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Piston motion control of a free-piston engine generator: A new approach using cascade control

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HIGHLIGHTS

- The global control structure for a FPEG prototype is presented.
- A Cascade control strategy is proposed for the piston stable operation level.
- TDC of the previous stroke and velocity of the current stroke are taken for feedback.
- Controller performance is improved on control delay, peak error and settling time.

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ABSTRACT

The free-piston engine generator (FPEG) is a linear energy conversion system, which is known to have greater thermal efficiency than an equivalent and more conventional reciprocating engine. The piston motion of a FPEG is not restricted by a crankshaft-connection rod mechanism, it must be controlled to overcome challenges in the starting process, risk of misfire, and unstable operation. In this paper, the global control structure for a FPEG prototype is presented. A Cascade control strategy is proposed for the piston stable operation level, and PID controllers are used for both of the outer loop and inner loop. The measured top dead centre of the previous stroke and the piston velocity during the current stroke are taken for controller feedback, and the injected fuel mass is used as the control variable. The proposed cascade control implemented in the FPEG is shown to have good performance, the piston returns to a stable state in 0.5 s. Compared with a single loop control strategy, the performance of cascade control is improved in terms of the control delay, peak error and settling time.

1. Introduction

1.1. Background

The free-piston engine (FPE) is a linear energy conversion system, and the term ‘free-piston’ is widely used to distinguish its linear characteristics from those of a conventional reciprocating engine [1–3]. Without the limitation of the crankshaft mechanism, as known for the conventional engines, the piston is free to oscillate between its dead centres. The piston assembly is the only significant moving component for the FPEs, and its movement is determined by the gas and load forces acting upon it [4]. During the operation of FPEs, combustion takes place in the internal combustion chamber, and the high pressure exhaust gas pushes the piston assembly backwards. The chemical energy from the air fuel mixture is then converted to the mechanical energy of the moving piston assembly. Due to this linear characteristic, a FPE requires a linear load to convert this mechanical energy for the usage of the target application [1]. As the load is coupled directly to the piston assembly, the technical requirements for the free-piston engine loads are high, which are summarised as:

(1) The load must provide satisfactory energy conversion efficiency to make the overall system efficient.
(2) The load may be subjected to high velocity.
(3) The load may be subjected to high force from the cylinder gas.

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(4) The load device may be subjected to heat transfer from the engine cylinders.
(5) The size, moving mass and load force profile are feasible to be coupled with the designed FPEs.

Reported load devices for the FPEs include air compressors, electric generators and hydraulic pumps [5–7]. In this research, the FPE is connected with a linear electric generator (free-piston engine generator, FPEG) and is investigated with the objective to utilise the configuration within a hybrid-electric automotive vehicle power system. Since the FPEG was first proposed, it has attracted interest from all over the world. Different research methods and prototype designs have been reported using the FPEG concept [8–11]. However, to date, none of these have been commercially realised in part due to the challenges of system control.

In conventional engines, the crankshaft mechanism provides piston motion control, defining both the outer positions of the piston motion (the dead centres) and the piston motion profile. Due to the high inertia of the crankshaft system, the piston motion cannot be influenced in the timeframe of one cycle [12]. In the free-piston engine, the piston motion is determined by the instantaneous sum of the forces acting on the mover, and the piston motion is therefore influenced by the progress of the combustion process [13]. Moreover, the piston motion profile may be different for different operating conditions. Variations between consecutive cycles due to cycle-to-cycle variations in the in-cylinder processes are also possible [7,14,15]. Overcome controlling of the FPEG engine is a challenging task.

1.2. Literature review

A model-based controller was developed for the European Commission-funded Free Piston Energy Converter (FPEC) project. The controller was implemented in a real-time control prototype system and tested on a FPEG simulation model [16]. The controller consisted of an observer, and output power controller, an ignition time controller, and a servo controller that was used to control the velocity of the moving mass. The outer control loop was used to meet the output power requirement, and the inner loop was used to set the optimal ignition timing for ignition. The electromagnetic force and the input fuel mass were selected as control inputs, and output power and ignition timing were the control outputs [16].

Johansen et al. proposed a control structure for the FPE [17–19], which was a multi-level control system. The upper level was the supervisory control and optimisation, aimed to perform logic control and adapt the operating characteristic. The next level was the piston motion control, where commands were given to the timing subsystems to control the piston motion. At the lowest level there was timing control, *i.e.* fuel injection timing and valve timing for each cycle. A hierarchical multi-rate electronic control system was developed for an experimental engine, focusing on piston motion parameter estimation, valve and injector timing, and a piston motion control system. The present results showed that the current state of the art electronic control technology provided the required processing capacity and resolution to implement the required control system functionality of modern high-speed FPEs. A major challenge was to optimise the engine and control system to get sufficiently high reliability, fault tolerance and robustness [18,19].

Mikalsen and Roskilly discussed the basic features of a single piston FPEG under development at Newcastle University and investigated engine control issues using a full-cycle simulation model [13,20,21]. The control structure was similar to that presented by Johansen. The response of the engine to rapid load changes was investigated using decentralised PID, PDF and disturbance feed forward. It was identified that PDF feedback control was more suitable for the FPEG than a conventional PID controller. The engine was found to be sensitive to immediate electric load changes, whilst the effect of cycle-to-cycle combustion variations was reported as not critical. It was concluded that the control of the FPEG was a challenge, but the proposed control strategy was technically feasible [21].

To reduce the time delay in the control loop, a predictive control system was further proposed by Mikalsen and Roskilly. The piston TDC was predicted from the piston velocity in the compression stroke, rather than measured from the previous operation cycle to improve the dynamic performance of the controller. Significant improvement was observed using the proposed control method compared with a conventional PI feedback controller, including a faster response and lower error [20]. The proposed control scheme was put forward to make use of a more advanced fuzzy control system which could take the nonlinear and multi-variable characteristic of the control problem into consideration [20].

1.3. Summary

As the piston motion of FPEG is not restricted by a crankshaft – connection rod mechanism, the piston is free to move between its TDC and BDC, and the movement is only controlled by the gas and load forces acting upon it. This induces problems such as difficulties in the starting process, misfire, unstable operation and complex control strategy [2,4,22]. For different configurations, the control objectives vary and these are summarised in Table 1. To meet these challenges, a robust control system is required for the FPEG. Control of piston TDC position is crucial for stable operation. It should be controlled within tight limits to ensure a sufficient compression ratio for ignition and efficient combustion, but must also to avoid mechanical contact between the piston and cylinder head.

As the piston is free to move between its instantaneous TDC and BDC positions, and this movement is only controlled by the gas and load forces acting upon it. This creates challenges in the starting process, risk of misfire, and unstable operation [23,24]. In this paper, control challenges for the FPEG will be analysed and the global control structure will be presented. As the control of piston dead centres are crucial for the FPEG compared with conventional reciprocating engines, the piston motion control is selected as the main objective in this research. A Cascade control method is proposed to be implemented, and the controller performance will be simulated and discussed.

Table 1
Control objectives for different configurations.

FPEG configuration	Control objectives	
	Similarity	Difference
Single piston	o System demand for energy o Reach target TDC • Ensure compression ratio • Avoid mechanical contact o Timing control • Valve timing • Ignition timing • Injection timing	o Control of rebound device o Engine operating frequency (speed)
Opposed piston		o Synchronization control o Rebound device control o Engine operating frequency (speed)
Dual piston		o Accurate BDC control (TDC for the other side)