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A novel active free piston Stirling engine: Modeling, development, and experiment

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HIGHLIGHTS

- A novel active free piston Stirling engine is modeled, fabricated, and tested.
- A dynamic model of the engine is presented and experimentally validated.
- A systematic way to find gas temperature within the hot and cold spaces is proposed.
- The simulated thermal efficiency of 19.4% proves the potential of the concept.

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ABSTRACT

This paper focuses on mathematical modeling, development, and experimental evaluation of a novel active free piston Stirling engine (AFPSE). First, working principles of the proposed AFPSE are described and its advantages are introduced. Then, a comprehensive mathematical model of the proposed Mechatronic system is presented using kinematic, dynamic, thermodynamic, heat transfer, and electrical equations. The Schmidt's theory assumptions are used throughout the modeling scheme except for finite heat transfer and imperfect regeneration. Next, a systematic way to estimate the gas temperature in the expansion and compression spaces of the engine is presented taking into account the imperfect regeneration and finite heat transfer in the presented converter. Moreover, the engine performance, as well as the resonant frequency of the active converter, is investigated through simulation. Finally, the proposed AFPSE is developed and primarily tested. The obtained practical results clearly demonstrate the feasibility of generating power (i.e. 7.1 W) through thermal excitation of a one degree-of-freedom (1-DOF) dynamic system with its resonant frequency (i.e. 9.2 Hz). Furthermore, it is found that the experimental measurements are in an acceptable agreement with the simulation outcomes of the analytical model through which validity of the mathematical scheme is affirmed.

1. Introduction

Stirling engines can provide clean and reliable mechanical power when subjected to a temperature gradient. Unlike internal combustion engines, the Stirling engines do not require the distillate of fuels like gasoline and therefore, can operate using any heat source such as geothermal, solar, biomass, and nuclear energies. In addition, they are theoretically capable of achieving Carnot efficiency, with fewer moving parts than typical internal combustion engines [1–6]. As a result, they can be considered as an excellent solution to many energy conversion applications. The Stirling engines can be classified into two categories, namely, kinematic and dynamic Stirling engines [7–9].

Free piston Stirling engines (FPSEs) are known as one particular variety of the dynamic Stirling engines with variable stroke and extremely long operating life without maintenance [10,11]. In order to predict the performance of FPSEs via analytical methods, accurate thermodynamic and dynamic models are usually required. Beale presented the first analytical approach to predict the performance of FPSEs based on the Schmidt's theory [12,13]. However, the original Schmidt's method was first adopted to use in the kinematic Stirling engines, considering the unrealistic assumptions of perfect regeneration and infinite heat transfer [14–16]. Many researchers have proposed different mathematical models to justify the performance of such dynamic engines, each of which contains some advantages and drawbacks. Riofrio et al. [17] improved the Schmidt's analysis of FPSEs by introducing the concept of dynamic

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Nomenclature

C	damping coefficient of the power piston ($\mathrm{N\,s\,m^{-1}}$)
h	convective heat transfer coefficient ($\mathrm{W/(m^2\,K)}$)
I_e	equivalent inertia ($\mathrm{m^4}$)
i	current (A)
K	spring stiffness of power piston ($\mathrm{N\,m^{-1}}$)
L	length (m)
L_1	inductance (H)
M	mass of the power piston and magnets (kg)
m	total mass of the gas in the engine (kg)
m_k	mass of the gas in the compression space (kg)
m_h	mass of the gas in the expansion space (kg)
P_t	output power (W)
p	pressure (Pa)
$\acute{Q}_k$	heat for isothermal compression process considering perfect regeneration (J)
Q_k	total heat for isothermal compression (J)
$\acute{Q}_h$	heat for isothermal expansion process considering perfect regeneration (J)
Q_h	total heat for isothermal expansion (J)
Q_{loss}	heat loss due to imperfect regeneration (J)
Q_{reg}	stored heat in the regenerator (J)
r	ideal gas constant ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
R	resistance (Ω)
s_d	cross-sectional area of the displacer piston ($\mathrm{m^2}$)
s_{de}	heat transfer area in expansion space ($\mathrm{m^2}$)
s_p	cross-sectional area of the power piston ($\mathrm{m^2}$)
s_{pe}	heat transfer area in compression space ($\mathrm{m^2}$)
T_K	cold source temperature (K)
T_k	gas temperature in compression space (K)
T_H	hot source temperature (K)
T_h	gas temperature in expansion space (K)
T_m	DC motor torque (Nm)
t	time (s)
W	work (J)
V_h	volume of expansion space ($\mathrm{m^3}$)
V	applied voltage to DC motor (V)
V_{h0}	initial volume of expansion space ($\mathrm{m^3}$)
V_k	volume of compression space ($\mathrm{m^3}$)
V_{k0}	initial volume of compression space ($\mathrm{m^3}$)
x	power piston position (m)
$\dot{x}$	power piston velocity ($\mathrm{m\,s^{-1}}$)
$\ddot{x}$	power piston acceleration ($\mathrm{m\,s^{-2}}$)
y	displacer position (m)
$\dot{y}$	displacer velocity ($\mathrm{m\,s^{-1}}$)
$\ddot{y}$	displacer acceleration ($\mathrm{m\,s^{-2}}$)
Δt	time step (s)

