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Frequency-based design of a free piston Stirling engine using genetic algorithm

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ABSTRACT

This paper focuses on the frequency-based design of a FPSE (free piston Stirling engine) using a GA (genetic algorithm). First, a mathematical description of the FPSE is presented. The engine design parameters including mass and stiffness of power and displacer pistons and cross-sectional area of the displacer rod are considered as unknown variables. Then, based on a desirable operating frequency, positions of closed-loop poles of the engine system are selected. The unknown design parameters are thus found via an optimization scheme using GA. A new objective function based on the eigenvalues of the state matrix of the FPSE is proposed and GA is used to obtain the optimal values of design variables so that the objective function is minimized. Next, the effectiveness of the proposed design is evaluated through numerical simulation. Two mathematical approaches are presented to compute the phase difference between the motions of power and displacer pistons. Furthermore, the generated work and power of the FPSE are found based on the computed phase angle. Finally, the designed FPSE is constructed and primarily tested. It is found that the simulation results are in a good agreement with the experiment through which validity of the presented design technique is affirmed.

1. Introduction

The increase of world population on one hand and the reduction of fossil fuel resources, on the other hand, led researchers to renewable energy technologies. One of the most useful renewable energy sources is known as solar energy. Different converters can be employed to utilize solar energy one of which is known as the Stirling engine. The Stirling engines can be classified as kinematic and dynamic engines. In the kinematic Stirling engines, the displacer and power pistons are connected together via a linkage mechanism. In contrast, in the dynamic Stirling engines (i.e. free piston Stirling engines) there is no constraint between the motions of power and displacer pistons [1]. In other words, the pistons are free to move independently and the motions of the pistons are coupled through the pressure dynamics. Beale [1] invented the first free piston Stirling engine in 1964. It is a mechanical converter that operates based on the Stirling cycle. The Stirling cycle is an ideal thermodynamic cycle, which contains two constant-temperature and two constant-volume regenerative processes [2,3].

The FPSEs are among the external combustion engines and hence, different fuels e.g. radioisotope energy, solar energy, geothermal energy and so on can be used to power them. Wood and Lane [4] evaluated a free piston Stirling engine powered by radioisotope fuel. It was reported that the engine generated a power of 35 W. Jakubowski [5] designed and analyzed a 2 kW free piston Stirling engine. In this work, the radioisotope fuel was used as the heat source of the Stirling engine.

Free piston Stirling engines can be analyzed through simultaneously solving dynamic and thermodynamic equations. In addition, linear control tools such as root locus, bode plot and *etc* can be used to evaluate the effects of variations of system parameters on the engine performance. Riofrio et al. [6] presented a dynamic model for an FPSE and examined the effects of each constitutive parameter (e.g. damping and temperature) on the instability of a free piston engine. This study proposed the application of linear control methods such as root locus, Bode and Nyquist diagrams to design the FPSEs. Barth and Hofacker [7] extracted the dynamic and thermodynamic equations governing an FPSE and then, transformed the obtained equations into state space. Accordingly, the eigenvalues of the state matrix were used to investigate the closed-loop poles of the system. Hofacher et al. [8] compared 5th-order and 4th-order models of the FPSEs in state-space. Next, the

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Nomenclature

A	Cross sectional-area of the piston and displacer (m^2)
A_r	Cross sectional-area of the displacer rod (m^2)
B	Damping coefficient between displacer rod and power piston potion ($N\ s\ m^{-1}$)
b_d	Damping coefficient of the displacer piston ($N\ s\ m^{-1}$)
b_p	Damping coefficient of the power piston ($N\ s\ m^{-1}$)
K_d	Spring stiffness of displacer ($N\ m^{-1}$)
K_p	Spring stiffness of power piston ($N\ m^{-1}$)
M	Total mass of the gas in the engine (kg)
M_d	Mass of displacer (kg)
M_p	Mass of the power piston (kg)
P	Linear pressure (Pa)
P_0	Initial pressure of working gas(Pa)
P_w	Power generation (J/s)
$\widehat{P}$	Nonlinear pressure (Pa)
R	Ideal gas constant ($J\ kg^{-1}\ K^{-1}$)
T	Time (s)
T_h	Gas temperature in expansion space (K)
T_c	Gas temperature in compression space (K)
W	Work (J)
V_h	Volume of expansion space (m^3)
V_{h0}	Initial volume of expansion space (m^3)
V_c	Volume of compression space (m^3)
V_{c0}	Initial volume of compression space (m^3)
V_r	Volume of the regenerator (m^3)
x	Displacer position (m)
$\dot{x}$	Displacer velocity ($m\ s^{-1}$)
$\ddot{x}$	Displacer acceleration ($m\ s^{-2}$)
y	Power piston position (m)
$\dot{y}$	Power piston velocity ($m\ s^{-1}$)
$\ddot{y}$	Power piston acceleration ($m\ s^{-2}$)
Z_1	Power piston stroke (m)
Z_2	Displacer piston stroke (m)
Δt	Time step (s)

