

Investigation of Combustion Optimization Control Strategy for Stable Operation of Linear Internal Combustion Engine-Linear Generator Integrated System

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ABSTRACT

The linear internal combustion engine-linear generator integrated system (LICELGIS) is an innovative structure as a range-extender for the hybrid vehicles, which contains two opposed free piston engines and one linear generator between them. The LICELGIS is a promising power package due to its high power density and multi-fuel flexibility.

In the combustion process of linear engines, the top dead center (TDC) position is not stable in different cycles, which significantly affects system operations. Otherwise, pistons move away from the TDC with high-speed because of the tremendous explosive force, which incurs the short residence time of pistons around the TDC and rapid decrease of in-cylinder temperature, pressure and the combustion efficiency. In order to address this problem, a scientific simulation model which includes dynamic and thermodynamic models, is established and a combustion optimization control strategy is proposed. The control strategy is based on the variable electromagnetic resistance force of the system. The electromagnetic resistance force is predictive and adjustable based on the velocity of midpoint and piston displacement.

The simulation results indicate that under this control strategy, the TDC position is stable in different cycles and the power of the linear engine in one working cycle increased 5.6% than that without this control strategy. The control strategy based on combustion law and compression ratio of different fuels should be useful to control the piston trajectory around the TDC or even the whole cycle to realize high-efficiency combustion of different fuels.

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INTRODUCTION

The Linear Internal Combustion Engine (LICE), which is also called the Free-Piston Engine, was developed gradually from the 1920s. The LICE eliminates the crankshaft and decreases side force applied on the cylinder wall, so that friction loss is reduced. Therefore, the LICE mechanical efficiency is higher than the traditional internal combustion engine. When the Linear Generator integrates with the LICE, they develop into the LICELGIS. As an innovative generating unit, it can be applied in the range-extended vehicles because of mechanical simplicity and high power density. Much work has been undertaken by a number of research groups worldwide to explore the operation characteristics of the LICELGIS [1, 2, 3, 4, 5].

The electronic control method is the main challenge in the current LICELGIS research, where the core point is the control of piston motion. Piston motion control includes the control of TDC, bottom dead center (BDC), and velocity in which TDC control is of vital

importance. Due to the elimination of crankshaft, piston motion is totally free, resulting in the TDC position variation during the operation process. Furthermore, the TDC position variation causes variable compression ratio, so the combustion is impacted and system efficiency decreased. Thus, it is necessary to control the TDC position during the operation process [6, 7].

The LICELGIS piston motion is affected by the electromagnetic force, friction force and in-cylinder gas pressure. Therefore, the control of the LICELGIS operation is realized by controlling the electromagnetic force. This paper focuses on the combustion optimization control strategy based on variable electromagnetic force control, detailed sub-models were established for starting process and stable operation, and simulation results were obtained.

LITERATURE REVIEW

Researchers at West Virginia University finished numerical studies of parameters to predict the behavior of the engine over a wide operating range. The model with the combination of dynamic and thermodynamic analysis was built and validated against the operation of the prototype. The dynamic model consisted of an evaluation of the frictional forces and the load of the engine. The thermodynamic analysis consisted of an evaluation of each process that characterize the engine cycle based on the First Law of Thermodynamics. A time-based Wiebe function model was applied to calculate the heat release during the combustion process. The numeric model also provided the basis for a parametric study of an engine similar to the constructed prototype. The result showed that heat addition and combustion duration influenced peak pressure, engine frequency and compression ratio similarly [8,9,10].

Researchers at Sandia National Laboratories finished an investigation about a Free-Piston engine and analyzed the steady-state operating characteristics using a zero-dimensional, thermodynamic model with detailed chemical kinetics, and heat transfer, scavenging, and friction sub-models. They used eight different fuels at low equivalence ratio and initial temperatures. The results indicated that the cycle thermal efficiency can be improved (56% measured) relative to current combustion systems. The primary cause of this high conversion efficiency is nearly constant volume combustion at high compression ration ($\sim 30 : 1$) [11].

Researchers at Toyota Central R&D Labs Inc developed a Free Piston Engine Linear Generator consisting of a two-stroke combustion chamber, a linear generator and a gas spring chamber. They developed one-dimensional cycle simulation. In this simulations spark ignition combustion and premixed charged compression ignition combustion were assessed, with output power of 10kW. High thermal efficiency of 42% was realized in the PCCI combustion case. The results indicate that rapid combustion occurs in the TDC position, however, the solution of addressing the problem is not proposed [4,5].