Greek symbols

γ	heat capacity ratio
θ	angle of rotation of the DC motor
ρ	gas density ($\mathrm{kg/m^3}$)
φ	phase difference (degree)
ω	engine frequency (rad/s)
η_{reg}	regenerator efficiency
η	ideal engine efficiency

instability into the system. They could justify the instability of FPSEs using control-based analytical techniques such as root locus and Bode plot. However, the presented techniques were only used in the linear dynamic analysis of FPSEs [18–23]. Rogdakis et al. [24] investigated the performance of an FPSE based on a thermodynamic model. The effect of gas mass on the engine dynamics and the phase angle was thus investigated. Furthermore, based on the required criteria for stable operation of the engine, a mathematical model was obtained to estimate the engine design parameters. Zare and Tavakolpour-Saleh [25] presented a comprehensive mathematical model and a genetic algorithm-based optimization for a passive FPSE namely SUTech-SR-1 considering nonlinear variations of gas pressure. They then obtained the phase difference between the motions of power piston and displacer through simulation and experiment. Finally, the simulation results were compared to those of the experimental work. In another research, Tavakolpour-Saleh et al. [26] applied the perturbation method to model and analyze a passive FPSA possessing nonlinear springs. Consequently, they proposed a set of very useful formulas to predict the performance of FPSEs. Mou et al. [27] investigated the gas action effect on the performance of a passive FPSE by the method of rotation vector decomposition. Then, they proposed a method to increase the engine efficiency. Furthermore, the influence of gas action on the phase difference between the motions of power piston and displacer was investigated. Karabulut [28] presented a nonlinear dynamic model of a passive FPSE and then, studied the dynamic response of the engine system corresponding to the variations of engine parameters such as hot source temperature, damping coefficients of the pistons, diameter of displacer rod, initial positions of the power piston and displacer, mean pressure, and stiffness of the pistons' springs. Sim and Kim [29] proposed a dynamic model to predict the performance of a passive FPSE along with a nonlinear damping load. They estimated the motion amplitudes of the pistons and output power of the engine via numerical simulation of the presented dynamical model considering both linear and nonlinear damping terms as the external loads. In addition, the experimental results of the engine prototype (namely RE-1000) were compared to the predicted data by the model so as to verify the reliability of the analytical relationships.

As mentioned so far, the majority of presented FPSEs are passive in that they do not require any external source of electrical energy to run. Almost all papers on modeling, development, and evaluation of FPSEs have been focused on the passive type. Although the passive FPSEs (i.e. B10-B and SUTech-SR-1 [25]) provide a simple and a reliable way to convert thermal energy into mechanical form, there exist some limitations associated with the use of such passive FPSEs. The passive FPSEs cannot adapt themselves to adverse operating conditions and unpredictable uncertainties [30–32]. Besides, the passive FPSEs require an onset temperature to operate. On the other hand, active FPSEs may achieve a much better performance than the passive converters by employing adjustable actuators such as the piezoelectric devices, hydraulic pistons and DC motors. Besides, the shape of the thermodynamic cycle can be adjusted such that the practical cycle of the active converter resembles the ideal Stirling cycle through which a higher efficiency and output power can be acquired. Moreover, the engine system can be excited by its resonant frequency so that a maximum possible output power is generated. It is also possible to easily make the engine self-starting via the active methodologies.

In spite of the mentioned benefits of the active FPSEs, there was no published paper in which an active free piston Stirling engine is presented. Consequently, this article attempts to present an active free piston Stirling converter with a novel configuration that is activated by a DC geared motor. The main idea of this work is to generate power from the resonance state of a 1-DOF dynamic system under thermal excitation. First, the working principles of the proposed converter are described. Then, a comprehensive mathematical model of the active converter is presented using dynamic,