VEHICLE HYBRID FREE-PISTON ENGINE-GENERATOR

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Abstract. The study of dynamical performance and effectiveness of on-board power generators having free-piston linear internal combustion engine combined with electrical generator completed with auxiliary drive is presented. The proposed concept is successfully applicable in all types of automobiles, specifically in hybrid vehicles and electric motor cars, and would be used for a design of all kinds of motor vehicles, cars, trucks, off-road machines, transport and agricultural machinery.

Keywords: free-piston linear internal combustion engine, electrical generator, controlled auxiliary engine drive.

Introduction

The on-board power generators presented by free-piston linear internal combustion engine without crankshaft combined with electrical generator are widely discussed in recent publications as a device that radically reshapes the hybrid vehicle powertrain. The studies dealt with systematic analysis and synthesis of the main parts of this type of on-board power generators: free-piston linear internal combustion engine without the crankshaft, electrical generator and the control system interconnecting the two above-mentioned components. An important improvement for free-piston linear internal combustion engine without crankshaft combined with electrical generator is the usage of generating component as a partial auxiliary engine drive developed by the authors of the current study. The term "combined" means that the considered device is assembled as one unit. One of the latest perspective devices is presented in [1; 2], where Toyota Central R&D Labs Inc. demonstrates a free piston engine linear generator consisting of a two-stroke combustion system, a linear generator, and a gas spring chamber. The authors paid a lot of attention (among others) to a. control of precise position of the piston, and its velocity as well; b. periodically stop operation of the generator as a driving motor during the generating operation. The authors wrote that they used two versions of combustion: spark ignition – SI, and premixed charged compression ignition – PCCI. For SI case the power output was 10.4 kW, and overall efficiency was 36.2 %; for PCCI case the power output was 12.7 kW, and overall efficiency was 42.0 %.

The industrial evaluation of all existing free-piston engine – electric generating devices reflects two major problems: it is difficult to create the piston motion automatically achieving the desirable top-dead-center (TDC) and bottom-dead-center (BDC) at the necessary moment in the absence of the crankshaft; there is increased the heating problem due to close location of two heat sources, i.e. the piston in the cylinder and the electromagnetic generator. The focus of the current study is development of the auxiliary drive in the generator scheme for raising the effectiveness of free-piston linear internal combustion engine by achieving the stroke parameters and combustion equal to regular values of Internal combustion engine having the crankshaft.

Synthesis of new device

Some basic ideas and functional components of the proposed device were synthesized in [3; 4]. The schemes of the control system for the linear electromagnetic generator were designed using the features presented in [5-7]. A schematic composition of the apparatus is in Fig. 1.

The apparatus consists of a turbocharged four cylinder four-stroke combustion system, electric generating devices -1, and a governing – control system built from subsystems 2 (engine control), 3 (generator control), 4 (auxiliary electric drive control), 5 (overall device control). The combustion system is organized in two units completed with a two-cylinder subsystem. Each of the two-cylinder subsystems has dual piston type concept. The pistons (in two-cylinder unit) are connected by the rod firmly. The generators *G* (or auxiliary drive motor ADM) of each two-cylinder units are interconnected by a link. The accepted geometrical notes are: the distance between the TDC and BDC *a-b* equal to stroke, and the distance *c-d* reflects the space for the electromagnetic mechanism.

The different projections of the designed scheme of the free-piston engine – electric generator are shown in the left part of Fig. 2 (side view) and the right part of Fig. 2 (plan view). For instance, there

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are consecutive operational time moments shown in the left part of Fig. 2. Eight moments are selected and must be marked by numbers, for instance, 1,2...8.

