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Stability analysis of hydraulic free piston engine ☆

Shuanlu Zhang, Changlu Zhao, Zhenfeng Zhao *

School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China

HIGHLIGHTS

- The solution of the nonlinear vibration model was given by the generalized harmonic KBM method.
- The reasons affect the constant amplitude and decentration were analyzed.
- The factors that affect stability of oscillatory system were investigated.
- The scavenging effect influenced by the port opening was researched and validated by experiment.
- The stability range of the piston constant amplitude and judging in equation were proposed.

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ABSTRACT

Based on the piston force analysis of the hydraulic free piston diesel engine, a nonlinear vibration model is established. Then the solution of the nonlinear vibration model is given by the generalized harmonic KBM method. The reasons that affect the constant amplitude of the nonlinear vibration model are analyzed according to the expression of the constant amplitude. The constant amplitude is limited by many factors and the system will be unstable if the correlated variables are out of range. The influential factors, such as the fuel injection position and quality, are investigated. In addition, the fluctuation of pump chamber caused by the variation of response characteristics of check value also influences the constant amplitude. All these reasons may lead to the unstability of the oscillatory system. Because the combustion condition is influenced by the air intake and fuel injection, the selection of unstable region is decided by the scavenging and combustion. Therefore the scavenging influenced by the port opening is researched and the results are validated by experiment. In order to get the optimal design of HFPE, the stability range of the piston constant amplitude and judging in equation are proposed, and the parameters in the stable region are obtained. All these efforts establish the theoretical foundation for control strategy of stability improvement.

1. Introduction

Recently, potential advantages of the hydraulic free piston diesel engine (HFPE), such as higher thermal efficiency, lower frictional losses and better emission performance, make the research of HFPE prosperous [1–4]. However, Compared with the conventional internal combustion engine, the HFPE has one disadvantage [2,3]: The piston motion is not restricted by a rotating crankshaft, which leads to the variation of TDC and BDC. Consequentially, the actual injection time and the combustion conditions are changeable, which leads to the unstability of HFPE. Therefore the stability study of HFPE still needs much effort in this field.

In the history of HFPE, it has been presented as an economical and high efficiency power unit for a fork-lift truck by Innas Company [4]. From then on, the free piston engine characteristic is frequently investigated by discrete numerical methods: Zero-dimensional modeling of free piston engines has been discussed [5–8]. Some literatures [4,9–11] have investigated free piston engines using multidimensional simulation models. Although the numerical methods could achieve the instantaneous dynamics of the engine piston with a high degree of precision, the numerical results only give the discrete numerical solution rather than the internal parameters relationship with the system stability. Therefore the numerical solutions make less contribution to analyzing the stability of HFPE. Actually, the stability of HFPE has been analyzed by

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* Corresponding author. Tel.: +86 1068912295; fax: +86 1068912514.
E-mail address: zhzhf@bit.edu.cn (Z. Zhao).

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Nomenclature

Latin

a	amplitude, m
a_0	the constant amplitude, m
b	decentration, m
b_0	the constant decentration, m
D	bore diameter, mm
E_{cyc}	input energy of fuel injection in one cycle, J
F_b	gas force produced by the fuel combustion, N
F_C	compression chamber force, N
F_e	the pure compression gas force, N
F_f	friction force, N
F_H	force of high pressure pump chamber, N
F_P	working pump chamber force, N
F_s	area of gas port in different position, mm^2
g	acceleration of gravity, m/s^2
k	adiabatic exponential
k_g	Gas spring stiffness in cylinder, N/m
h_{m0}	port height of full opening, m
h_{p0}	port height, m
L	distance between the piston balance position and the cylinder head plate, m
L_0	distance between the piston air intake position and the cylinder head plate, m
Me_{E}	mechanical energy function
p_b	gas pressure brought by the fuel combustion, MPa
p_C	compression pressure in control pump, MPa
p_e	gas pressure in the pure compression process, MPa
p_{e0}	initial value of the in-cylinder gas pressure, MPa
p_H	hydraulic working pressure, MPa
$p_{\max}$	maximum value in-cylinder, MPa
Po_E	elastic potential energy function
p_P	the working pressure in pump chamber, MPa
p_s	pressure of intake air, MPa
p_z	in-cylinder gas pressure, MPa
R	universal gas constant, J/(mol K)
T	temperature of intake air, K
V_e	arbitrary value of the in-cylinder gas volume, m^3
V_{e0}	initial value of the in-cylinder gas volume, m^3
x_{Piston}	displacement of piston, m
S_C	sectional area of control pump piston, mm^2
S_H	sectional area of high pressure pump piston, mm^2
t	time, s

Greek symbols

α	constant 0.55–0.65
β	constant 1.3–1.42
δ	active range of the combustion force, m
ε	reciprocal of piston mass, 1/kg
Φ_0	function of the amplitude
ϕ	the fuel air equivalence ratio
φ	phase
γ	specific heat ratio
η_i	indicated thermal efficiency
μ_m	flow coefficient 0.62–0.65
θ	constant
τ	function of time, a and b

Abbreviation

BDC	Bottom Dead Center
HFPE	hydraulic free piston diesel engine
KBM	Krylov–Bogoliubov–Mitropolskii
TDC	Top Dead Center

many researchers for the control strategy. S. Tikkanen etc deem that the energy balance principle in the control of HFPE's compression ratio works. They also found that the load of the HPFE should be constant but can change within certain limits [12]. Mikalsen R etc also researched the free piston engine control [13]. They got the conclusion that the BDC position must be controlled to ensure efficient scavenging of the cylinder. If the piston travels far outside the default dead center, it will lead to mechanical contact between the piston and cylinder head, which is fatal for the engine. A semi-analytical model has been developed for the free-piston engine analysis [1,14]. Wu et al. [1] believe that the stability of the piston oscillation is determined by the energy balance and the expansion stroke is deeply affected by the fuel combustion energy. The scavenging affected by the BDC should be paid special attention to ensure the stable piston oscillation. All above researchers analyzed the stability of HFPE qualitatively and have made significant achievements for their unique perspective. However, the specific influence and relationship between the technical parameters and the stability of HPFE were not analyzed further.

In order to study the stability of HFPE, this paper aims at analyzing the forces on the piston and establishes the piston oscillation model. We solve the HFPE model with the KMB method. The reasons affect the system stability are analyzed according to an approximate solution of the constant amplitude and decentration. The scavenging condition influenced by the port opening is researched. In order to get the optimal design of HFPE, the stability range of the piston constant amplitude and the judging in equation are proposed.

2. Nolinear vibration model of HFPE

2.1. Prototype of HFPE

The schematic of HFPE is shown in Fig. 1. The HFPE 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 fuel. A hydraulic–electronic unit injector from Caterpillar is used for the injection system, which is shown in Fig. 2. The prototype of the HFPE consists of the hydraulic pump part, the combustion engine part, the pump chamber and the compression chamber. The check chamber restricts the rebound of the piston around BDC after the expansion stroke. The pump chamber delivers one part of the high pressure fuel in the expansion stroke. The other is delivered by the check chamber in the compression stroke. The compression chamber completes the compression stroke by the hydraulic power stored in the compression accumulator. The frequency control valve is used to control the working frequency of the HFPE. The specific working process can be obtained in literature [15] and the main technical parameters of the HFPE prototype are shown in Table 1.

2.2. Piston force analysis

The piston force analysis of HFPE is shown in Fig. 3. In order to establish a relatively accurate nonlinear vibration model, the force analysis is necessary. The pressure in control chamber (p_C) can be treated as a constant value for its slight fluctuation. The hydraulic