Greek symbols

φ	Phase difference (degree)
ω	Engine frequency (rad/s)

calculated operating frequencies for each model were compared to those measured from an experimental engine prototype. Begot et al. [9] studied the stability of the FPSEs using thermodynamic and dynamic approaches. Then, the stability concept was investigated by evaluation of the eigenvalues of state matrix. Finally, the model validity was demonstrated by the compression of the obtained results with the experimental outcomes reported by NASA.

Investigations on the performance of the Stirling engines are known to be an important issue in designing the Stirling converter. Tavakolpour-Saleh et al. [10] designed and developed a low temperature differential Stirling engine with Gamma-configuration considering sink and source temperatures of 20° C and 100 °C respectively. A flat plate solar collector was used as an inbuilt heat source of the engine. The mathematical model of the engine was thus presented based on thermodynamic and heat transfer principles taking into account the regenerator efficiency and the actual temperatures of the gaseous working fluid in expansion and compression spaces. The optimum phase angle corresponding to maximum work of the engine was found at the phase difference of 90° using Schmidt's theory. Jokar and Tavakolpour-Saleh [11] designed and developed a novel solar–powered active Stirling converter with liquid power piston and solid controllable displacer. They applied an active strategy to control the displacer piston so that a maximum power was achieved. An optimization scheme was thus provided to find the optimum speed of the active converter corresponding to different working conditions. They then studied the effects of regenerator efficiency on the gas temperatures in hot and cold chambers. Ding et al. [12] evaluated the efficiency and performance of a Stirling engine. An optimization procedure was conducted to design the engine considering thermal resistance, heat loss, regeneration loss and mechanical losses using the Senft's mechanical efficiency model along with finite time thermodynamic method. Hsieh et al. [13] evaluated an FPSE engine powered by the waste heat of incinerator. With the assumption of constant temperature in the hot and cold spaces, the engine power was calculated using Lagrange multipliers. Kwankaomeng [14] designed and constructed a single acting free piston Stirling engine. Power generation and efficiency corresponding to different frequencies of the system were thus investigated. The experimental results of the free-piston Stirling engine clearly demonstrated that a maximum output power of 0.68 W was found at 6.4 Hz engine speed using a 10 W heat source. Karabulut [15] obtained the governing equations of the free piston Stirling engines in both closed and open cycles. Then, power generation per cycle for different values of the engine parameters such as spring stiffness and damping coefficient was computed. It was found that the output power of the engine was more sensitive to the variation of damping coefficient. Therefore, increasing the damping coefficient by 1 Ns/m resulted in reducing the output power by 535 W. Furthermore, reduction of 6 K in gas temperature inside the expansion space caused some decreases in the output power from 563 W to 30 W. Mabrouk et al. [16] evaluated the effect of leakage loss on the efficiency and performance of β type Stirling engine. They proposed an unsteady analytical model to calculate the gas leakage mass flow rate by considering an oscillating flow in the annular clearance. Finally, sensitivity of the engine to parameter changes is discussed. Timoumi et al. [17] evaluated the efficiency and performance of a Stirling engine (model: GPU-3). They studied the effects of heat absorption and rejection between compression and expansion spaces with displacer movement (shuttle effect). Lia et al. [18] investigated the effects of compact porous-sheets heat exchangers on performance of a Stirling engine.

Nowadays, artificial intelligence methods have become the main candidates in optimization and design of complex energy systems. Tavakolpour-Saleh and Jokar [19] applied a neural network controller to a novel solar-powered active Stirling converter and effectiveness of the proposed intelligent Stirling system was demonstrated experimentally. Kalogirou [20–22] is among eminent researchers who conducted extensive studies on the applications of artificial intelligence techniques such as ANNs (artificial neural networks), GAs and FL (fuzzy logic) for modeling and performance prediction of energy systems. Genetic algorithms are known as the most effective evolutionary algorithms inspired by both natural selection and natural genetics that can be effectively applied to complex optimization problems. Although there are many papers on the application of GAs for optimization of different energy systems, there are a very small number of published reports on the GA-based optimization of Stirling engines. Kraitong and Mahkamov [23] investigated the optimal design parameters of a low-temperature differential Stirling engine using a genetic