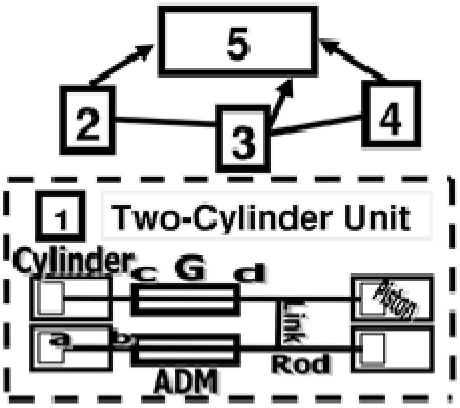

Fig. 1. **Graphical presentation of apparatus general composition**

The first moment is shown in the upper side 1 in the left part of Fig. 2. The left cylinder contains the left piston, that piston just approaches the TDC and gets ignition. The power stroke will start next moment in the left cylinder. The left piston is connected solidly to the right piston sitting in the right cylinder. The connecting rod is configured as a part of the electrical generator.

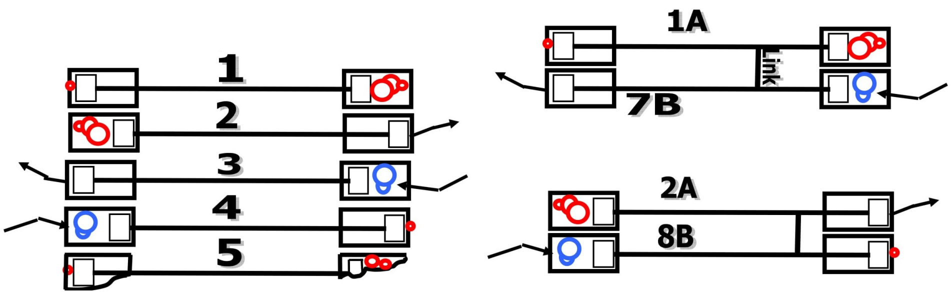

Fig. 2. **Kinematic presentation of apparatus composition**

A moment ago, ignition was in the combustion chamber of the right cylinder, and the right piston was pushed during the power stroke (expansion stroke) to the *BDC*. Hence, it is a snapshot at moment 1 of reciprocating movement in the considered unit (two-cylinder subsystem). The second snapshot is made at the moment 2, when the left piston is pushed by burned gases to the *BDC*, the power stroke is practically over, and the solidly connected right piston swept out the burned gases (exhaust stroke). The third snapshot is made at the moment 3, when the left piston swept out the burned gases (exhaust stroke), and the fresh mixture entered into the right cylinder (intake stroke), and so on. The picture in the right side of Fig. 1 illustrates that the beginning of each consecutive stroke starts with ignition in one of the cylinders. Hence, the whole engine has the moving force in the starting point of each stroke. The electromagnetic mechanism 1 converts the work of this force into electricity. The moving force created in certain one cylinder is going on overcoming electromagnetic resistance (during electricity production), resistance of gases and air in other 3 cylinders and apparatus friction forces. As a result the distance travelled by the piston is not equal to *a-b*, and the auxiliary drive system ADM is introduced for compensation of this disadvantage, which occurs due to absence of the crankshaft. Figure 3 shows a schematic diagram of a fragment of the auxiliary electric drive control (equipped by measurement system) for co-operating with the engine. The engine is equipped with 1 piston location sensor, and 2 piston speed sensor. The signal SD "displacement signal" is transmitting from 1 to processor 3, and the SD is converting in 3 to definite digital number for piston coordinate (displacement). The signal SV "velocity signal" is transmitting from 2 to processor 4, and the SV is converting in 4 to definite digital number for piston speed. The measured displacement is comparing to needed displacement Do in comparing unit 5. The needed displacement Do is coming from Prescribed Data Unit 7 to unit 5. The measured speed is comparing to needed speed Velo in comparing unit 6. The needed speed Velo is coming from Prescribed Data Unit 8 to unit 6. The difference between needed displacement Do and measured displacement is "delta D" is directing from unit 5 to analyzing and processing governor 9. The difference between needed speed Velo and measured speed "delta V" is going from unit 6 to analyzing and processing governor 9. The power source or battery 10 supplies the electricity to the chain and the governor 9 as well. The governor 9 sends the commands "on/off " to the switch 12 of a generator/auxiliary drive to stop electricity generation and start pushing the pistons. Also the governor 9 generates the necessary induced current for an auxiliary drive, and delivers it to ports 11. The engine control subsystem is similar to regular one. The generator control subsystem is composed in a manner like in [1-2] with additional incorporated elements from [5-7].

