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TWO-STROKE DIRECT FUEL INJECT FREE PISTON GENERATOR FROM THEORY TO PRACTICE

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ABSTRACT

The paper presents the development process of the free-piston generator. During the study, we developed the generator concept taking into account modern trends in the field of free-piston generators. Based on the selected concept we performed the calculation of the generator units and subsystems and created a 3D model. While developing the 3D model of the generator we used 3D finite element methods to calculate the cooling system and mechanical strength in the model and, finally, created design documents. Besides, the control algorithms and control system were developed. As soon as the power generation system was produced, the installation and startup works were held. In order to perform the testing of the free-piston power generator, we constructed a test-bench, which provided the generator with air, fuel, oil and coolant. It also contains a powerful active electric load. During the tests, the generator achieved the output power of 16.87kW. The testing results allow choosing the future ways for construction development in order to increase and upgrade the characteristics of the free-piston generator.

Keywords: free piston engine, linear generator, two-stroke, direct injection, power plants.

INTRODUCTION

Nowadays the power generator systems for transportation and energy generation use thermal engines as primary sources of energy. The actual requirements to those systems become more and more restricted depending on their application. Those are the requirements to economy, power generation and ecology. The modern level of the systems for monitoring and controlling the engines, power supply and exhaust gas neutralization systems allows achieving highly efficient and ecological working parameters for the gasoline and diesel engines being developed. On the other hand, in order to increase actual working parameters we must critically consider all achievements and original constructions presented today in this field.

During the development of a fundamentally new power plant, we decided to step away from the classical scheme of the internal combustion engine with a crank mechanism to the internal combustion free pistons one. Though it is not fundamentally new, this scheme has a high development potential in the direction of reducing mechanical losses and improving the internal combustion engine working process due to flexible converting fluid energy into mechanical energy and a variable compression ratio. The last peculiarity allows using various hydrocarbon fuels.

Free piston engine construction has been known since the 1930s. However, in the 1960s their usage was constrained only as air compressors and gas generators for power turbine (Mikalsen & Roskilly, 2007). Free-piston engines were forgotten due to the development of gas turbines, which replaced the free-piston gas generators in the chain: gas generator - power turbine. Finally, they stayed only in the group of piling machines or diesel hammers. However, the modern free piston engines seem to be very promising due to the increase of the calculation speed of modern control system, to the appearance of compact linear electrical machines and power electronics – the most important thing, which allows receiving and converting generated energy. This is confirmed by the research applications of this type of power plants as a hybrid vehicle propulsion system (Ferrari & Friedrich, 2012), (Kosaka, *et al*., 2014), (Mikalsen & Roskilly, 2008), (Hibi & Ito, 2004), (Zhaoping & Siqin, 2010), (Waqas, *et al*., 2002), (Kock, *et al*., 2013), (Carter & Wchner, 2003). Free piston generators do not have a rigid piston connection, such as in the classical crank engines. Their movement depends only on the sum of the forces acting on it at any given time; so the control system of that type of power plants requires a separate study, described in (Goto, *et al*., 2014), (Nemecek, *et al*., 2006), (Mikalsen & Roskilly, 2010), (Ibrahim, *et al*., 2011), (Zulkifli, et al., 2009), (Pohl & Graf, 2005). Many different options for its implementation were considered during the development of the free piston power plant such as single-cylinder engine, two-cylinder, with a counter-moving pistons, etc. Such schemes of power plants are the research objects in many companies and research universities in the world such as NOAX and Innas (Denmark) (Achten, *et al*., 2000) having a single-cylinder engine and a hydraulic pump; Toyota Central R & D Labs Inc. (Kosaka, *et al*., 2014), (Goto, *et al*.,2014) working on a single piston engine and a linear electric generator, Sandia National Laboratories and Peter Van Blarigan (Goldsborough & Van Blarigan, 2003); (Van Blarigan, *et al*., 1998) having a two-cylinder free piston engines and a linear electric generator. Besides, there are schemes of the power plants having counter-moving pistons in University Toyahashi (Hibi & Ito, 2004), working on two hydraulic pumps, and the German Aerospace Center (DLR) (German Aerospace Center (DLR), 2013), running on two linear electric generators. Each of the schemes mentioned above has its own

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advantages and disadvantages. From our point of view, in addition to the basic parameters - efficiency and environmental performance, another criterion of the power plant should be applied: the mechanical balance of the vehicle, which affects the vibro-acoustic performance. Considering all the above, we chose a construction of the free piston engine with counter-moving pistons, which is fully balanced as soon as its pistons move synchronously. Its circuit is shown on Figure-1.

