Development of a spark ignition free-piston engine

Thesis by

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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]
bmep	brake mean effective pressure [bar]
bte	brake thermal efficiency [%]
B	cylinder bore [m]

B_{cf}	term which varies linearly with peak cylinder pressure in the Chen-Flynn friction correlation [-]
c	clearance distance [m]
C_{enht}	user input multiplier [-]
C_{cf}	term which varies linearly with the piston speed in the Chen-Flynn friction correlation [-]
CA	crank angle [deg]
$CA50$	50% mass burnt point location [deg]
$(CR)_G$	geometric compression ratio [-]
Exh_Anchor	engine crank angle at maximum exhaust valve lift [deg]
Exh_Dur	exhaust valve open duration [deg]
f	engine frequency [Hz]
F_{cog}	cogging force [N]
F_f	frictional force [N]
F_{mot}	motoring force [N]
F_{p_1}	force from pressure in cylinder 1 [N]
F_{p_2}	force from pressure in cylinder 2 [N]
$(F_p)_c$	combustion force [N]
FAR	fuel-air ratio [-]
h_g	Woschni heat transfer coefficient [W m^{-2} K^{-1}]
H_P	enthalpy of the products [J]
H_R	enthalpy of the reactants [J]
$imep$	indicated mean effective pressure [kPa, bar]
Int_Anchor	engine crank angle at maximum intake valve lift [deg]
Int_Dur	intake valve open duration [deg]
I_{phase}	phase current [A]
I_{pw}	injector pulse width [s]
$K_{f-\Delta}$	motor constant for delta winding [N A^{-1}]
K_{f-Y}	motor constant for wye winding [N A^{-1}]
K_{AWI}	internally calculated parameter to allow θ_{dur} covering the range of 10-90% [-].
l	connecting rod length [m]
L	ultimate stroke [m]
m	moving mass [kg]

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]
Q_{cf}	term which varies quadratically with the piston speed in the 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_{exp}	user-entered exponent in Wiebe function
x	piston linear position [m]
$x_1(t)$	cylinder 1 piston linear position at time t [m]
$x_1(t)$	cylinder 2 piston linear position at time t [m]
x_{ivc1}	intake valve fully close position for cylinder 1[m]
x_{ivc2}	intake valve fully close position for cylinder 2[m]
$\ddot{x}$	piston/translator acceleration [ms^{-2}]

Greek Letters

γ_c	compression polytropic index [-]
η_c	combustion efficiency [-]
η_v	volumetric efficiency [-]
θ	crank angle from TDC [degree]
θ_{dur}	user-entered combustion duration (10%-90%).
θ_{EVC}	exhaust valve closing angle[° ATDC]
θ_{EVO}	exhaust valve opening angle[° ATDC]
θ_{IVC}	intake valve closing angle [°]
θ_{IVO}	intake valve opening angle [°]
ρ	air density [kg/m^3]
τ	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 CO_2 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.

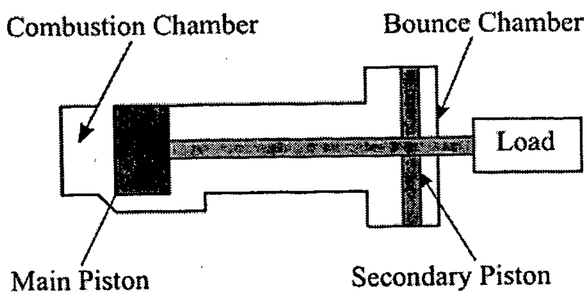

Figure 2.1: Basic configuration of a single piston free-piston engine [11]

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].

