Development of a snark ignition free-piston engine

Thesis by
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In Partial Fulfilment of the Requirements
for the Degree of
Doctor of Philosophy

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June 2015
Abstract

A dual-piston type two-stroke spark-ignition free-piston engine generator prototype has been developed. A comprehensive review on recent published researches and patent documents from academia and industrial organisations on free-piston engine generator, especially on the applications for series hybrid electric vehicles, was conducted. Relevant parameters affecting the operating performance and a number of challenges had been identified as the common denominator for this technology. Modelling and simulations using one-dimensional tools were conducted in parallel with the development activities. Three main simulation models for the crankshaft engines were developed, validated and optimised before converted into the free-piston engine model. This was done by using imposed-piston motion sub-model. The two-stroke free-piston engine model had undergone parametric study for valve timing optimisation. This model was validated by using motoring experimental results using the developed free-piston engine generator prototype. From the experimental results, the free-piston engine generator motoring performance was able to meet the targeted cyclic speed and compression pressure for starting. However, the free-piston engine generator operating speed was limited to 5Hz and below due to valve delay inherent in the pneumatic actuators. The motoring results were used to validate the free-piston engine model which showed a good agreement at various starting speeds. Finally, performance and parametric investigations were conducted using the final validated and refined free-piston engine model. From the simulation, it was found that the free-piston engine had similar response to air-fuel ratio and ignition position variations compare to crankshaft engine with the free-piston engine performance was slightly reduced. Further, the reduced frictional losses contributed little to its performance gain. However, the high influence of piston motion around TDC on the engine performance, observed in free-piston engine, could be manipulated to increase its performance significantly.
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Nomenclature

Abbreviations

1D one-dimensional
ABDC after bottom dead centre
ATDC after top dead centre
BBDC before bottom dead centre
BDC bottom dead centre
BTDC before top dead centre
CSE crankshaft engine
EGR exhaust gas recirculation
ETI Energy Technologies Institute
EVC exhaust valve close
EVO exhaust valve open
FPE free-piston engine
FPEG free-piston engine generator
HCCI homogeneous charge compression ignition
IPM imposed piston motion
IVC intake valve close
IVO intake valve open
MBT maximum brake torque
$PV$ pressure-volume/indicator diagram
TDC top dead centre

