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Experimental Evaluation on the Starting Process of an Opposed-piston Free-piston Linear Generator

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Abstract—Free Piston linear Generator becomes a new solution and device for energy conversion highly integrated engine and linear machine due to its potential application on hybrid vehicles. This paper investigated the starting process of an opposed-piston free-piston linear generator (OPFPLG), and a prototype was built to carry out the experimental research of the startup process. The prototype adopts a piston synchronization mechanism and a pipeline connecting two bounce chambers to improve the self-balance performance of the system. The linear machine is used to start the engine because of its flexibility and controllability. The control strategies combining mechanical resonance and synchronization control methods were applied on the prototype for starting operation, and the test data collected for further analysis. When the linear motor's thrust force was 240N, the maximum pressure in combustion cylinder achieved was beyond 11.8 bar with a compression ratio of 12:1, indicating that the mixture was ready for ignition. The system frequency was up to 14Hz, and the piston amplitude was about 56.5mm with a synchronization error of the opposed pistons less than 1.5mm. Especially, the piston synchronization error of the inner and outer dead center was nearly zero. Both the variation of synchronization error and the cyclic fluctuation of starting process were demonstrated with different synchronization control methods. The piston sync error of the dual current command control mode was found to be lower than that of the master-slave mode, and the cyclical fluctuation was smaller. The dual current command control method will be implemented to the prototype to start and maintain the piston motion synchronization during the starting process of the OPFPLG system.

Keywords—opposed-piston, free-piston engine, starting process, cyclic fluctuation, synchronization control strategy

I. INTRODUCTION

As traditional internal combustion engine (ICE) widely used in power devices is of low fuel efficiency, the powertrain will require to improve efficiency due to the ensuring energy and environmental problems. The electric car is being developed for this purpose, and the electrical machinery has high efficiency. However, the electric car is relatively expensive for low battery energy density and limited battery range. In addition, the battery recycling and exploitation are also problematic. To save energy and reduce emission, the researches focusing on hybrid power systems are carried out. Compared with traditional ICE, free piston engine has the characteristics of simple structure, high efficiency , fuel flexibility, low NO_x formation[1], and direct electricity output, so it is very suitable for hybrid electric vehicles. The opposed piston design has a better vibration and noise condition because its symmetrical structure and movement. Such advantages has attracted researchers worldwide, and many simulation and experimental analysis studies have been done.

The opposed piston engine-alternator system developed by Sandia National Laboratories was successfully achieved low equivalence ratio HCCI combustion with compression ratios ranging from 20:1 to 70:1, and net indicated thermal efficiency were between 50% and 55%[2]. To start the piston motion on motoring process, a high pressure pneumatic drive system was devised to reach a desire compression ratio. The mirror image coil pairs of the alternator stators were designed to keep piston motion in sync without complex active controls. But the passive synchronization of the piston is of low robustness that needing a more perfectly balanced system.

The Toyota Central built a single piston engine-linear generator system while a gas spring chamber was used to provide compression energy for the next cycle[6]. The experimental results from stable operation showed that the cycle frequency was 23Hz with a low compression ratio of 7:1. The linear generator generated only in high speed area and provided a mean DC power up to 2462W, and its peak power was up to 12kW. The linear generator drove as a motor to accelerate the piston, which also corrected piston motion relative to an ideal reference cycle with a fairly complex feedback control system.

Although having the great advantages mentioned, the free piston also has many technical problems in cyclic fluctuation, state switching, piston motion control and start up[3]. From which, a rapid and stable startup operation is the very first step of the operation system, beneficial for the gas intake, mix and compression to achieve desired ignition state. The mechanical resonance method[4] is the most widely used by providing a small motor force to reciprocate the pistons. During a few cycles, the maximum in-cylinder pressure increases gradually until the ignition condition is reached.

