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A fast response free-piston engine generator numerical model for control applications

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HIGHLIGHTS

- The numerical model of FPEG is simplified to a one-degree forced vibration system.
- Simplified model was successfully validated with respect to experimental data.
- The state-space equations and the transfer function of the system can be obtained.
- Feasible to be implemented to HIL simulation due to simplicity and flexibility.

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ABSTRACT

This paper presents a linearization of the dynamic equation for a free-piston engine generator (FPEG), and simplifies it to a one-degree forced vibration system with viscous damping. The analogy between a mass-spring damper and a FPEG system is expressed, and the solution to the vibration system is solved. The model was successfully validated with respect to experimental data obtained from a prototype. The simulated piston displacement during steady operation showed similar trends with the test results and the error of the displacement amplitude was controlled within 3%. The state-space equations and the transfer function of the system are obtain using the fast response numerical model. An example of model application in the real FEPG control system was provided. Compared to the previous numerical model with differential approaches, the solving time of the proposed fast response model can be significantly reduced. The simplicity and flexibility of the proposed model make it feasible to be implemented to several computing software, *i.e.* Matlab, AMESim, Labview, Dymola et al. It can be easily implemented to real-time Hardware-in-the-Loop (HIL) simulation model for the future piston dynamic control system development. In addition, since it reveals how an FPEG operates in a resonant principle, the model is useful for parameter selection in the FPEG design process.

1. Introduction

1.1. Background

The free-piston engine (FPE) is a promising power generation device which offers the benefits of simplicity and high thermal efficiency [1–5]. Unlike conventional reciprocating engines, the piston is not restricted by a crankshaft mechanism, and therefore its application has a number of reported advantages such as: mechanical simplicity, high efficiency, reduced NO_x formation and multi-fuel/combustion mode flexibility [6].

Known FPE applications include electric generators, hydraulic pumps and air compressors [1]. The dual piston free-piston engine generator (FPEG) considered here consists of a dual piston type FPE coupled with a linear electric generator. Combustion occurs alternately in each chamber to drive the mechanically unconstrained mover back and forth, a linear generator converts parts of the kinetic energy of the mover to electricity. Much work has been undertaken by a number of research groups worldwide including the authors' group to explore the operation characteristics of FPEG [7–12].

Different FPEG prototype designs have been reported by now. The FPEG prototype developed by the German Aerospace Centre consisted of an engine, a linear generator and a gas spring [13,14]. A power output of approximately 10 kW at 21 Hz was reported [13]. Researcher at Nanjing Institute of Technology

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Nomenclature

A	piston area (m^2)	p	cylinder gas pressure (Pa)
AFR	air–fuel ratio	p_0	ambient pressure (Pa)
B	cylinder bore (m)	p_{cm}	pressure due to heat release (Pa)
c	damping coefficient	p_{cp}	cylinder pressure due to volume change (Pa)
C_v	heat capacity at constant volume (J/m^3 K)	Q_{in}	heat released from the combustion process (J)
CR	set compression ratio	Q_{LHV}	low heating value (J/kg)
F	excitation force (N)	V	cylinder volume (m^3)
F_0	magnitude of excitation force (N)	V_o	cylinder volume at the middle stroke (m^3)
F_e	resistant force from generator (N)	V_c	clearance volume (m^3)
F_l	gas force from the left cylinder (N)	V_l	volume for the left chamber (m^3)
F_r	gas force from the right cylinder (N)	V_r	right chamber's volume (m^3)
k	spring constant or stiffness	W	output work (J)
k_v	coefficient of the load force	x	mover displacement (m)
K_t	throttle opening coefficient	Δp_{cm}	pressure increase heat release process (Pa)
L_s	half stroke length (m)	ΔU	the difference of the internal energy (J)
m	moving mass (kg)	ΔT	temperature increase of the mixture (K)
m_{air0}	air mass at full throttle (kg)	ω_n	angular natural frequency
m_{fuel}	fuel mass in the mixture (kg)	σ	unit step function
L_c	clearance length (m)	η_c	combustion efficiency

proposed a novel new FPEG design, which was consisted of a single cylinder operating on four-stroke cycle, a linear electric generator, and a mechanical spring kickback system [15]. A 2.2 kW average power output was obtained with an efficiency of 32% [15]. The dual piston FPEG prototype developed by Beijing Institute of Technology was reported to misfire every one to two cycles, with severe cycle-to-cycle variations [16]. The possible reasons of the variations and unstable operation were analyzed.

Modeling and simulation are key elements of machine design, and the FPE is commonly modeled using zero-dimensional models to obtain the piston dynamics and predict engine performance. There have been detailed numerical models validated and reported, in which the effects of the heat transfer, gas leakage were considered [17–25]. Many of the numerical models were developed in Matlab/Simulink, and multiple sub-systems were required to represent each equation. In our previous paper, a detailed numerical modeling of a spark-ignited FPEG and the model validation with test results have been presented [26]. However, the differential equations were solved iteratively and required a considerable computational cost, which makes it challenging to be implemented to real-time Hardware-in-the-Loop control systems. Therefore, when more complicated control strategy needs to be developed and implemented, a simplified model is necessary for the further real-time control system development.

As there is gas in both cylinders, which is compressible. Therefore, the gas in the cylinder acts like nonlinear springs, and the FPEG system is analogous to a mass-spring system. For a dual piston FPE, the engine is operated in a two-stroke cycle, and combustion occurs alternately in each chamber during stable operation. This means that the system is running under an external excitation, which is determined by the heat released during the combustion process. As a result, the dual piston FPE will show similar characteristics with a vibration system under external excitations after proper simplification.

1.2. Previous work on FPE oscillation characteristics analysis

A free-piston Stirling engine was considered as a heat driven mechanical oscillator by Redlich et al. from which power can be extracted. Linear dynamics was applied to obtain a stability criterion, means for calculating the frequency, characteristics of the oscillation system, and effects of friction force on starting process and the locus of the roots of the system determinant. Three common configurations of these engines were investigated [27].

Nakhaie Jazar and Farid Golnaraghi presented a nonlinear model for a hydraulic engine mount. They introduced a simple nonlinear mathematical model, which showed agreement with the test results available in the literature [28]. Applying the multiple scale perturbation method, they examined the behavior of the mount at resonance. The significant difference between the performance of the nonlinear model and the linear model at resonance was the existence of a jump phenomenon [28].

Xiao et al. established a numerical model of the FPEG [29–31]. The natural frequency of the oscillation system was obtained from their model. A simulation program was developed in Matlab/Simulink to solve these mathematical equations, and the simulation results showed that the motion of FPEG was a forced vibration system with variable damping coefficient and stiffness [29].

Hansson et al. investigated the resonant behavior of a FPEG. They linearized the system after expanding the equation around an equilibrium point [32]. Finally, the approximations of the free-piston oscillation characteristics were achieved. However, only compression pressure forces were calculated in their model, and the pressure increased by the heat release of the gas fuel mixture was not considered.

1.3. Research aims and methodologies

This paper aims to describe the dynamic operation of a dual piston FPEG, with the objective of obtaining an understanding of the piston oscillation characteristics. Both of the compression pressure force and the pressure increased by the heat release were considered. By linearizing the system, a forced vibration equation with viscous damping can be achieved, and the approximations of the mass spring constant and the natural frequency can be obtained. Based on that, the vibration equation and the solution for the displacement can be derived.

2. Linear dynamics model

2.1. Dynamic equation

The main parts of the FPEG consist of two opposing combustion chambers and a linear electric machine. A linear magnet mover