Symbols

\(a\) crank radius (half the stroke) [m]
\(A_p\) piston area [m]
\(A_{cf}\) constant portion of the Chen-Flynn friction correlation [-]
AFR air-fuel ratio [-]
\(amep\) accessory mean effective pressure [bar]
\(bme\) brake mean effective pressure [bar]
\(bte\) brake thermal efficiency [%]
\(B\) cylinder bore [m]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{cf}$</td>
<td>term which varies linearly with peak cylinder pressure in the Chen-Flynn friction correlation [-]</td>
</tr>
<tr>
<td>$c$</td>
<td>clearance distance [m]</td>
</tr>
<tr>
<td>$C_{enht}$</td>
<td>user input multiplier [-]</td>
</tr>
<tr>
<td>$C_{cf}$</td>
<td>term which varies linearly with the piston speed in the Chen-Flynn friction correlation [-]</td>
</tr>
<tr>
<td>CA</td>
<td>crank angle [deg]</td>
</tr>
<tr>
<td>CA50</td>
<td>50% mass burnt point location [deg]</td>
</tr>
<tr>
<td>$(CR)G$</td>
<td>geometric compression ratio [-]</td>
</tr>
<tr>
<td>Exh_Anchor</td>
<td>engine crank angle at maximum exhaust valve lift [deg]</td>
</tr>
<tr>
<td>Exh_Dur</td>
<td>exhaust valve open duration [deg]</td>
</tr>
<tr>
<td>$f$</td>
<td>engine frequency [Hz]</td>
</tr>
<tr>
<td>$F_{cog}$</td>
<td>cogging force [N]</td>
</tr>
<tr>
<td>$F_f$</td>
<td>frictional force [N]</td>
</tr>
<tr>
<td>$F_{mot}$</td>
<td>motoring force [N]</td>
</tr>
<tr>
<td>$F_{p1}$</td>
<td>force from pressure in cylinder 1 [N]</td>
</tr>
<tr>
<td>$F_{p2}$</td>
<td>force from pressure in cylinder 2 [N]</td>
</tr>
<tr>
<td>$(F_p)_c$</td>
<td>combustion force [N]</td>
</tr>
<tr>
<td>FAR</td>
<td>fuel-air ratio [-]</td>
</tr>
<tr>
<td>$h_g$</td>
<td>Woschni heat transfer coefficient [W m$^{-2}$ K$^{-1}$]</td>
</tr>
<tr>
<td>$H_p$</td>
<td>enthalpy of the products [J]</td>
</tr>
<tr>
<td>$H_R$</td>
<td>enthalpy of the reactants [J]</td>
</tr>
<tr>
<td>imep</td>
<td>indicated mean effective pressure [kPa, bar]</td>
</tr>
<tr>
<td>Int_Anchor</td>
<td>engine crank angle at maximum intake valve lift [deg]</td>
</tr>
<tr>
<td>Int_Dur</td>
<td>intake valve open duration [deg]</td>
</tr>
<tr>
<td>$I_{phase}$</td>
<td>phase current [A]</td>
</tr>
<tr>
<td>$I_{pw}$</td>
<td>injector pulse width [s]</td>
</tr>
<tr>
<td>$K_f-\Delta$</td>
<td>motor constant for delta winding [N A$^{-1}$]</td>
</tr>
<tr>
<td>$K_f-Y$</td>
<td>motor constant for wye winding [N A$^{-1}$]</td>
</tr>
<tr>
<td>$K_{AWI}$</td>
<td>internally calculated parameter to allow $\theta_{dur}$ covering the range of 10-90% [-]</td>
</tr>
<tr>
<td>$l$</td>
<td>connecting rod length [m]</td>
</tr>
<tr>
<td>$L$</td>
<td>ultimate stroke [m]</td>
</tr>
<tr>
<td>$m$</td>
<td>moving mass [kg]</td>
</tr>
</tbody>
</table>
\( m_f \) mass of fuel [kg]
\( \dot{m}_f \) mass flow of fuel [kg s\(^{-1}\)]
\( mep \) mean effective pressure [kPa, bar]
\( MFB \) mass fraction burned [%]
\( N \) engine speed [rpm]
\( N_{rpm} \) cycle-average engine speed [rpm]
\( p_1 \) pressure in cylinder 1 [Pa, bar]
\( p_2 \) pressure in cylinder 2 [Pa, bar]
\( pmep \) pumping mean effective pressure [bar]
\( P \) pressure [Pa, bar]
\( P_b \) brake power [kW]
\( P_i \) indicated power output produced by the engine [W]
\( P_{max} \) maximum cylinder pressure [bar]
\( P_o \) standard air pressure (101.325 kPa)
\( P_{off} \) wrist pin offset [m]
\( P_{tf} \) total friction power [W]
\( rfmep \) rubbing mean effective pressure [bar]
the term which varies quadratically with the piston speed in the
\( Q_{cf} \) Chen-Flynn friction correlation [-]
\( Q_{HV} \) heating value of fuel [J/kg].
\( \dot{Q}_{in} \) rate of heat input [W]
\( R_{air} \) ratio of universal gas constant over molar mass of air
\( R_f \) fuel injector delivery rate [kg/s]
\( s \) piston position in reference to its TDC position, with positive
being away from its TDC position [m].
\( S \) cylinder stroke [m]
\( tfmep \) total friction mean effective pressure [bar]
\( T \) temperature [K]
\( T_A \) ambient temperature [K]
\( T_o \) standard air temperature (288.15 K)
\( v_c \) characteristic velocity [m s\(^{-1}\)]
\( V_C \) clearance volume [m\(^3\)]
\( V_S \) swept volume [m\(^3\)]
\( \dot{V} \) volumetric flow of air [m\(^3\)/s]
$W_{\text{exp}}$ user-entered exponent in Wiebe function

$x$ piston linear position [m]

$x_1(t)$ cylinder 1 piston linear position at time $t$ [m]

$x_2(t)$ cylinder 2 piston linear position at time $t$ [m]

$x_{\text{icv1}}$ intake valve fully close position for cylinder 1 [m]

$x_{\text{icv2}}$ intake valve fully close position for cylinder 2 [m]

$\ddot{x}$ piston/translator acceleration [m/s$^2$]

**Greek Letters**

$\gamma_c$ compression polytropic index [-]

$\eta_c$ combustion efficiency [-]

$\eta_v$ volumetric efficiency [-]

$\theta$ crank angle from TDC [degree]

$\theta_{\text{dur}}$ user-entered combustion duration (10%-90%).

$\theta_{\text{EVC}}$ exhaust valve closing angle [$^\circ$ ATDC]

$\theta_{\text{EVO}}$ exhaust valve opening angle [$^\circ$ ATDC]

$\theta_{\text{ivc}}$ intake valve closing angle [$^\circ$]

$\theta_{\text{ivo}}$ intake valve opening angle [$^\circ$]

$\rho$ air density [kg/m$^3$]

$\tau$ torque [N.m]
Chapter 1. Introduction

1.1 Background

The recent report by Energy Technologies Institute (ETI) has highlighted that light vehicles contribute around 16% of UK CO₂ emissions [1]. It was proposed that a drastic approach for reducing such emissions would be to adopt electric vehicles and phasing out internal combustion engines. The less risky route is by using a combination of different fuel types such as bio-fuel and ethanol as well as increasing hybrid vehicle use on the road.

