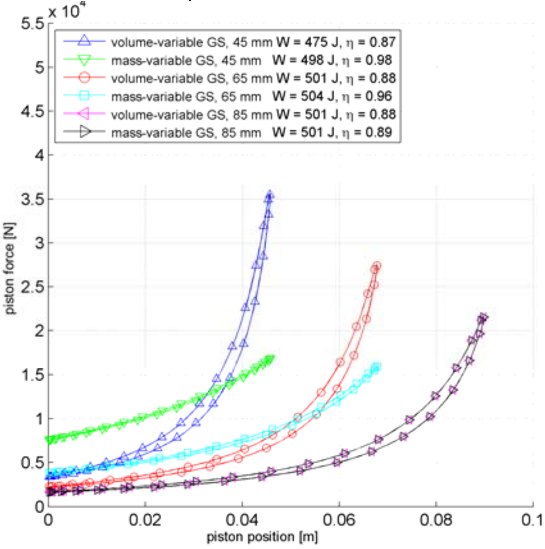

Figure 6: Force diagrams of mass-variable and volume-variable gas spring at different strokes [7]

The the area enclosed by the graphs in Figure 6 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 effiency 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 6). 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 reduction of losses around TDC.

Secondly, the trunk piston entering the cylinder increases the effective wall area. With the trunk piston positioned in the cylinder, not 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.

E Conclusion Gas Spring

Two different concepts of a gas spring were presented. The volume variable gas spring is clearly preferable as the effiency is better in almost every operating point. Only at full load, both alternatives perform equally well. The reason for the differences in efficiency was found in the wall heat losses. Separate measurements led to the result that wall heat losses of the volume variable gas spring are up to 10 times as high as the wall heat losses of the mass variable gas spring.

5. Linear Generator

The linear generator is the component that converts the mechanical energy into electrical energy.

The outcome of this simulation is that a maximum electrical output of 50 kW is assumed for the design of the linear generator. As the free-piston linear generator must have two systems running in opposition to one another to balance the masses in motion, the electrical output per linear generator is 25 kW. This corresponds to a force around 3000 N assuming a frequency of 50 strokes per second and a stroke of 90 mm.

A 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 under consideration of the boundary conditions explained in chapter 3.

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 P_{mech} 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 P_v. In [5] the main focus is on finding the optimum by increasing the magnetic force.

$$\eta = \frac{P_{el}}{P_{mech}} = \frac{P_{mech} - P_v}{P_{mech}} = 1 - \frac{P_v}{P_{mech}} \qquad (6)$$

The base of the calculation 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 7 every important geometry parameter can be varied by changing the coordinates x(1)..x(n) and y(1)..y(n). Additional the width of the slot and the magnets can be varied.

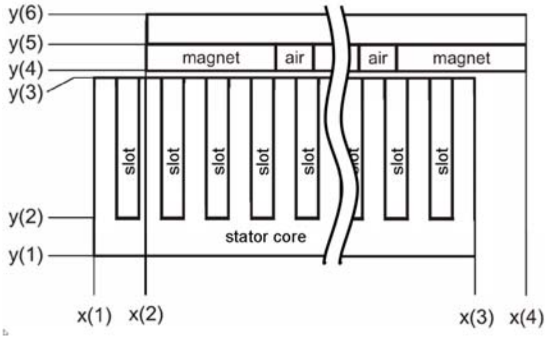

Figure 7: 2-D FEA Model

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 outcome of a lot of variations in [5] leads to the optimal geometry and system assembly. The calculated average force by using a current density of 10 A/mm2 is 5260N.

B 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. In Figure 8 the measured efficiency and the calculated efficiency of an optimized linear generator (pot) are presented at different frequencies. The operation point is by a stroke of 80 mm.

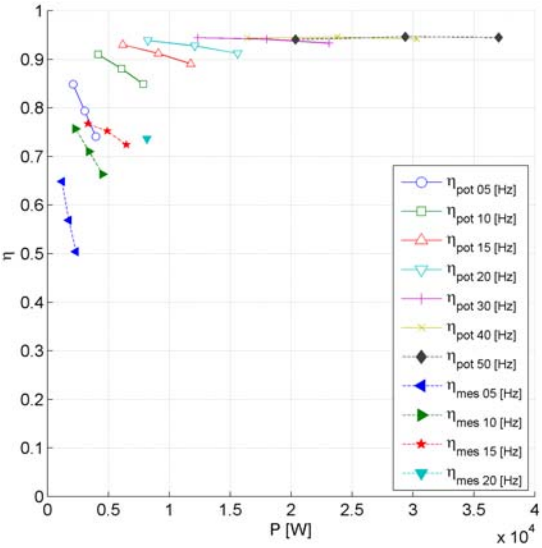

Figure 8: Efficiency LG stroke 80 mm

C Conclusion Linear Generator

The efficiency of the actual linear generator design is good and it can be increased by reducing the losses especially the iron losses in the mover [5].

6. Combustion

A Basics

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

Also, the four stroke process commonly used in automotive applications is not applicable to the FPLG as the reversion of the piston motion at the end of the exhaust stroke would require large forces which can be provided efficiently only 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 Otto fuel is injected directly into the combustion chamber using a common rail injection system.

B Combustion test rig

In order to develop the combustion section, prototypes of all combustion components are attached to the hydraulic actuator mentioned in section 4. As far as possible, mass production parts are used. In many cases like for example the cylinder head a basic mass production design is modificated to fulfill the special requirements of the FPLG.

As a result, an extremely flexible internal combustion engine test stand could be 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.

C 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, although the way to the above-mentioned 50 Hz is still far.

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 10^7 Pa were measured, resulting in an indicated power around 12 kW. A measured p-v-diagram as well as the indicated efficiency at different operating points are given in Figure 9 and Figure 10, respectively.

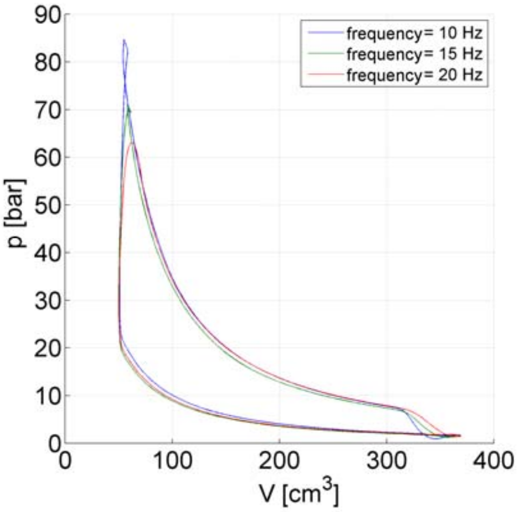

Figure 9: p-v-diagram

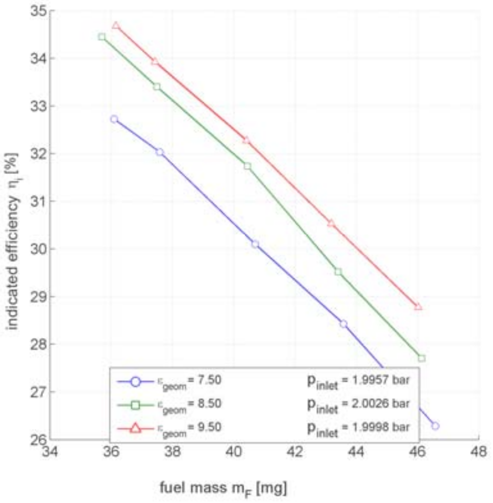

Figure 10: Efficiency combustion section

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 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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