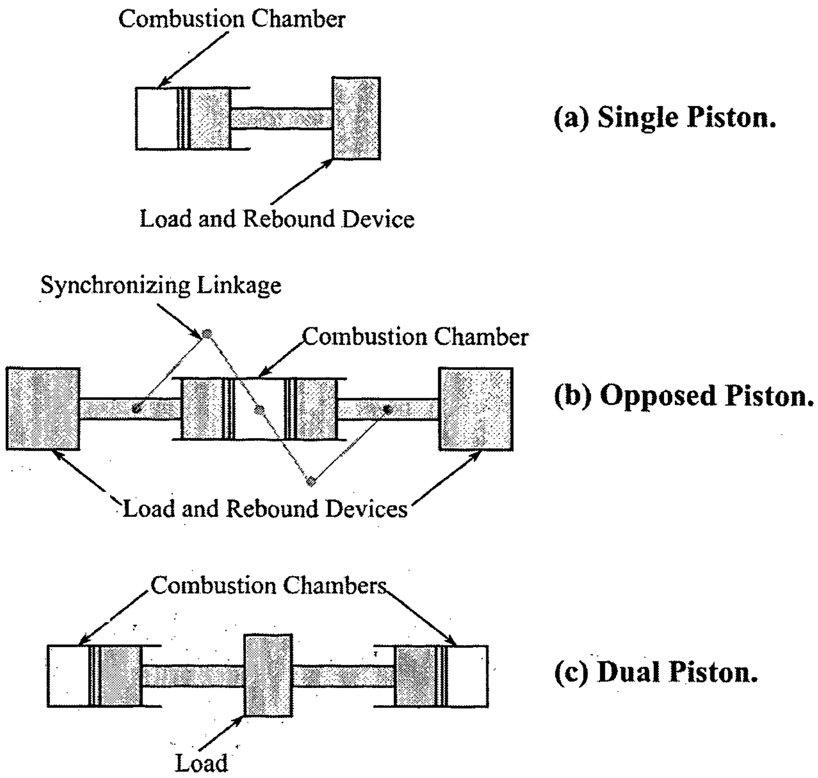

Figure 2.2: Three main configurations for free-piston engine [11].

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.

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Chapter 3. One-dimensional modelling and simulation

Towards the development of a free-piston engine generator, the need for a simulation model is inevitable. The model should be able to assist the design and development while capable of pushing the boundaries in predicting the performance of the prototype without jeopardising the systems' hardware.

This chapter describes one-dimensional modelling and simulation for the single cylinder gasoline spark ignition two-stroke free-piston engine using Ricardo WAVE. Two-stroke free-piston engine model was developed from validated four-stroke crankshaft engine model as explained in Section 3.3. The simulation results were used for prototype development in Chapter 4 and free-piston engine model validation in Chapter 5. The optimised single cylinder free-piston engine model in this chapter formed a basic model for dual-piston free-piston engine generator model in Chapter 6 for final performance investigations.

3.1 Theoretical review

One-dimensional (1D) modelling of an internal combustion engine is one step beyond standard engine thermodynamic analyses. The coding comprises fundamental thermodynamics equations and empirical relationships which are able to simulate the overall engine behaviour sufficiently to provide preliminary performance and emissions characteristics of an engine under development.

A 1D modelling and simulation tool is used for engine development by major automotive companies to assist prototype development due to its capability to produce realistic results quickly. Further, it requires less overhead cost and computational cost without the need for three-dimensional computer aided design (CAD) design of the engine. Therefore, 1D tool was selected to assist the prototype development for the aforementioned advantages.

WAVE is a computer-aided engineering software package developed by Ricardo which allows the analysis of the dynamics of pressure waves, mass flows, and energy losses in ducts, plenums, and manifolds of the engine. It provides a time-dependent solution of fluid dynamics and thermodynamics 1D equations. The software has complex sub-models to simulate friction, heat transfer, scavenging, combustion, knock and exhaust emissions.

3.1.1 *Engine Parameters*

The terms and definitions used in this section is a combination of information obtained from Heywood [8], Blair [100] and Pulkrabek [40] for crankshaft engines.

The definitions for combustion chamber and cylinder geometry are shown in Figure 3.1. The diameter of the cylinder is the bore (B). The stroke (S) is defined as the distance travelled by the piston from (bottom dead center) BDC to (top dead center) TDC and the volume within the stroke is known as the swept volume (V_S). For a free-piston engine, the nominal stroke (S_{nom}) will be defined as the stroke length is not constant. When the piston is at TDC, the remaining space between the top of the piston and the cylinder head is known as the clearance volume (V_C), which is contained within the clearance distance (c).