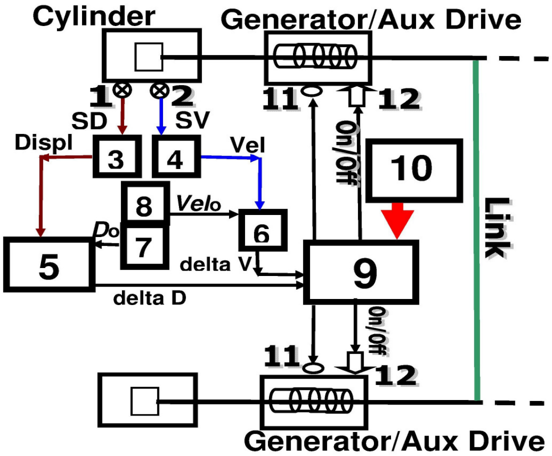

Fig. 3. **Schematic diagram of fragment of auxiliary electric drive control model**

Some preliminary notes must be mentioned for modelling of the free-piston engine-generator. All 4 pistons are firmly interconnected, so the power stroke has non-stop cycling. Assume that the TDC is at a time mark (time moment) 90º and the BDC is at a time mark 270º. The spark occurs before the mark 90º (say at 75º), so it could be stated that external force would be applied to the piston at this moment. The exhaust valve opens approximately at the time mark of 187º. The shape of the applied external force is close to the positive part of the sinusoidal function in that time interval. This analysis tells that the starting moment of the power stroke in the proposed model could be settled at the mark 75º, so the end of the power stroke would be assumed at the mark 255º. After that moment (mark 255º) the new power stroke happens in other cylinder, and all forced process repeats as the previous one.

Assume that total mass of all 4 pistons, 2 rods with elements solidly attached to them and the link is M, and x is moving piston position along the horizontal X axis. The system dynamics is described by ordinary differential equation (see, for instance [8])

$$M\ddot{x} = F_{p1} - F_2 - F_3 - F_4 - F_E - F_f\,, \tag{1}$$

where $F_{p1} = F_{p1}(t)$ is the power drive force in the first cylinder having the power stroke;
F_2 is the gas resistant force (for example – exhaust) in the second cylinder;
F_3 is the gas resistant force (for example – intake) in the third cylinder;
F_4 is the gas resistant force (for example – compression) in the fourth cylinder;
F_E is the force created in the electrical generator;
F_f is the frictional force.

Practically it is impossible to predict accurately the losses initiated by gas/mixture movements in the considered engine at this stage of the research, i. e. the formulas for F_2, F_3, F_4 would be very approximate and it is possible to attract the results found in [9] in that case.

$$F_2 = f_2 v^2;\; F_3 = f_3 v^2;\; F_4 = f_4 x;\; v = \dot{x}, \tag{2}$$

where $f_{2\text{-}4}$ are coefficients of gas exhaust, gas intake and gas compression.

Some studies say that frictional force F_f could be modelled mostly as dry friction force

$$F_f = fMg\,\mathrm{sign}\dot{x}, \tag{3}$$

where f is a the friction coefficient. A real value of the friction coefficient depends actually on the piston speed $\dot{x}$, but hereinafter it would be assumed as constant (for model simplicity).

The generator included in the system brings two additional interconnected equations (see [5]):

$$F_E = \tfrac{1}{2}\mu(iw)^2 S_a \delta^{-2} - Fv, \quad e = -Li + Ri + C_m \Phi v \,, \tag{4}$$

where i is the induced current;
C_m is the coefficient used for mutual interconnection of the mechanical parameter – speed of the piston and the electromagnetic parameter – induced current,;
μ is the magnetic permeability of the core material, w is the number of turns;
S_a is the area of the air gap;
δ is the air gap;
Φ is the magnetic flux linkage;
e is external voltage;
L is inductance;
R is electrical resistance;
F is the frictional resistance in the generator.