Researchers at Newcastle University finished an investigation into the basic control of a free-piston engine generator using a full-cycle simulation model. The control variables were identified with TDC, BDC and speed. The investigation showed that even small variations in TDC position lead to large changes in engine compression ratio and the main challenge with free-piston engines was the control of the piston motion. They presented a predictive motion control strategy based on the TDC position, which showed superior performance to that of a standard PI controller [7,12].

Zuo et al. at Beijing Institute of Technology provided numerical simulation modelling of a spark ignited free-piston engine generator with in-cylinder thermodynamic sub-model, including heat transfer,

gas leakage, combustion and scavenging. The compression and expansion processes were not regarded as ideal gas isentropic processes. During the steady operation process, the difference was less than 5% and the areas enclosed on the pressure-volume were similar [13,14,15].

Wang et al. at Tongji University developed the LICELGIS since 2006. Based on the structure and performance of linear engine, they designed and optimized a three-phase tubular permanent magnet ISG matching with linear engine by using electromagnetic field finite element analysis method. Experiment was done to a LICELGIS prototype and results showed that the engines could start successfully and operate for a few cycles, but stable operation had not been achieved in experiment [16, 17].

PROTOTYPE DESCRIPTION

The LICELGIS adopts opposed two-cylinder configuration, and the linear generator is located between two free piston engines. The connecting rod is fixed to the generator's moving shaft axially. The LICELGIS is shown in Fig. 1. The linear generator operates as a motor to start engines to reciprocate back and forth, triggering injection and ignition when the condition is met. Subsequently, the linear generator is switched to generator after success of combustion and the piston's kinetic energy is transferred into electrical energy.

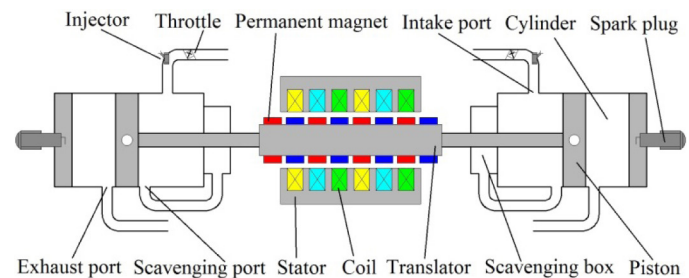


Figure 1. Structure of LICELGIS

Due to the elimination of crankshaft, piston motion is not restricted and the compression ratio is adjustable according to different fuel characteristics so that different fuels could be used. Meanwhile, the piston's reciprocating movement eliminates side forces between piston rings, piston skirt and the cylinder wall, ensuring that the LICELGIS friction loss is reduced and mechanical efficiency is raised. However, this feature incurs a large challenge that the free piston engine motion is completely affected by the force applied on it, which in turn increases the difficulty of piston motion control.

To better understand the LICELGIS's investigation, the prototype which was designed and developed is shown in Fig. 2. Two commercial two-stroke engines were adapted for the prototype, which eliminated crankshaft and redesigned scavenging air box. Fuel injection, which is under electronic control, occurs in air inlet. Two spark plugs are mounted on top of the engine for ignition purposes.