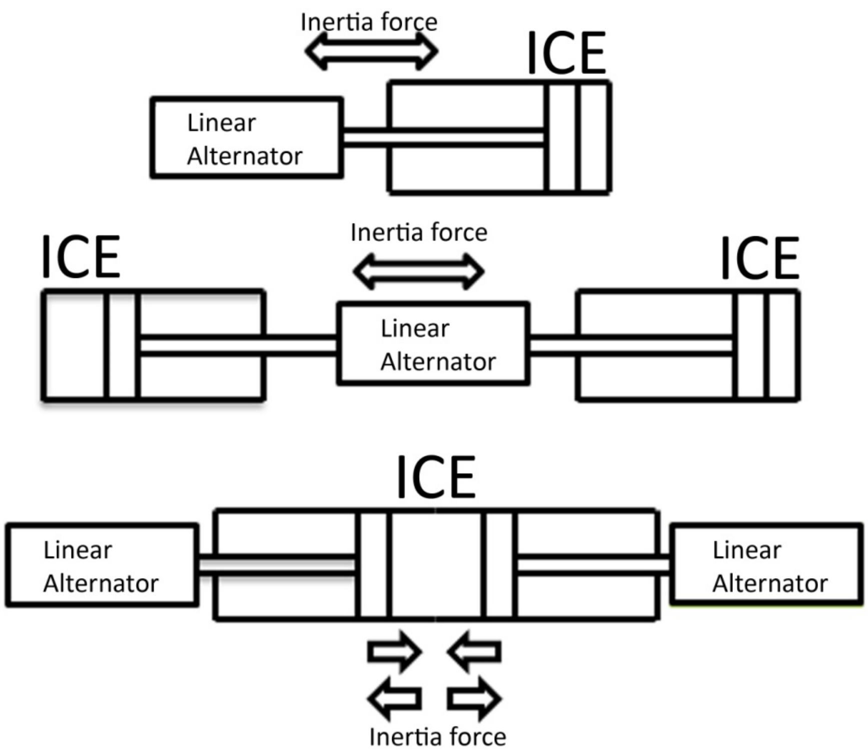

Figure-1. Free piston engines circuit.

Besides, this balanced scheme does not need classical valve timing system, since the gases exchange through the scavenging and exhaust ports and, in case of the laboratory tests, the gas exchange is carried out by a compressor.

METHOD

The selected scheme of the free-piston engine determines a set of the tasks to be completed during the research, such as the following: the implementation of the compression stroke, weight reduction of moving parts, the implementation of the generation startup process and the implementation of effective control algorithms. The use of the current system of gas exchange leads to the two-stroke operating cycle, which, though, has high specific characteristics. The linear electric machines were selected as power converters due to their high efficiency. Another task was to implement the compression stroke in the free piston engine, which does not have a flywheel as the classic one. Initially, it was decided to use electric machines in motor mode with a battery unit. However, the calculations showed that it leads to a dramatic decrease of efficiency. The movement of the piston in a free piston engine depends on the sum of the forces acting on it and the weight of moving parts. Therefore, the higher the required force on the translator of the linear electrical machine, the higher the weight of moving parts and the lower the maximal frequency of reciprocation. The calculation results show that the frequency depends on the mass of the translator as shown on Figure-2, provided the parameters of the operating cycle are constant.

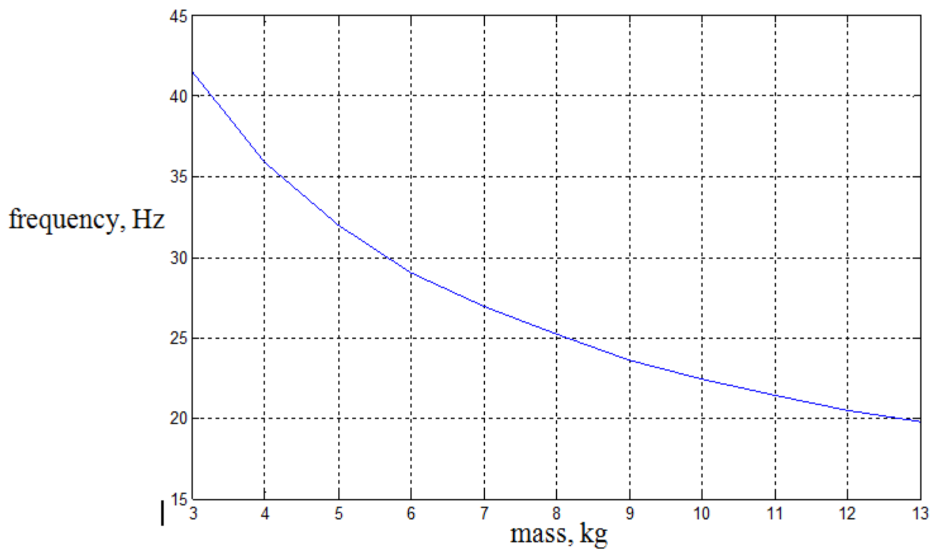

Figure-2. Reciprocation frequency vs translator mass translator.