The aim of the starting process of opposed piston design is not only to achieve the required condition for ignition, but also to ensure the synchronous motion of the twin pistons. Here the mechanical resonance method combined with the synchronization control strategy is adopted to meet the requirement. Firstly, the construction and improvement of the opposed-piston free-piston linear generator will be described. Then, the operating state and the gas pressure in both combustion cylinder and bounce chamber in starting process is briefly described. Finally, the synchronization error and cyclic fluctuation of the two pistons are compared, and starting control strategy is improved.

II. OPFPLG CONFIGURATION AND EXPERIMENT SYSTEM

A. Overview of OPFPLG

The physical prototype shown in Fig.1 is an opposed-piston Free-piston linear generator(OPFPLG). It consists of a combustion chamber, two linear machines and two rebound devices. The pair of opposed pistons is reciprocating oppositely due to the symmetrical structure. The combustion chamber in the center is placed between the two linear electrical machines. The two symmetric moving masses consist of the power piston, rebound piston, and permanent magnets. The power pistons share the same combustion chamber, where the ignition plug, fuel injector, inlet port, exhaust vents are arranged along the circumferential direction.

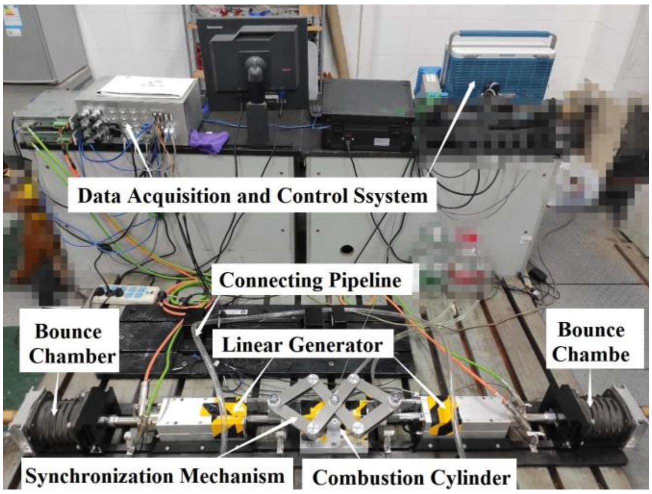

Fig.1 Opposed-piston Free-piston Linear Generator Prototype

The two bounce chambers are located on both ends of the OPFPEG, connecting through the pipeline to eliminate the gas pressure difference between the two bounce chambers. The use of pipeline ensures that the two cylinders have the same rebound pressure and improve the internal balance characteristics of the system. A check valve and a gas pressure sensor are installed on the cylinder head of the rebound cylinder. The check valve is designed to open from the outside to the inside of the cylinder with low opening pressure of 10kpa. At the beginning of the startup operation, the check valve supplies air from the outside to the chamber to adjust the initial in-cylinder pressure in order to adapt to the requirements of the rebound gas force under different operating conditions. After repeated design and adjustment, the parameters of the main physical prototype are shown in Table I.

The piston synchronization mechanism is a detachable component connecting the two pistons but not put limit on the piston stroke. When the two pistons are not synchronized, the synchronization mechanism places a force on the leading piston to offset the asymmetry.

TABLE I PARAMETERS OF THE OPFPLG PROTOTYPE

Parameters	*value*
Cylinder bore(mm)	56
Maximum stroke(mm)	60
Effective stroke(mm)	56
Working volume(L)	0.17
Compression ratio	8:1~13:1
Moving part mass(kg)	4.0
Distance at TDC(mm)	10
Bounce chamber diameter(mm)	115

The OPFPEG design adopts two-stroke cycle spark ignite engine with uniflow scavenging and low pressure direct injection system. Linear electrical machines are used for power conversion and piston synchronization, while rebound chambers are used for energy storage to provide compression work for the next cycle. At the end of the expansion stroke, the fresh mixture is scavenged through the inlet ports and charged in the combustion chamber. When the compression stroke begins, the inlet and exhaust ports close in turn, and the mixture is compressed. As the piston moves close to the top dead center (TDC), combustion begins and high-pressure gas pushes the piston to bottom dead center (BDC). Meanwhile, part of the kinetic energy is converted into electricity directly via the linear electrical machine and the remaining is stored in the rebound chamber to overcome the compression force in the next cycle. The exhaust vent and inlet port open in sequence to exchange the mixture.