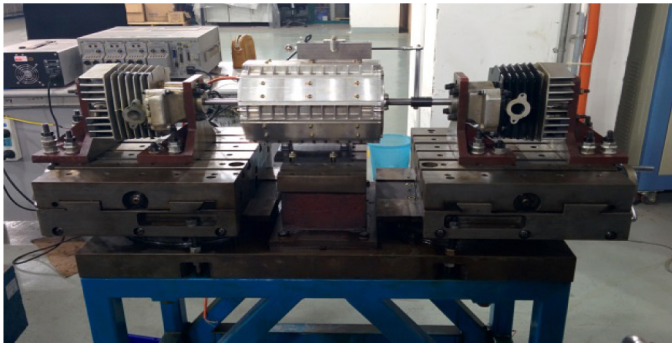


Figure 2. Prototype test bench of LICELGIS

COMBUSTION OPTIMIZATION CONTROL STRATEGY ANALYSIS

The conventional internal combustion engine moves more slowly around the TDC due to restriction of crankshaft, ensuring that the combustion of air fuel mixture around the TDC is close to constant volume combustion and the transient combustion process is highly efficient. During the combustion process of the LICELGIS, pistons move away from the TDC with high-speed because of the tremendous explosive force, which incurs the short time residence of pistons around the TDC and rapid decrease of in-cylinder temperature and pressure. Engine combustion constant volume degree (which means the proportion of constant volume combustion during the whole combustion process) and combustion efficiency also decreases. The two-stroke free piston engine and generator of West Virginia University could operate smoothly in 24.5Hz, and spark plug ignites at 4.65mm before TDC, combustion duration is 5.85ms and approximately, the proportion of combustion duration in the whole cycle is 14.4% [18].

In order to increase the LICELGIS short residence time around the TDC, on one hand, improving the quality of fuels so as to increase combustion velocity is a practical method. For example, Nicholas Joseph at the National Sandia Laboratory applies many different fuels to observe characteristics of fuel combustion and the change of heat efficiency [11]. The results indicate that gaseous fuel under normal temperature is very suitable for free piston engine operation. On the other hand, it is feasible to develop relevant combustion optimization control strategy to increase piston residence time around the TDC.

Of the control objectives, TDC position is that of highest importance[6]. Fig. 3 shows the effect of TDC deviation on the compression ratio in the current integrated system. It can be seen that even small deviations in TDC position result in large variations in compression ratio. Once the compression ratio varies much, combustion conditions will be affected evidently, which may incur knock and stalling. Thus, stable TDC position is the premise for ensuring the system stable operation.

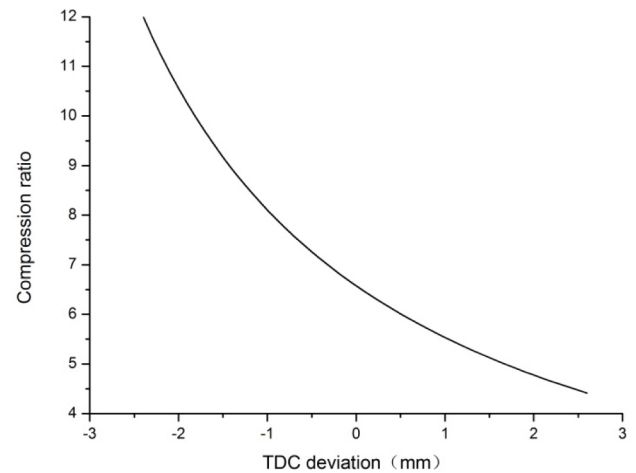


Figure 3. Effect of varying TDC position on engine compression ratio

In consideration of the relationship between the velocity of midpoint and the resulting TDC position that is close to linear correlation [7], this paper proposes a combustion optimization control strategy which varies the electromagnetic resistance force based on the velocity of midpoint (the half-stroke point in the compression stroke), and the block diagram for control logics is shown as Fig. 4.

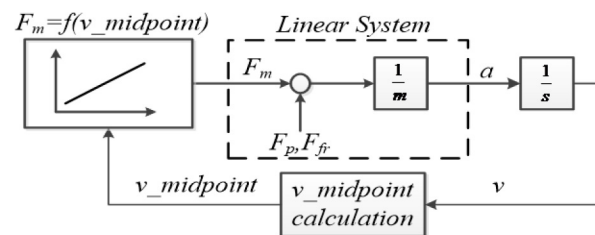


Figure 4. The block diagram for control logics

Fig. 4 illustrates that for the TDC control circuit. This includes the piston velocity of midpoint and the electromagnetic resistance force. For the purpose of combustion optimization, electromagnetic resistance force is calculated and varied based on the velocity of midpoint, ensuring that the TDC is stable in different cycles. Thus, the crucial part is the relationship between the electromagnetic resistance force and the velocity of midpoint.

For the better evaluation of the control effect, this paper defines cyclical fluctuation rate, which refers to peak fluctuation coefficient of cylinder pressure. It is shown in Eqs. (1) and (2).

$$\delta_{mc} = \frac{\sigma}{\bar{T}} \times 100\% \quad (1)$$

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (T_i - \bar{T})^2} \quad (2)$$

Where, δ_{TDC} is cyclical fluctuation rate, σ is standard deviation of TDC position, n is period number, T_i is TDC in each cycle, $\bar{T}$ is set-TDC.