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Semi-analytical modelling of a hydraulic free-piston engine

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HIGHLIGHTS

- A semi-analytical method for the HPFE parameter design is proposed.
- The HFPE piston oscillation is a hard self-oscillation.
- The piston oscillation has an unsymmetrical oscillation characteristic.
- Stable running of a single piston HFPE prototype is realised.

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ABSTRACT

The hydraulic free-piston engine is a hybrid of a hydraulic plunger pump and a free-piston engine. This paper presents a semi-analytical method for the hydraulic free-piston engine parameter design. An oscillation function described the piston oscillation were established. The piston oscillation characteristics were analysed. The parameter sensitivity and the limit cycle stability of the piston oscillation were investigated. The results show that the single piston free-piston engine system is a hard self-oscillation with variable damping and stiffness. External energy is required to start the piston oscillation. The piston oscillation has an unsymmetrical oscillation characteristic. The dead centres of the piston motion are determined by the energy balance. The energy supply and the energy consumption are determined by the generalised damping in the piston oscillation function. The piston oscillation frequency should satisfy the minimum compression ratio requirement for the compression ignition. In the steady operation, the piston motion is a self-excitation oscillation. The trajectory stability is mainly determined by the fuel combustion energy supply. The scavenging affected by the BDC should be paid special attention to ensure the trajectory stability.

1. Introduction

The free-piston concept was firstly proposed by Pescara in 1920s [1] and developed fast from 1930s to 1960s [2,3]. However, for many reasons, the free-piston engine (FPE) was replaced by advanced crank internal-combustion engines and practically abandoned since the 1960s [3]. Potential advantages of the FPE, such as optimised combustion through variable compression ratio, and lower frictional losses due to the simple structure with few moving parts, makes the FPE concept receive more interest in recent years [4–7].

Compared to the conventional crank internal-combustion engine, the FPE has two typical features [2,3]:

(a) The piston motion is not restricted by a rotating crankshaft, as known from crank engines.

(b) The power is taken out by media, not by gear or shaft.

The FPE concept can be divided into three categories according to the number or position of the piston. With different media of loads, the FPE can be converted into different power engines. Most of them are designed as power sources for automotive applications [3]. The General Motors XP-500 completed in 1957 was the first free-piston automobile [3]. The XP-500 was powered by the General Motors Research 4-4 'Hyprex' engine. The General Motors Research 4-4 'Hyprex' was a dual opposed piston, diesel free-piston engine. It had a power output of around 185 kW [8]. Because of technical shortcomings and more promising research in other areas of alternative propulsion, General Motors halted further development on the free-piston automobile within three years of the XP-500's completion [9]. Ford, like General Motors, saw a potential in the free-piston gas generator for automotive applications in the mid-1950s [3]. Frey and co-researchers proposed an analytical model for the design of a free-piston gas generator and described the development of a 112 kW prototype [10]. The

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Nomenclature

a	amplitude
A_1	function of the amplitude
b	decentration
c	generalised damping
c_{equi}	equivalence damping
c_o	damping coefficient
D	cylinder bore
E_{cyc}	energy released by fuel combustion in one cycle
f	piston oscillation frequency
f_c	simplified combustion gas force
F_{ch}	check chamber force
F_{co}	compression chamber force
F_g	in-cylinder gas force
F_{gC}	force brought by the fuel combustion
F_{gCmax}	maximum value of force brought by the fuel combustion
F_{gV}	force determined by the changing of gas volume
F_{pu}	pump chamber force
F_r	friction force
F_{r0}	value of friction force
K	generalised nonlinear stiffness
L	distance between the piston balance position and the cylinder head plate
m	moving piston mass
p	in-cylinder gas pressure
p_0	initial value of the in-cylinder gas pressure
p_c	hydraulic compression pressure
p_{gC}	gas pressure brought by the fuel combustion
p_{gV}	gas pressure in the pure compression process
p_w	hydraulic working pressure
$Para$	design parameter value
$Para_{rated}$	design parameter rated value
S	piston cross-section area
S_1	cross-section area of the check chamber
S_2	cross-section area of the pump chamber
S_3	cross-section area of the compression chamber
V_0	initial value of the in-cylinder gas volume
y	state variable
x	piston displacement
x^*	displacement in the calculation coordinate system
x_1^*	function of the amplitude
x_{CSBDC}	BDC in the compression stroke
x_{ESBDC}	BDC in the expansion stroke

