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Disturbance analysis of a free-piston engine generator using a validated fast-response numerical model

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HIGHLIGHTS

- Different types of system disturbance with specific occurring times were identified.
- The influence of each disturbance on the FPE system was characterised.
- Technically feasible control variables were identified.
- Control variable coupled with a system controller design was presented.

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ABSTRACT

In this paper, a fast-response numerical model was used to investigate potential disturbances to a free-piston engine generator (FPEG), i.e. engine cycle-to-cycle variations, misfire and immediate electric load change. During the engine operation, there could be one disturbance taking place or several disturbances take place simultaneously. By identifying different types of system disturbance with specific occurring times, the influence on the system was characterised. It was found that a step change of electric load would induce a corresponding top dead centre (TDC) step change. Low variations on piston TDC are observed when cycle-to-cycle variations take place. When unsuccessful ignition occurs, the engine will stop after one oscillation cycle. Reducing the electric load after misfire would cause more oscillation cycles and require a restart of the engine. Technically feasible control variables were identified and coupled with a PI feedback controller design to minimise the impact of each kind of disturbance, a design which could be used in future FPE control system designs. The controller performance was seen to be satisfactory for the electric load step change, and the piston TDC was controlled to back to the set point in 0.5 s.

1. Introduction

The free-piston engine (FPE) is a linear engine conversion device that compromises a linear combustion engine coupled with a load system [1–4]. The reported effective efficiency of FPE is up to 46% at a power level of 23 kW with promising emission results [5]. Due to the lack of crankshaft mechanism, the complexity of the engine is significantly reduced, and the piston assembly is the only significant moving part. This gives a number of advantages upon conventional engines such us reduced frictional losses, higher power-volume ratio, and multi fuel/combustion mode possibility [6–8]. Typical modern applications of the FPE concept have been proposed with electric load or hydraulic load, and are now being investigated worldwide [9–17]. However, the piston movement for FPE is not limited by the crankshaft-connection rod system, it moves freely between its dead centres. Hence, the piston dynamics is prone to be influenced by disturbances from both internal and external sources [18], which could induce to unstable operation, even engine misfire. As a result, the identification and control of disturbance to FPE are of significant importance to the further development of control system, while there has not been detailed research report this specific area.

Mikalson and Roskilly investigated the FPE control variables and disturbances using a full-cycle simulation model [19,20]. The

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Nomenclature

A	piston surface area (m^2)
C	controller transfer function
C_1	constant
C_2	constant
C_v	heat capacity at constant volume (J/m^3 K)
CR	set geometric compression ratio
c	damping coefficient
c_c	critical damping coefficient
E	control error
F	excitation force (N)
G	transfer function of the FPEG system
H_u	low heating value of the fuel with the combustion efficiency (J/kg);
H_n	engine speed (Hz)
K_p	proportional gain
K_i	integral gain
K_d	derivative gain
k_v	coefficient of the load force (N/m s^{-1})
k	spring constant
L_c	clearance length (m)
L_s	length of half stroke (m)
m	moving mass of the mover with the pistons (kg)
m_f	injected fuel amount (kg)
p_0	ambient pressure (Pa)
R	reference input for the control loop
U	control variable
V_0	cylinder volume at the beginning of the compression stroke (m^3)
x	mover displacement (m)
x_{TDC}	target top dead centre (m)
Y	system output
γ	heat capacity ratio
ω	angular natural frequency (rad/s)
η_c	random combustion efficiency

load force from the electric machine was identified as a disturbance to the FPE, and carried a high influence on both the engine speed and dead centre positions [19]. Variations in the injected fuel mass were found to affect the indicated mean effective pressure and peak in-cylinder pressure, and the variations were observed to be higher for the FPE than for the conventional engine. This was reported to be due to the variations in the combustion energy from cycle 1 which would influence the compression ratio for the cycles 2, 3, 4, etc. The combination of variations in both compression ratio and injected fuel mass would be expected to lead significantly higher peak cylinder pressure variations in the FPEG technologies [20].

A high-speed free-piston diesel engine was developed by Johansen et al. aimed at marine applications as an alternative to both gas turbines and traditional diesel engines [21–23]. Timing inaccuracies were reported to lead to disturbances on the piston force balance, furthermore the piston motion would vary from cycle-to-cycle. A slightly late opening of the exhaust valve would induce a higher pressure in the combustion chamber and result in an undesired increase in the stroke length [21]. Cycle-to-cycle variations would also induce to pressure disturbance in the intake and exhaust manifold. The variability in the stroke was demonstrated to be controlled within 2 mm out of a stroke of about 200 mm [21].

The free-piston engine generator (FPEG) prototype developed by Beijing Institute of Technology was reported to misfire every one to two cycles, with severe cycle-to-cycle variations [24]. The possible sources of the variations and unstable operation were considered to be (1) the air/fuel mixture formation might vary from cycle to cycle in cold engine conditions, (2) the spark and initial flame propagation could have cyclic variations as normal SI engines, (3) the unstable combustion could lead to an undesired piston profile and then influence the heat release process in the next cycle [24].

The FPEG prototype developed by Toyota Central R&D Labs Inc. was a single piston type with a gas rebound device [25,26]. A power generation experiment was carried out, and results demonstrated that the prototype operated stably for a long period of time [26]. Pre-ignition was found to occur during the test, and the cylinder pressure in the combustion chamber increased earlier than the spark timing. As a result, the oscillation frequency was disturbed, and temporary unstable operation was observed. With the help of the designed feedback control system, the system was reported to recover from the unstable state in less than 1 s [26].

This paper aims to analyse the possible disturbances to the FPEG prototype using a fast-response numerical model, and reject the disturbances with feasible controller. By identifying different types of system disturbance with specific occurring times, the influence on the system can be characterised. Technically feasible control variables were identified and coupled with a system controller design to minimise the impact of each kind of disturbance, a design which can be used in future FPE control system designs.

2. FPEG System simulation

2.1. FPEG configuration

The designed spark-ignited FPEG prototype is illustrated in Fig. 1. The system is compromised two opposing internal combustion engine, and a linear electric generator is placed in the middle of two cylinders. The engine is operated using a two-stroke gas exchange process, and the power stroke is controlled to take place alternately in each cylinder to drive the compression stroke in the opposite side. As a result, the mover reciprocates between its dead centres, and the generator converts this mechanical energy into electricity, which will be stored by an external load. More information about the prototype development approach can be found in elsewhere [27].

2.2. Fast-response numerical model description

The FPEG is commonly modelled using several differential equations to characterise the piston dynamics and simulate engine performance [7,14]. All the design parameters are coupled with each other in these models, making them overly complex to be used in the real-time control system as the differential equations are solved iteratively. As a result, assumptions are made to simplify the system, i.e. (a) energy consumed by the heat transfer to the cylinder walls and gas leakage through the piston rings are ignored; (b) the running cycle of FPEG is two adiabatic compression/expansion processes connected with a constant volume heat release process. The FPEG system is finally described by a forced mass-spring vibration system under external excitation, which is illustrated in Fig. 2. Details for the simplification and derivation can be found in our previous publications [28].

The simplified dynamic equation is expressed as:

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{1}$$

$$c = k_v \tag{2}$$