The initial conditions for the system of equations (1) – (4) are: when $t = 0$, it happens at the TDC, then $x_O = a\text{-}b$, $\dot{x}_O = v_O = 0, i_O = 0$. When the piston moves to the *BDC* the time would be equal to half of the cycle $t_{BDC} = \pi\omega^{-1}$, and $x_{BDC} = 0$.

The coefficients f, f_2, f_3, f_4 are dependent of time. That is why the analysis of the composed model could be done using the method described in [10]. Usually the driving force could be modelled approximately for half of a cylinder period as a positive part of the sinusoidal function. The compression resistance force F_4 has physical properties of springing element. That is why the equation (1) of piston motion has the properties of the oscillating system with natural frequency equal to $\upsilon = (f_4/M)^{½}$. It is known from the theory of vibrations that when such system is forced by sinusoidal load having frequency ω, the maximal deflections in that oscillating system are in resonance ($\omega = \upsilon$). The effect of the applied external force is maximal in this case.

It was proposed to design the device having the cycle oscillating frequency of 50 Hz. According to that requirement, the force from ignition close to optimal “rectangular sinus” shape was created and then converted to stroke expansion gas force pushing the piston. The time of moving back and forth of one piston is one period T_0. There are 2 power strokes during one period of time in the system. It is possible to obtain the solutions x, v, i for the system (1) – (4) for one stable period $T_0 = 2\pi\omega^{-1} = 0.02$ s now.

Results and discussion

Taking into account the proposed solutions consisting of installation of the auxiliary electric drive having the control subsystem as shown in Fig. 1 and Fig 3, the dynamical behaviour for one cylinder of the engine coupled to the generator is presented in Fig. 4. The abscissa axis stands for time in seconds, specifically showing half of one period ($\pi/\omega = 0.01$ s). The brown dashed curve is reflecting the piston movement (coordinates), the blue dotted curve is for the piston speed, and the solid red curve is for the induced current.

In the proposed case, each half of the period should have one power stroke. The electromagnetic device stops operation as a generator and starts operation as an auxiliary drive in the vicinity of the BDC position. The theoretically built process presented in Fig. 4 illustrates improvements and corrections of dynamical behaviour achieved in the proposed free-piston engine-sliding generator. It is assumed that the power stroke in one cylinder happens in this time. The accepted engine parameters are: designed stroke is 102 mm, bore is 58 mm, compression ratio is 11.2, oscillating frequency is 50 Hz. It is necessary to underline that these parameters are the same for all cylinders. The graphs of piston motion in Fig. 4 show that the piston is moving from the TDC to the BDC covering total distance a-b, in other words the piston operation for the proposed free-piston engine is equal to piston operation in a regular cylinder for the engine with the crankshaft. The part having negative values of current in Fig. 4 illustrates the operation of an auxiliary drive consuming this current. Power output P_{out} produced by the sliding generator equipped with auxiliary electric drive could be determined using the formula $P_{out} = i^2R$. The numerical analysis shows that the regular turbocharged four-stroke cycle spark ignition 4-cylinder engine with the crankshaft would provide to the generator power allowing to get at generator output 19.22 kW, and the model presented in Fig. 4 could generate electrical power of 18.93 kW.