The dimensions of the cylinder piston were selected based on the calculations and the required electric power of the power plant, which could not be less than 15 kW. The engine has the following parameters: cylinder diameter of 92 mm, piston stroke (a) of 80 mm, and compression ratio of 13. The selected values are based on the required characteristics and the peculiarity of the gas exchange system.

In order to continue the work on the project, one should have solved two other problems: the reduction of the mass of the moving parts and the implementation of the compression stroke. If an electric machine generates the energy only on the expansion stroke, then it works during 40% of the cycle, being the remaining 60% only an additional inertial mass. Moreover, in order to generate required power it must be oversized by almost 2.5 times. Therefore, in order to achieve the objectives we decided to use an electric machine as a generator on both cycles of free-piston engine and added an air spring into the construction. This spring stores a part of the energy on the expansion stroke and uses it to perform the compression. This design solution allowed reducing the maximum power of the electric generator, thus reducing the weight of the moving parts and increasing the frequency of power plant operation and its efficiency for the given output parameters.

INTERNAL COMBUSTION ENGINE UNITS

In order to provide a high efficiency of the power plant, we decided to use a direct fuel injection system, which leads to minimum air-fuel mixture emission in the exhaust manifold, thus improving the overall engine efficiency and environmental parameters. In addition to the direct fuel injection, free piston engines can perform on different compression ratios, thus leading to the use of various grades of gasoline, alcohols, esters, and natural gases. Free-piston engine lubrication system differs from the one of the classical crank engine, which lubrication is performed by the oil mist in the crankcase. Free piston engines use oil injection nozzles, which spray oil under the piston to lubricate its parts. The construction of the piston and the installation location of piston rings are chosen in such a way that the scraper rings do not reach the gas exchange ports, thereby preventing oil from entering the intake and exhaust system, which in turn reduces the amount of harmful emissions. The construction of the free-piston internal combustion engine has another advantage: the absence of the relaying of the piston when it passes through the top dead center (TDC) and bottom dead center (BDC). Thus, the design took in to account the fact that the piston skirt will have no contact with the surface of the cylinder, which, in turn, will reduce the friction losses and the increased thermal stress will be compensated by oil cooling. In addition to the oil lubrication system, we performed the research of the use of solid lubricant coatings on the mirror motor sleeve, which proved its efficiency in reducing the friction losses (Lesnevskiy, et al., 2014). Free-piston engine has a liquid cooling system; two cooling cavities surround each of the engine liners and four surround the combustion chamber. Such design is also chosen because of the location of the scavenging and exhaust ports that do not allow cooling the entire surface of the liner.

In order to implement the mixing in the free-piston engine cylinder, it was decided to use two nozzles located opposite each other, which, together with a twist of purge air inlet by tilting scavenging ports, provide good mixture formation. For ignition of the air-fuel mixture the spark plug and two opposite each other are placed. On the next stage of the development, we created a three-dimensional model of the power plant.

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LINEAR ELECTRIC MOTOR

According to initial estimates, each electric generator was supposed to provide a force of at least 1400 N, thus the calculation and design were based on this value. During the development, we considered several optional designs of electric generator and finally chose a three-phase electrical generator with a cylindrical translator. We also took into account that the power plant is constructed as a single unit, where the engine, electrical machines and pneumatic spring are combined with two rods. For the first estimation of the machine's geometry, a linearized model was chosen. It has the following assumptions: the magnetic permeability of the cores is infinite, there is no leakage flux in the central rod, the maximum current is constrained only by thermal limits, the flux density has sinusoidal gap distribution, and the armature reaction field is neglected. The calculations based on the model above allowed choosing basic geometry and permanent magnets. The last are the neodym magnets with axial magnetization, having dimensions of 90x60x5mm and maximal flux density of 1.45T. The relative permeability is 1.05. Based on some publications, we chose the inner/outer stator diameter ratio of 0.618 that corresponds to optimal axial force per unit (Bianchii, *et al.*, 2003).

The force calculations for different options of pole pairs, air gap and pole pitch allowed having an optimal solution. Figure-3 shows the calculation results of the axial force of the electric generator depending on the air gap and the number of pole pairs. It can be seen that the required nominal force of 1.4 kN is achieved when the number of pairs of poles equal to 4 and 2 mm gap. This translator weight is 6.2 kg.