In recent years, free-piston engine generator has increasingly been developed by a number of groups worldwide [2-4]. One of the vital motivations of these research efforts is arguably the potential of free-piston engine generator to provide a compact and efficient power generator for hybrid electric vehicles. Free-piston engine generator inherit variable compression ratio capability with fewer modifications compared to conventional crankshaft engine, hence is suitable for multi-fuel operation [5]. Further, its high efficiency and rapid transient response makes it suitable for hybrid electric vehicle application [6]. Due to these reasons, free-piston engine generator is a suitable technology for substituting conventional crankshaft engine in light vehicles.

In this research a free-piston engine generator specifically suited for series hybrid vehicle application was developed with the aim of achieving high thermal efficiency and low emissions.

1.2 The free-piston engine

A free-piston engine is an engine which operates without the crankshaft or any other rotating mechanisms. The engine operates directly via dynamic balancing of the longitudinal forces acting on a single moving translator which can be coupled with an air compressor, a hydraulic pump or a linear generator.
The free-piston concept has a long history which conceptually begins with the Otto-Langen atmospheric free-piston engine in 1867 [7, 8]. This early prototype of a free-piston engine was meant for rotary applications which were made possible by the use of rack and pinion mechanisms. Among the fundamental problem with this configuration was the difficulty to sustain the cyclic operation. Later, this issue was solved by integrating a crank-slider mechanism for cyclic operation and a flywheel as energy storage device to sustain the cyclic operation. This configuration produced the basic form of crankshaft engine for internal combustion (IC) applications.

With increasing concern on global warming and sustainability, crankshaft IC engine technology has been under intense scrutiny due to its relatively low efficiency and poor exhaust gas emissions. The modern IC engine efficiency for hybrid vehicle application has been reported as 30-37% for SI and 40% for CI [9]. Therefore, an alternative prime mover is seek, especially one that can give higher efficiency and low emission for the application of hybrid electric vehicle; i.e. the free-piston engine generator.

The appeal of the free-piston engine lies in its promising advantages, such as high power to weight ratio, multi-fuel capability, and low manufacturing cost and low maintenance due to less components plus its mechanical simplicity [5, 10-12]. This technology when coupled with a linear generator and energy storage system can fulfil the essential requirements of the electric vehicle or auxiliary power unit [13].

Further, the absence of the crankshaft and flywheels may result in higher thermal efficiency and capable of operating with varying compression ratios. It has been reported that the indicated thermal efficiency could be is as high as 56% in rapid compression expansion machine experiments [14].

Previous successful operation of a free-piston engine coupled with a hydraulic pump and air compressors have been reported [5]. However, the free-piston engine coupled with a linear generator is still hindered with problems such as misfire, unstable operation, piston motion control challenges and complexity in the control system design [15-18]. Although the published work on free-piston engine generators is extensive, very few report successfully running prototypes. These are the main motivations for embarking on this research work.

1.3 Aims and objectives

The aim of the research is to develop and test a dual-piston type free-piston engine generator prototype. In order to achieve this aim, the following specific objectives of the research were set:
1. To develop a one-dimensional model of a two-stroke spark ignition free-piston engine generator.

2. To optimise operational parameters of the simulation model.

3. To build a dual-piston type free-piston engine generator prototype and its experimental test rig.

4. To evaluate free-piston engine generator prototype motoring performance during starting.

5. To conduct parametric and performance investigation of the free-piston engine generator through validated simulation model.

1.4 Methodology and thesis outline

The content of the thesis was organised according to the methodology of the research and comprised of the following chapters:

Chapter 2 introduces the free-piston engine generator fundamental principles and then presents literature review on the parameters and challenges in the area as reported by major research groups worldwide. In addition, patented concepts and technologies by key automotive companies were described. These patents review illustrate key design aspect and technological mitigation on some of the challenges highlighted by free-piston engine researchers. From the review, a number of challenges have been identified as the common denominator for this technology amongst academic and industrial researchers.

Chapter 3 describes the development of four main simulation models using one-dimensional simulation tools. All models were a single cylinder engines. Both four-stroke crankshaft engine models had been validated while the two-stroke crankshaft engine model was optimised for performance through parametric investigations. The final optimised two-stroke crankshaft engine model was converted into the two-stroke free-piston engine model by using the imposed-piston motion (IPM) sub-model. The free-piston engine model was optimised for maximum performance and the findings are discussed.

Chapter 4 presents the development of the prototype and test rig of the free-piston engine generator. The design and components selection are outlined and relevant procedures and data acquisition sequences established prior to experimental investigation are described.

Chapter 5 presents experimental investigations conducted on the prototype for motoring performance during starting, pneumatic valve actuators and in-cylinder
pressure assessments. The motoring results were used for validating the free-piston engine simulation model developed in Chapter 3.