During the starting process, the linear electrical machines both work in motoring mode to drive the piston back and forth until it reaches the ignition conditions. The two opposed pistons are driven from the BDC to the TDC with the help of linear electrical machines and the bounce chambers. During the cold start up process, the ignition and combustion process are disenabled, focusing on the compression and expansive process of the mixture in the follow section.

B. Startup and Control system

The linear generator is the key component of the engine-linear generator system, and the performance parameters of it are shown in Table II. The continuous force is about 488N, and the peak force is up to 1617N, ensuring that the motor is able to drive the piston at a idling frequency to reach the pressure required for ignition. At the same time, it is of high efficiency to transform the kinetic energy of piston to electric energy stored in batteries or power the external load.

During the startup process, the linear motor runs in motoring mode with appropriate power electronic control. The linear motor force accelerates the piston in the direction of piston velocity to achieve mechanism resonance during the test. Two synchronous control methods were applied on the tests to reduce the piston synchronization error and improve the stability of startup operation. The dual current command control method means that the two motors directly drive with the same current commands at the same time base to output the motor force with different direction. The master-slave control method means that the master motor is directly driven by current commands while the slave motor works at a position loop to follow the position of the master one.

The control system needs to debug the hardware connection, software programming to achieve complex process such as auto homing, startup, protection, stop, and so on. A programmable multi axis controller of DELTA TAU is used to achieve the control strategies.

TABLE II PARAMETERS OF THE LINEAR GENERATOR

Parameters	***value***
Continous stall force(N)	488
Peak force(N)	1617
Continous stall current(A)	6.2
Peak current(A)	28
Force constant(N/A)	81.6
Back EMF constant(V/(m/s))	69
Resistance(Ohm)	6.2
Inductance(mH)	11.6

C. Data acquisition system

In order to detect the running status of the OPFPLG in real time, it is necessary to arrange plenty of sensors and use a signal acquisition device to provide synchronization clock in data-gathering, which contains the measurements of gas pressure in combustion and bounce chamber, piston displacement, voltage and current of linear motor. The pressure in those chamber is measured by Kistler piezoelectric pressure transmitter, and the displacement of piston is measured by the internal Hall sensor in linear motor, avoiding vibration affecting measurement accuracy. The displacement is an important feedback control parameter, and is converted into piston speed and cylinder volume for analysis. The linear motor current and voltage are collected by the internal hall sensor in the driver, and obtain the real time drive control current through Park-Clark transformation.

All physical signals are converted into voltage signals and collected into a Tektronix high precision acquisition device. The sampling trigger signal is based on the piston speed, once the speed value is larger than 0.025m/s, a trigger signal generates. The oscilloscope detects the trigger signal and starts sampling at the same time base, ensuring the real time synchronous sampling.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. starting state

As above, the in-cylinder pressure of 10 bar and the compression ratio of 8:1[4] are required for ignition. With the dual current command control method, the parameters of the starting process on experimental perform well meet the requirement. Fig.2 shows the displacement and synchronization error of the opposed piston during the starting process. Fig.3 shows the curve of the pressure of combustion and bounce chamber on starting tests. With a constant driving force to reciprocate the piston, the stroke increases gradually by mechanical resonance, and the starting status tends to be stable after five cycles. The system is operated at a constant piston frequency of about 14Hz, and a piston amplitude of 56.5mm. The combustion chamber pressure grows to over 11.8 bar with a compression ratio of 12:1.