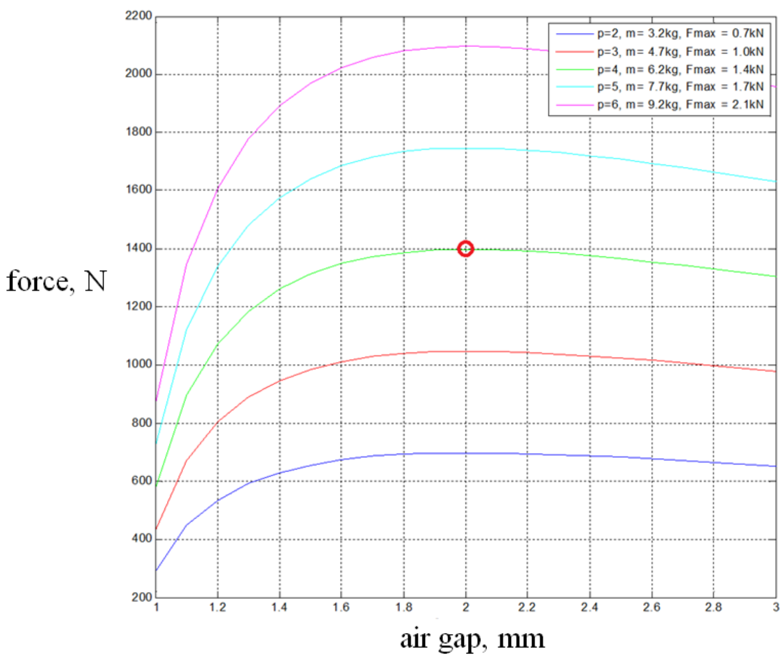

Figure-3. Force depending on air gap and the number of pole pairs.

Figure-4 shows the dependence of force on the translator of the electric generator and its weight on the value of the pole pitch for the gap of 2 mm. The graph shows that the pole pitch of 15 mm provides the necessary force of 1.4 kN.

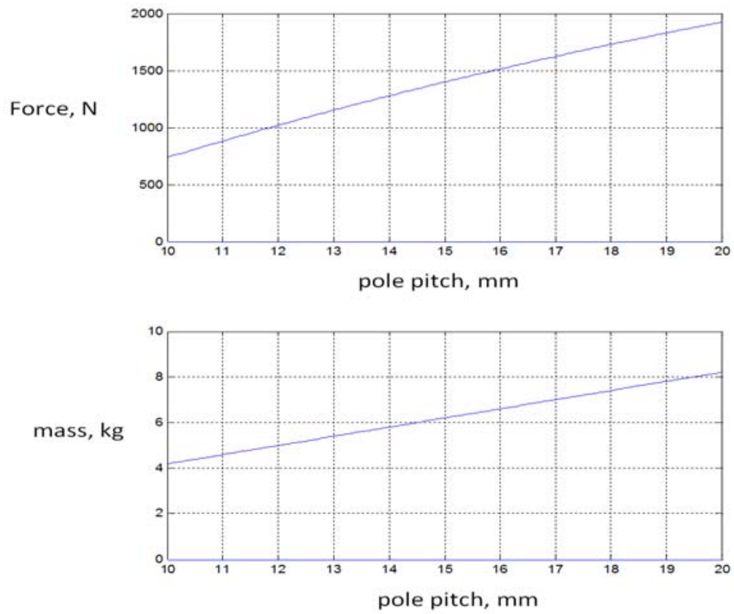

Figure-4. Dependence of force on the translator of the electric generator and its weight on the value of the pole pitch for the gap of 2 mm.

The most practical stator winding type for the current machine, considering small tooth steps and dimensions, is the tooth winding, since it is technologically the simplest winding for assembly.

In order to minimize the higher harmonics of the flux density and match the chosen number of slots and number of poles, considering that the poles and stator teeth have very close dimensions, we chose a winding with the number of slot per phase and pole q = 3/8. It shows good results in simulation and corresponds to the requirement: if Z is a multiple m, $1 < Z / p < 4$. This leads to $Z \neq 2p$, and this condition is necessary to exclude the braking force and avoid “sticking” of the translator.

The designed geometry was calculated for electromagnetic state using finite element approach. The distribution of the flux density and winding EMF of the electric generator is shown on Figure-5, simulating the translator linear movement at a speed of 10 m/s.