Chapter 6 presents the dynamic modelling and simulations in MATLAB Simulink to improve the piston motion profiles in the imposed piston motion IPM sub-model. The final dual-piston type free-piston engine generator model was developed from the single cylinder free-piston engine model in Chapter 3. Parametric study and performance investigations were conducted on the final models of the free-piston engine generator and crankshaft engine.

Finally, Chapter 7 summarised the significant findings and research contributions together with proposed improvements and future research.

1.5 Contribution to existing research

A substantial number of publications on free-piston engine generator technology revolve around the numerical modelling and simulations. A small number of running prototypes have been reported and no significant effort towards commercialisation has occurred.

This work contributes to existing research by developing running prototype of a free-piston engine generator. The engine is a two-stroke dual-piston type with poppet valves to control the gas exchange process which has the potential of major operational benefits.

The simulation tool used for this research has been used for a direct comparison between crankshafts versus free-piston engine models. The free-piston model results have been validated against an actual running prototype during its starting operation over a wide range of engine speeds. Further, the simulation has shown the positive impact of piston motion around TDC on the free-piston engine performance.
Chapter 2. Free-piston engine development and challenges

This chapter is dedicated to the literature study of recent designs and concepts for free-piston engine generators amongst industrial organisations and key areas focused by researchers. By studying recent patent documents and publications, an insight into research effort on free-piston engines is obtained. Further, these publications provide a useful indication as to what these developers see as the main technical challenges for this technology.

Several numerical investigations are studied and reported efficiency and performance are highlighted. Further, parameters affecting performance and operation of such engine are discussed. This review aims to correlate various crucial reports on free-piston engine generator in order to identify gaps in the area and to assist prototype development.

Parts of the work presented in this chapter were presented by Hanipah, et al. [19].

2.1 Free-piston engine generator fundamental principles

A free-piston engine works on the principle of dynamic forces which produces linear reciprocation motion. Such an engine is said to be dynamically constrained as opposed to a kinematically constrained crank-slider engine [11]. Dynamically constrained means the piston stop positions (TDC and BDC) are not constant and its motion profile is not governed by any mechanical component as in the crankshaft engine.

In the crankshaft engine, the piston stop positions are consistent and can be represented by a kinematic relationship between crankshaft radius, connecting rod length and crank angle. Further, due to the absence of the crank-slider mechanism, the fundamental principle of operation of this engine requires a new approach.

The basic configuration of a free-piston engine is shown in Figure 2.1, which is a single piston configuration. Primarily, for cyclic operation to be possible, a free-piston engine requires a bounce device to ensure the piston returns to initial top-dead-centre position for the next engine cycle.
This cyclic operation can be achieved in the following forms:

- second combustion chamber [17, 20]
- compressed air storage [21]
- hydraulic fluid storage [22]

Since neither a flywheel nor a crankshaft is available to provide inertial energy for continuous operation. Farmer [23] described a ‘cushion’ cylinder which may be utilised as an energy storage device. In conventional crankshaft engines, the angular momentum of the crankshaft mechanism and the flywheel aides starting. Different techniques have to be devised for starting a free-piston engine and generally, for a free-piston engine, the starting mechanism can be provided using:

- wound springs [23]
- compressed air [23]
- hydraulic fluid [22]
- linear motor [17]

In terms of the engine cycle, a free-piston engine naturally operates as a two-stroke cycle although complex four-stroke cycle versions are possible [24, 25]. The two-stroke version is simpler and thus more widely adopted since combustion occurs at every stroke to provide expansion energy required for reciprocation thereby increasing its power density.

2.1.1 Configurations

Generally, free-piston engine design can be categorised into three main configurations as shown in Figure 2.2 reported by Aichlmayr [11] and Mikalsen and Roskilly [5].
2.1.1.1 **Single Piston**

Single piston type free-piston engine is the basic design which is comprised of single piston, single combustion chamber, a load and a rebound device. This design is mainly employed for air compressor and hydraulic pump applications [5]. Thus, the load and rebound device in such application can be integrated. The main advantage of this design is its simplicity and easier to control but the design is not mechanically balanced [11].

2.1.1.2 **Opposed Piston**

An opposed piston type free-piston engine comprises of two opposing single piston design linked together with a synchronising linkage. A common combustion chamber is placed in the middle while each individual piston can have its own load and rebound device. It has been reported in compressor [23], gasifier [26] and hydraulic applications [27]. The main advantage of this design is; it is inherently balance when symmetrically designed, with equal masses of pistons and synchronising linkage added [5, 11]. However, the overall design is more complex and bulky than single or dual piston type. Further, the synchroniser linkage pose additional frictional losses and mechanically constrained the piston, hence it is not exactly 'free-piston' design.