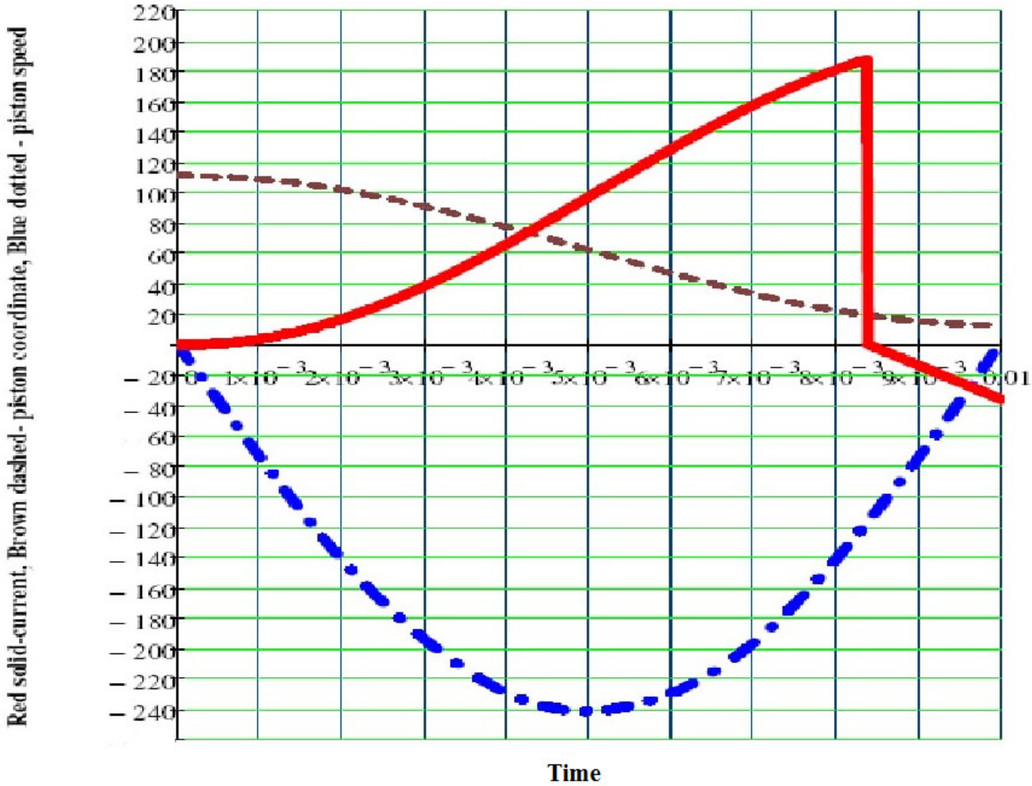

Fig. 4. **Piston movement, piston speed and generator current in one cylinder of engine – generator model with auxiliary electric drive**

The prototype of the proposed combination of gasoline free-piston linear internal combustion spark-ignition engine linked to electrical generator was designed, fabricated, assembled and tuned mainly using the schemes and theoretical models shown previously. The prime attention was paid to the engine subsystem and control network for additional auxiliary drive configuration. The target for the control system of the additional auxiliary drive is to establish and keep the time moment of re-switching in the generator – auxiliary drive scheme. The design foresees to use the standard parts, elements, and industrial/science solutions in maximal amount for all device subsystems where it is possible. It gives the opportunity to simplify the device, and make it close to regular units for comparison purposes. The main parameters of the prototype are presented in Table 1.

Table 1

Main parameters of prototype

Name	Info
Displaced volume.	1.186 dm^3
Stroke	102 mm
Bore	60 mm
Engine Type	Four-stroke
Compression ratio	11.2:1
Number of Cylinders	4
Oscillating Frequency	50 Hz
Fuel	Gasoline
Ignition	Spark-ignition

A photo of one of the prototype cylinders is presented in the left side of Fig. 5, and connection of the cylinder with the generator is demonstrated in the right side of Fig. 5.

Fig. 5. **Prototype cylinder (left view) and prototype cylinder connected to linear generator (right view)**

The recorded data were systematized, and the output induced current was visualized specifically for convenience purposes as a graph in coordinates: ordinate "current in Amps" vs. abscissa "time in seconds".