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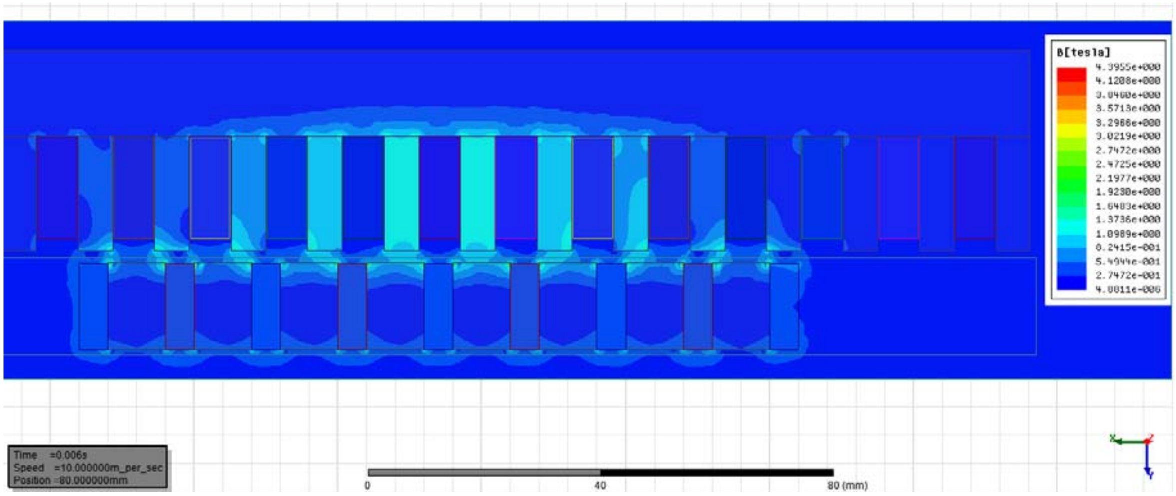
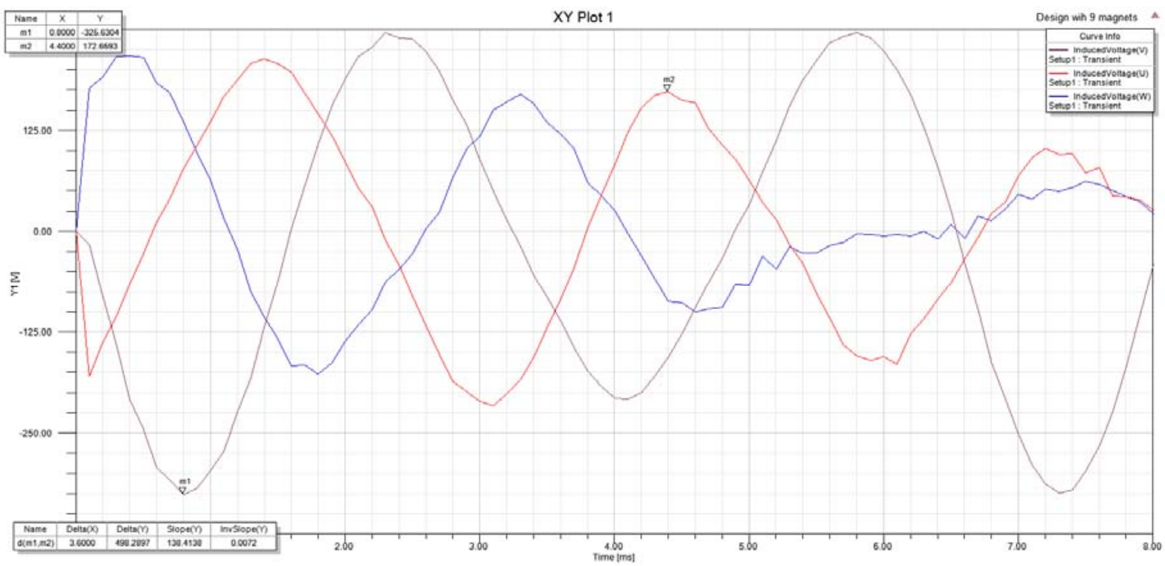


a)



b)

Figure-5. (a) Distribution of the flux density; (b) Winding EMF.

PNEUMATIC SPRINGS

In order to perform the compression stroke and store the energy, which is consumed by electric machine on the compression stroke, a pneumatic spring was designed. Since it will be used in the experimental bench, we decided to make it with variable compression ratio, which could function on the speed up to 10 m/s. The piston of a pneumatic spring is installed on the opposite end of the electric machine's translator. It moves inside the cylinder of a pneumatic spring, which has another piston on its opposite side. Its movement provides the possibility to change the compression ratio of the spring. Such a high value of linear speed of 10 m/s imposes significant limitations on the material of the seals. Piston size is chosen greater than the one of the internal combustion engine and has a value of 130 mm. This reduces the maximum pressure in the gas springs and thereby reduces the maximum temperature. Reducing the maximum operating temperature of the body allows using of PTFE sealing elements Ecoflon type 2, which operate under specified conditions and have a very low coefficient of friction.

THREE-DIMENSIONAL MODELING

After solving particular design problems, the three-dimensional models of free-piston internal combustion engine were developed, including electrical machines and pneumatic springs. After that, we created three-dimensional model of the power plant and developed joints between them, dimensional and technological elements of units. Three-dimensional model of the power plant is shown on Figure-6.