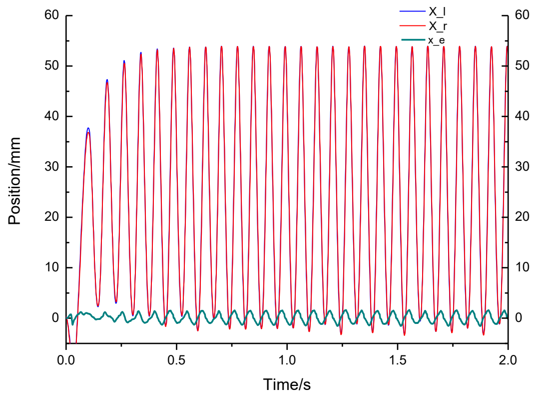

Fig.2. Positon and synchronization error of the opposed piston

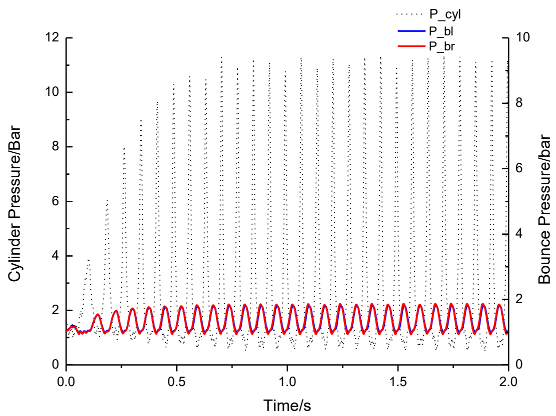

Fig.3. Pressure of combustion and bounce chamber

The synchronization error of the two opposed pistons also increases with the piston frequency, and it fluctuates within a range of ±1.5mm after the startup process is stable. The maximum synchronization error is about 1.5mm at mid-stroke of piston motion, while the synchronization at the inner and outer dead center positions is almost 0. It is helpful to improve the balance and symmetry performance of the system, providing a favorable condition for the subsequent ignition stage.

The bounce chamber pressure at the inner dead center is 1 bar, in other words, the minimum pressure is close to the atmospheric pressure. It means that the bounce chamber can ensure sufficient pressure and maintain continuous operation without using the complicated booster equipment during the entire startup process. However, due to the heat dissipation and leakage of the piston ring, a low pressure check value is required to supply air. When the chamber pressure is lower than the ambient, the check valve opens automatically, and a small amount of gas is replenished into the chamber to maintain the minimum pressure of 1 bar.

Fig.4 shows the starting state of applying different motor force on the test rig. When the constant motor force is over 240N, the OPFPLG system operates at 13.3Hz with a stroke of 53mm, and the maximum in-cylinder pressure is up to 9.6 bar and ready for ignition. A smaller constant force driving the piston at a stroke of 35mm fails to startup the engine. Since the bounce piston is twice the diameter of the combustion piston, the linear motor needs to output a higher force to overcome the friction and bounce force. For a motor force of 280N, the displacement of piston almost increases to the maximum stroke of 60mm, with frequency of 14.5Hz, and the maximum pressure grows to 14bar, which appropriate for igniting.

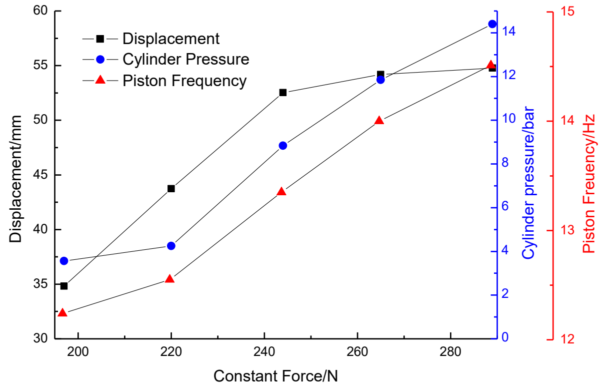

Fig.4. Piston displacement and frequency, cylinder pressure for various constant force

B. *Synchronization error analysis*

The OPFPLG design with a dual set of piston is perfectly balanced with low NVH when the opposed pistons operate synchronously. The prototype adopts a piston synchronization mechanism and a pipeline connecting two bounce chambers to improve the self-balance performance of the system. During the experiment of the starting process, different synchronization control strategies were implemented to keep the piston motion in sync. The graph in Fig.5 shows the piston synchronization error for various control strategies. Among them, the data of Tek130 and Tek126 is controlled in master-slave mode without the synchronization mechanism, and the piston sync error is in range of ±3.5mm. The Tek097 and Tek095 are the collected data when the system operates in the master-slave mode with synchronization mechanism, and the error is ± 2mm. Tek105 and Tek106 are the synchronization error in dual current command control mode, ± 2mm, and sometimes reduced to ±1.5mm. It is no doubt that the synchronization mechanism improves the balance of system and eliminates the external disturbances to reduce the synchronization error.