Greek symbols

γ	in-cylinder gas adiabatic exponent
δ	active range of the combustion force
ε	compression ratio
η_i	indicated thermal efficiency
φ	phase
Φ_0 and Φ_1	functions of the amplitude and the phase
ω	change rate

favourable torque-speed characteristic of the prototype led Ford engineers to conclude that the Ford model 519 free-piston power plant was ideally suited for installation in the Ford Typhoon tractor [3]. A hydraulic free-piston engine (HFPE) has been proposed as a low-cost and high-efficiency power unit for a fork-lift truck by Innas [4]. The HFPE is a combination of a free-piston engine and a hydraulic pump. The HFPE gets higher efficiency compared to the conventional assemble of a crank internal-combustion engine and a hydraulic plunger pump [11].

The free-piston engine characteristic is often investigated by discrete numerical methods [12–22,7]. Zero-dimensional modelling of free-piston engines has been proposed [12–19]. Some have investigated free-piston engines using multidimensional simulation models [20–22,7]. The numerical methods could achieve the instantaneous displacement, velocity and acceleration of the engine piston with a high degree of precision. However, the numerical result only contains the discrete numerical solution and the panorama of the system solution is still not completely offered. To achieve high precision numerical result, the numerical model is always complicated and the time-consuming for the model calculation is long. The numerical result is inconvenient for analysing the piston oscillation and the contributing factors. The result also cannot fully satisfy the requirement for the engine parameter control system design. A semi-analytical model has been developed for the free-piston Stirling engine analysis [23].

This paper studies the design method of a single piston hydraulic free-piston engine (SPHFPE) as the power source of a hydraulic hybrid vehicle. Different from the discrete numerical method used in the engine parameter design, a semi-analytical method was used. The forces applied on the piston were analysed and the piston oscillation semi-analytical model was established. Extensive results of the oscillation model were presented, giving insight into piston oscillation characteristics. The transient process between different stable piston trajectories was analysed. The results indicate that the steady state of the designed free-piston engine is a hard self-excited vibration with variable damping and stiffness. The stable piston trajectories only appear in a special piston stroke range, which means that the engine is operated in energy balance conditions. The aim is to offer the piston oscillation panorama by the semi-analytical method.

2. Configuration of the SPHFPE

The configuration of the SPHFPE is shown in Fig. 1, firstly proposed by Innas BV [4]. The SPHFPE is a two-stroke diesel engine with uniflow scavenging and direct fuel injection. The exhaust valves and the scavenging pump are driven by the high-pressure

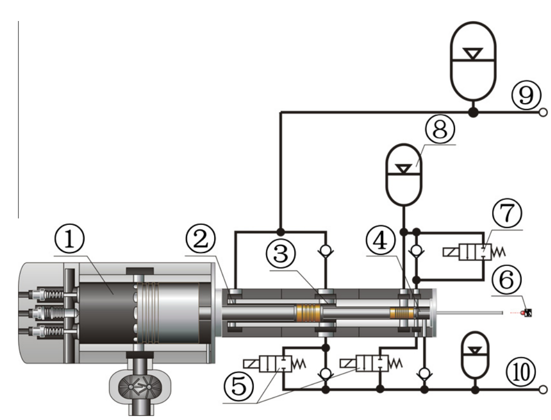

Fig. 1. SPHFPE configuration. ① Combustion cylinder, ② check chamber, ③ pump chamber, ④ compression chamber, ⑤ reset valve, ⑥ piston displacement transducer, ⑦ frequency control valve, ⑧ compression accumulator, ⑨ high-pressure rail, ⑩ low-pressure rail.