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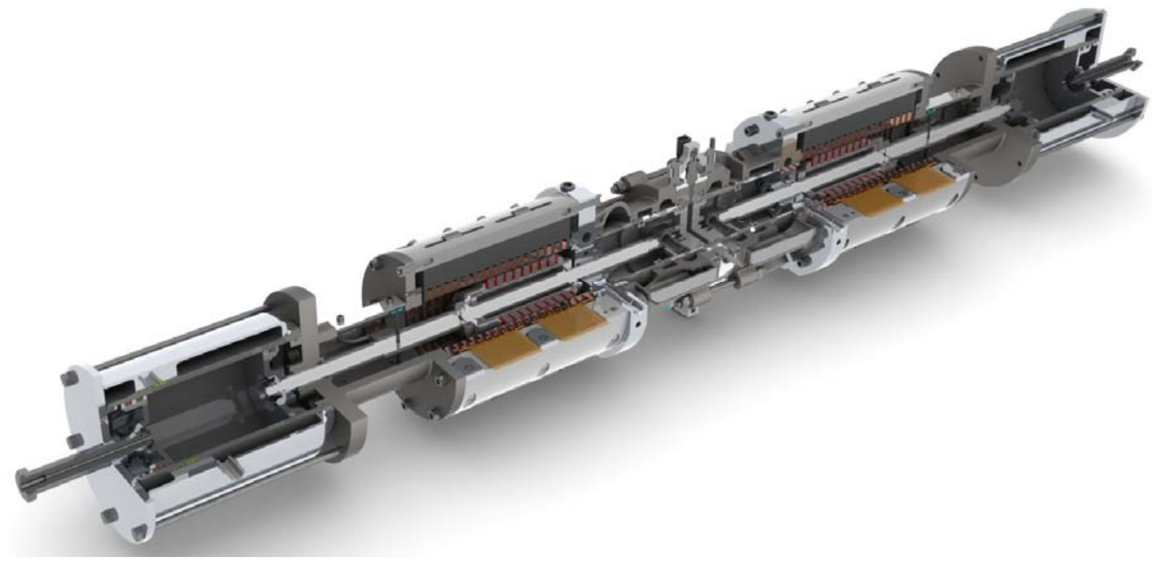

Figure-6. Three dimensional model of free-piston generator.

During the simulation, we also performed the calculation of the thermal-stress conditions of the piston and cylinder liner, the cooling systems of the free piston internal combustion engine and the electrical generators. Besides, we made the mechanical strength calculations of the translator, the rod, the piston mount, etc., which confirmed the correctness of the chosen design.

CONTROL SYSTEM

Another objective of the project is the development of power plant control system on a mathematical model. The control system becomes quite complex due to necessity of the synchronization of the mutual motion of two translators in order to avoid bias motion and timing. Synchronization must be provided considering the possible unevenness of friction, pneumatic spring forces and electromagnetic forces. The control system model of the free-piston generator was developed in Matlab/Simulink with the help of the physical simulation packs *SimScape* and *SimPower*. The complete model of the control system is shown on Figure-7.

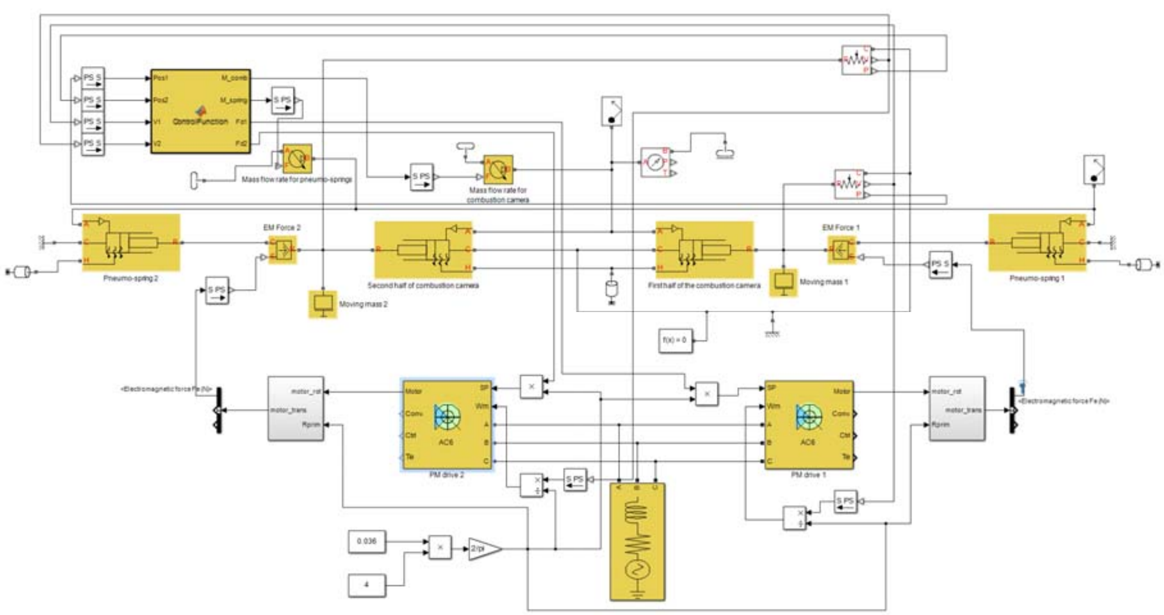

Figure-7. Model of the control system.