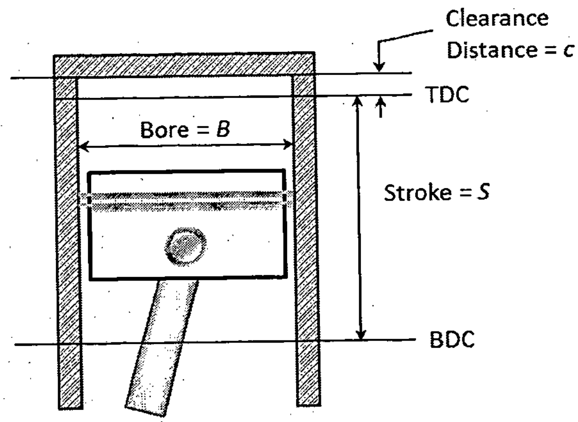

Figure 3.1: Cylinder geometry definitions for an engine with a flat top piston (without the bowl)

Further parameters and definitions are given by following equations:

- Swept volume, V_S:

$$V_S = \frac{(\pi B^2 S)}{4} \qquad [\mathrm{m^3}] \qquad 3.1$$

For a known clearance volume (V_C) above the piston at TDC:

- Geometric Compression Ratio, $(CR)_G$ is defined as:

$$(CR)_G = \frac{(V_S+V_C)}{V_C} \qquad [-] \qquad 3.2$$

3.2 Modelling approach and sub-models

Modelling and simulation in Ricardo WAVE programs suite is conducted using three sub-programs as shown in Figure 3.2. WaveBuild is the main pre-processor program used for initial setup of the simulation. The geometrical properties of the model and its boundary conditions are defined in this sub-program using its graphical user interface which is then converted into input format appropriate for the solver. WAVE is the solver used in this research to solve all the 1D fluid dynamics and thermodynamics time-dependent equations. Finally, the results are viewed and interpreted using WavePost post-processor in the form of 2D or 3D graphs, pictures, text-reporting or other media.

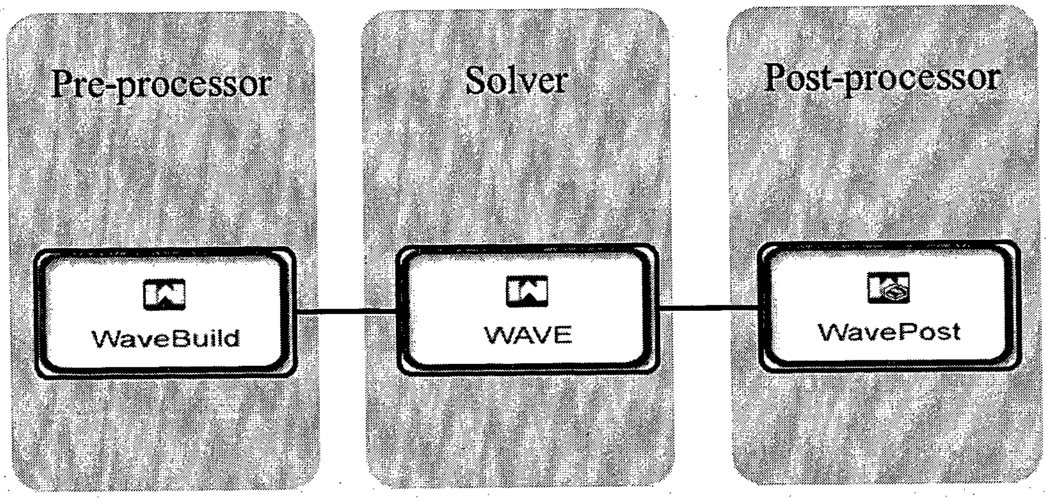

Figure 3.2: Three primary sub-programs in Ricardo WAVE programs suite employed in this research.

The first step in building an accurate model is to gather the geometric data. The engine can be broken down into the main subsystems, i.e. intake runner, intake valve inlet, cylinder, exhaust valve inlet, exhaust runner. The dimensions and characteristics related to the engine required are bore, stroke, connecting rod length, compression ratio, valves diameter, valves lift and valve timings. Engine operating parameters initial conditions must be defined and identified as engine operating speed, fuel type, air/fuel ratio and ambient conditions (i.e. temperature and pressure).

The model was built in the WaveBuild tool with the variables shown in Figure 3.3. In this basic model, the intake and exhaust sides are directly exposed to the ambient conditions. The throttle valve, intake and exhaust manifold dimensions were added during the optimisation phase of the simulation as presented in Section 3.3.2.