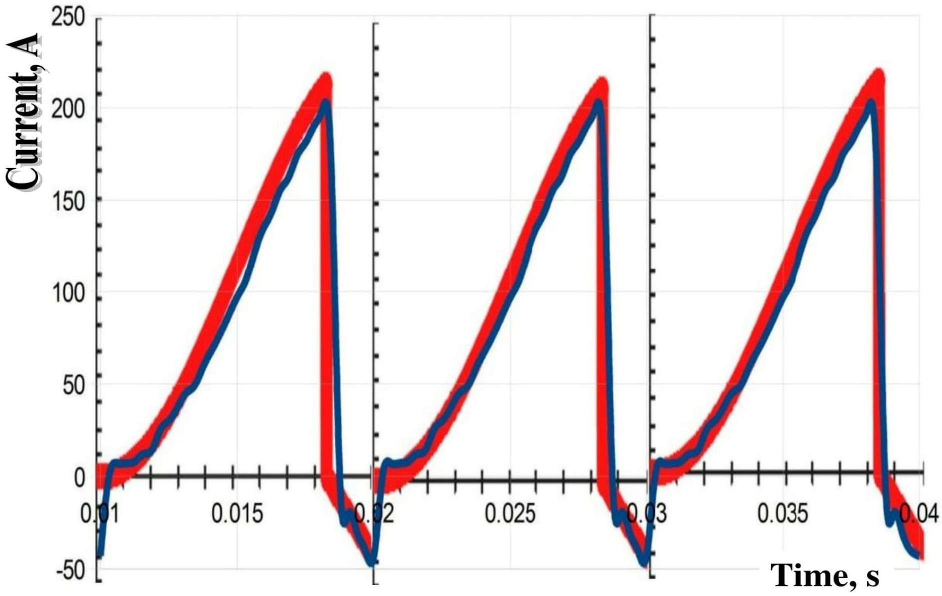

Fig. 6. **Comparison of recorded induced current (blue line) to theoretically modelled current (red line)**

The superposition comparison of the theoretical and recorded graphs is presented in Fig. 6. It illustrates the results of direct superposition comparison for 3 consecutive strokes; let us remind that the total cycle has 4 strokes. The time interval of one cylinder stroke is 0.01 sec. One can see that the real recorded induced current dynamics differs from the theoretical model, but the main trends are similar. The analysis of the recorded induced current demonstrates that there are additional losses in the real system; they were not taken into consideration during theoretical analysis and design. However, the comparison presented in Figure 6 demonstrates a satisfactory coincidence. The electrical resistance was determined after assembly, it was 17.7 ohms. The measured average current calculations were based on the process presentation in Fig. 5, i =31.9 A for 4 cylinder assembly package. Power output by the generator was determined as 18.01 kW. The comparison of magnitudes for the generated power in the theoretical model and in the real device allows conclude that the obtained real power output of 18.01 kW differs from the theoretically predicted 18.93 kW on 5.11 %. This statement illustrates a satisfactory compliance of the real manufactured device to the theoretically developed model. The measurements of the engine thermal efficiency were done using the methodology presented in [12]. The measured thermal efficiency of the engine was 56.8 % and the overall engine efficiency (keeping steps of the methodology described in [1-2]) was 43.2 %.

Emission tests were done using E8500 Chilled NOx portable emissions analyser. It measures, displays and records the emission-related information using 9 gas sensors and Software for real–time data logging, graphing and reporting with unlimited memory complying with USEPA CTM-030 and CTM-034 test methods. The results were compared to assumed 1.2L regular spark-ignition gasoline engine numbers – in $g \cdot kWh^{-1}$ (12.1 for HC+NOx, and 610 for CO). The recorded test results were (in $g \cdot kWh^{-1}$) 10.4 for HC+NOx, and 515 for CO. The obtained results demonstrate a visible reduction of the emission parameters.

The authors have to underline that the presented study does not include some important issues, e. g., protection from vibrations. One of the short notes is that the specific tuned mass dampers were successfully used, allowing combine two profits: the reduction of vibrations and "energy harvesting technology" [7,12-14], which in its turn increased the efficiency of the system.

The presented 18 kW on-board power generator could be considered as a module easy for population for designers' convenience. It is a way to build a vehicle power complex having the output power 36 kW, 54 kW, 72 kW and so on, and it could be applied for a design of all kinds of motor vehicles, cars, trucks, off-road machines, transport and agricultural machinery.

Conclusions

1. The usage of the proposed complex power source based on dual piston engine arrangement combined with the electrical generator equipped with additional functions of auxiliary engine drive gives the effective solution to generate the output power with 43.2 % efficiency.
2. The proposed complex has an attractive perspective for all types of vehicles because it provides:
   a. reduction of the fuel/energy consumption and emissions;
   b. increase of the lifetime of a vehicle, improvement of the driver's comfort.

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