It consists of the opposite-piston cylinder model, two pneumatic springs and two permanent magnet drives (PM drives). The opposite-piston cylinder model is assembled of two pneumatic cylinders, oppositely directed

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to each other and having common pneumatic and thermal circuits. Such assembly makes the gas dynamic and thermal phenomena to be equal and synchronous in both "half-cylinders". In order to simulate the combustion of the fuel-air mixture the model just bumps up the pressure in the cylinder during the particular cycle period. The pneumatic springs are simulated using the exact model from Simscape with the particular physical properties. The model contains a possibility to control the pressure in the pneumatic springs in accordance with the real system. We used the model of a rotating PM-synchronous machine and its drive as a model of a linear electric machine. Its parameters and input and output signals are converted according to the method, which was described in (Petrichenko, *et al.,* 2015).

The control algorithm is implemented as a Matlab function script. Based on the information about the current working mode, current coordinates and velocities of both pistons, the program forms the following controlling signals: combustion camera mass flow rate (controlling pressure), pneumatic springs flow rate, demanded force values for the electric machines 1 and 2. The system works in two modes: startup procedure and steady state mode. The startup procedure begins with setting the forces of electric machines in order to start the compression phase. The force is not enough to perform the complete compression immediately. Therefore, it takes several cycles of swinging the pistons with increasing amplitude. As soon as the pistons touch the top dead center (TDC), the system moves into the steady state mode.

In steady state mode, the system has the aim of controlling the demanded TDC (and compression ratio) in current conditions. The control system sets up a pressure rise when the pistons achieve TDC, thus simulating the ignition and combustion. This forces the pistons to go in other directions and compress their pneumatic springs. In this phase, electric machines convert part of energy into electrical load. When the BTC is achieved, the combustion camera windows open, which is simulated by pressure drop to atmospheric value. After that, the springs start moving the pistons back to each other, thus beginning the compression phase. During that phase, electric machines convert part of energy into electrical load again.

When electric machines are generating energy, the demanded forces on their translators are always of nominal values. The amount of converted energy is controlled by switching on and off the machines for a particular period of each phase. Such strategy allows compensating possible irregularities of the piston movements, thus synchronizing the pistons in time.

DEVELOPMENT PARTS AND ASSEMBLY

The parts, units and assemblies of the power plant were produced at the next stage of the project. In order to improve the processability, the geometry of certain components was simplified and optimized during the manufacturing. Free-piston internal combustion engine consists of cast steel blocks, which include cast-iron liners. Steel blocks are connected together through the combustion chamber, in which the spark plugs and the fuel injectors are installed inside piston liner sets. Having the engine assembled, the installation of the sealing elements of the thermo oil gasoline resistant rubber is performed. Assembled free-piston internal combustion engine is shown on Figure-8.