In one operating cycle, the synchronization error takes in the form of a triangular wave shown in Fig.6, and the value alternates between positive and negative. The piston synchronization error is related to the piston velocity, the maximum error occurs at the peak velocity, and zero error at the inner dead center and outer dead center. When the piston speed increases, the motor's back electromotive force increases based on Lenz's law. The current of the coil changes that leads to the motor's thrust fluctuations increasing, and the piston synchronization error increases as a result. The piston velocity of the inner and outer center is zero while the gas pressure in cylinder is maximum. On the contrary, higher stiffness of gas spring can lower down the disturbances and reduce the piston synchronization error.

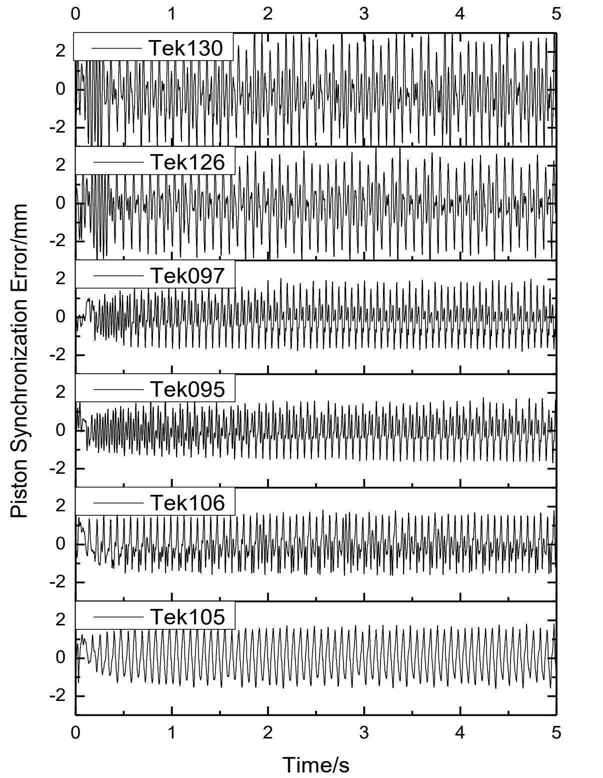

Fig.5. Positon synchronization error under difference control strategies

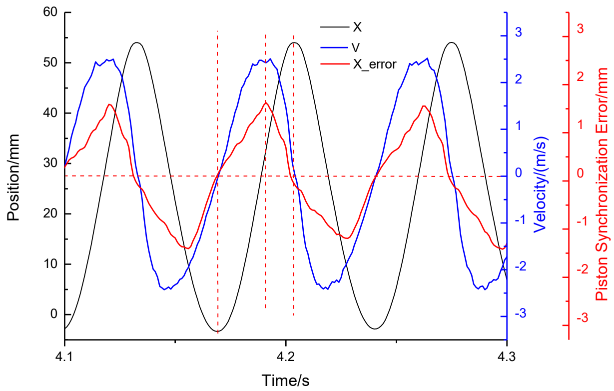

Fig.6. Piston synchronization error along with position and velocity

C. *Cycle fluctuation of in-cylinder pressure*

Another important observation from the experimental data is that the control strategies has effect on the cycle fluctuation of in-cylinder pressure. Fig.7 shows the cycle fluctuation of the gas pressure under difference control strategies. Tek097 is the data of the combustion pressure when the system operates with the master-slave mode, while Tek106 is with dual current command control method. The experimental results show that the in-cylinder pressure increases quickly and tend to be stable after 5 cycles for

Tek106 while Tek097 takes more time to reach its peak pressure. In the master-slave mode, the slave motor follows the position of the master, there must be a delay that working at a position control loop rather than a current loop.