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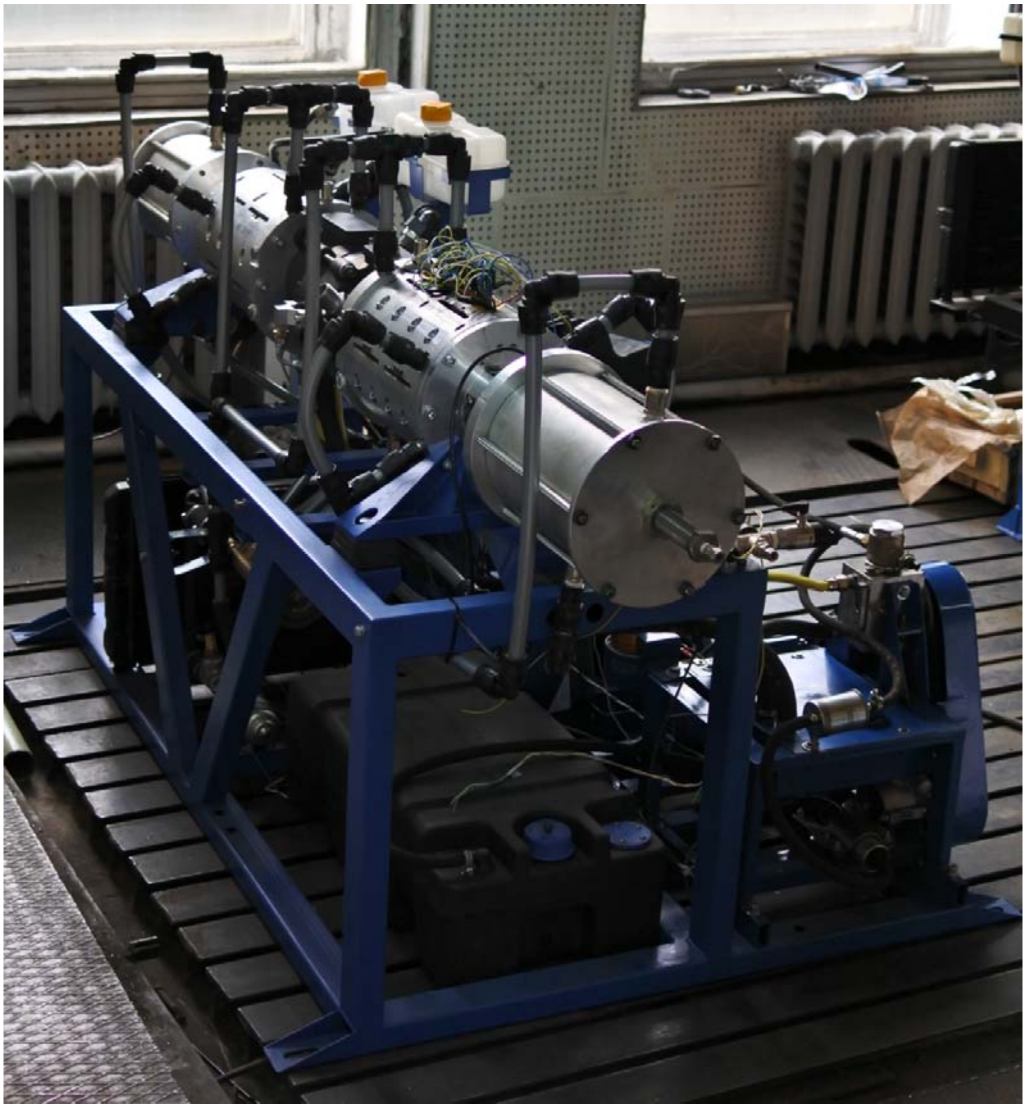

Figure-8. Assembled free-piston internal combustion engine.

The housing of the electric generator consists of two aluminum bodies, which contain electromagnetic stators made of laminated electrical steel bonded with compound. The slots of the stators contain two-layer stator winding. The butt ends of the stator are covered with the front and back coverings, containing linear ball bearing that directs the translator movement. Translator consists of a steel rod, which is surrounded by a stainless steel pipe. The translator contains magnets, poles and magnetic displacement sensor.

Pneumatic spring consists of an aluminum-cooling jacket, iron working cylinder, aluminum outer flange, which contains the second piston adjusting bolt. The adjusting bolt has a hole inside, which provides the air pumping and loss. The second flange of the electrical generator is used as the back cover of the pneumatic spring.

After manufacturing, the parts and components of the power plant were assembled together. After assembling, the power plant was installed on the test bench. The test bench provides the power plant with fuel, oil, air for the internal combustion engine, the compressed air to the pneumatic springs, coolant, electrical loading unit, as well as monitoring of basic parameter settings.

DEBUGGING SYSTEMS AND TESTS

Before starting the power plant tests, a series of tuning works was held, including: the calibration of the air spring forces depending on the degree of compression in it and the reference pressure, the calibration of the fuel injection system pressure and the fuel injection timing and calibration forces of linear electrical generators. Then we tuned up the compression process of the engine and the start sequence.

As the piston rings do not provide a complete seal, the cylinder pressure becomes atmospheric in some time. This leads to the effect that while attempting to dissolve the pistons from the current point to BDC, the cylinder pressure falls below atmospheric, which increases resistance very much. Therefore, at the first starting point, the pistons are slowly spread laterally to the region of the exhaust ports, after which the pressure in the cylinder is aligned with the atmospheric. After that, we start supplying the air into the pneumatic springs and begin swinging the pistons increasing the amplitude step by step. As soon as the amplitude achieves the value, which provides a desired compression ratio, the engine starts normal working mode. As soon as all the power plant units were tuned up, the tests on nominal power were performed. The generated electricity was consumed by the active electric load. According to the results of preliminary tests, the maximum obtained electric power in the power plant was 16.87 kW at a reciprocating frequency of 25.9 Hz.

CONCLUSIONS

This design is based on the two-stroke internal combustion free piston engine with direct fuel inject, two cylindrical linear electric generators and two pneumatic springs. The design of free piston engine allows providing variable compression and direct fuel injection which decrease fuel consumptions. Research of the use of solid lubricant coatings on the mirror motor sleeve proved its efficiency in reducing the friction losses. The use of the pneumatic springs allows decreasing mass of the translator and increasing frequency end efficiency. A designed free piston generator was produced and assembled. The results of calculations were confirmed by tests. The future research of the free piston power plant will be aimed at reducing the weight and size characteristics, making the oil, fuel and air supply units in order to maintain the autonomous work of the generator. The development of these units will help find wider applications of free piston power plants in hybrid vehicles.

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