Fig.8 shows the target current of the master and slave motor. The master motor is controlled in a current command, where current is in square wave with the same direction as velocity. Since the target current of the slave motor is calculated by the position command and needs to be adjust in real time. Considering that the linear motor is an inductance with electrical time constant, thereby the cycle fluctuation of the piston movement in the master-slave mode is relatively large.

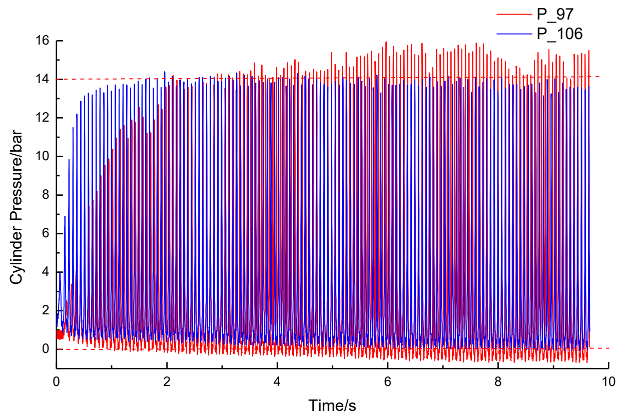

Fig.7 Cylinder pressure of various control method

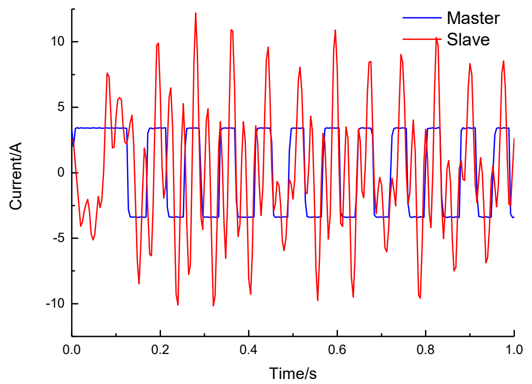

Fig.8 Target current of the mater and slave motor

The dual current command control method drives the two motors directly with the same current commands at the same time base. There is no hysteresis of the control command between the two motors, and the mutual influence of the current is avoided. With the help of the synchronization mechanism and connecting pipeline of two bounce chambers, the dual current command control method can guarantee the synchronization performance of the oppose pistons.

IV. SUMMARY AND CONCLUSION

This research investigated the starting process of an opposed-piston free-piston linear generator. For this purpose, a prototype has been developed to carry out the experimental research of the startup process. The prototype adopts a piston synchronization mechanism and a pipeline connecting two bounce chambers to improve the self-balance performance of the system. The experimental results shows that the synchronization mechanism can provide a more reliable starting operation, and the connecting pipeline can eliminate the gas pressure difference between the two bounce chambers.

The test results show that the mechanical resonance method can gradually accelerate the piston to complete the startup process. For a motor force of 240N, the system operates at 14Hz with compression ratio of 12:1, and the maximum in-cylinder pressure is up to 11.8 bar, which is ready for ignition. If the motor force is less than 240N, the pressure of combustion chamber cannot reach the ignition condition, and if it is higher than 240N, the piston will bump the cylinder on the startup process. A large motor force can increase the operating frequency, gain higher in-cylinder pressure, and achieve more profitable ignition conditions.

It is proved that the piston synchronization error is related to the piston velocity. The larger the piston velocity, the larger the synchronization error. The piston synchronization error at the inner and outer dead center is close to zero.

The piston synchronization error is varied with different control strategies. With the premise of the synchronization mechanism, the piston sync error of the dual current command control mode is smaller than that of the master-slave mode, and the cyclical fluctuation in long term continuous operation is smaller. Therefore, The dual current command control method will be implemented to start and maintain the piston motion on the starting operation of the OPFPLG system.

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