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A real-time model of an automotive air propulsion system

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HIGHLIGHTS

- Isentropic nozzles and control volumes are employed for modeling air propulsion system.
- A 15th-order state equation set is derived for system dynamics.
- Real-time simulation details the mass (rates), pressure, temperature, energy flow.
- Experimental platform constructed and model accuracy validation (error within 5–7%).
- Motor specification, controller designs and vehicle integration in the near future.

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ABSTRACT

This paper develops a real-time automotive air propulsion system for light-duty vehicles. This system consists of a high-pressure air tank, an electric-controlled throttle valve, and a vane-type air motor. The isentropic-nozzle element and control volume concepts were introduced with their governing equations. The tank and throttle valve were modeled as a second-order control volume and nozzle element, respectively. The air motor consisted of four control volumes (12th-order pneumatic dynamics), first-order mechanical dynamics, and a nozzle element as the exhaust port. A 15th-order nonlinear state equation set was derived by integrating these three subsystems. The controlled throttle angle and sequential switch between intake and exhaust processes for the motor chambers allow the whole system to operate properly. A Matlab/Simulink-based simulator was then used for a real-time simulation. Four throttle angles (30°, 50°, 70°, and 90°) were used to show that the derived model is feasible and physically rational. Key variables such as the mass flow rate, temperature, pressure, energy, and mechanical dynamics were investigated in detail for all subsystems. An experimental platform of a 1 kW air motor was constructed for model validation. The average experiment/simulation torque error and air flow rate error were 6.15% and 5.34%, respectively. It proves the high accuracy of the model. Future studies with this real-time model should investigate motor specification design, controller design (by hardware-in-the-loop platform), and integration with a light-duty vehicle simulator.

1. Introduction

Because of increasing environmental concerns and stringent laws, green energy and advanced power sources (powertrains) have attracted public attention. Several industrial applications, such as power stations, transportations, and consumer electronics products, are gradually beginning to use several types of green energy, such as solar energy, wind power, hydrogen fuel, and other renewable resources [1]. Various innovative and patented designs have been proposed as power sources, especially for automotive powertrains. High-efficiency, low (or zero) pollutants, and outstanding performance are the most desirable power source features. Hybridized powertrains, biofuel engines, and high-power motors or generators are promising future propulsion devices [2,3]. The air-driven powertrain is a novel system that transforms pneumatic energy into mechanical power.

Air-driven systems produce no pollutants and do not require fossil fuels. Hybrid system engines consume fuel and generate waste heat, vibration, and noise. The high cost and low energy density of battery modules inhibits the mass production of battery electric vehicles (EVs) [4]. The hydrogen fuel cell power module is a potential clean energy source that can be used in EVs. Although the cruising speed of EVs approaches that of fossil fuel-powered vehicles, certain inherent fuel cell weaknesses limit the marketing of fuel cell EVs. These include complex configuration, costly power modules, and immature hydrogen supply facilities [5]. Hence, the

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Nomenclature

A	cross-sectional area, m^2
a	switch of the intake process
B	damping coefficient, N s/rad
b	switch on/off of the exhaust process
D	diameter of the intake manifold, m
d	diameter of the throttle valve rod, m
E	energy, J
s	thickness of the motor, m
J	rotational inertia, kg m^2
m	mass, kg
V	volume, m^3
T	temperature, K
C_V	specific heat at constant volume, J/kg K
C_p	specific heat at constant pressure, J/kg K
C_d	discharge coefficient
R	ideal gas constant, J/kg K
R_1	radius of the motor rotor, m
R_2	radius of the motor stator, m
L	length from the rotor center to the stator wall, m
P	pressure, Pa
P_r	pressure ratio
θ	rotation angle, rad
α	throttle angle, rad
γ	specific heat ratio
τ	torque, N m

Subscripts

am	air motor
d	downstream
exh	exhaust
exp	experiment
i	ith chamber in the motor
ld	load
sim	simulation
tk	tank
th	throttle
u	upstream

air propulsion system is a good candidate for vehicular use. Certain international automotive manufacturers have begun to establish prototype air-driven vehicles for short-distance cruising using a patented air engine system [6].

Air motors are appropriate for implementing pneumatic power in light-duty vehicles such as bicycles and scooters because of mature technology and low costs. The advantages of a vane-type motor compared to other zero-pollutant power electric motors include the following [7]:

(1) High power density: the powertrain is light and occupies less space.
(2) Resistance to humidity, vibration, high temperature, and harmful surroundings (dirt and rain): the powertrain is highly reliable to ensure driving safety.
(3) Simple configuration and common: good maintenance and mature technologies accelerate the marketing schedule.
(4) Comparatively high rotational speed (wide-range operation): the reduction ratio and number of transmission gears can be reduced.

System modeling is required to efficiently design the configuration and to investigate the inner phenomenon of the air motor. Control strategies and controller designs can enhance motor performance to meet scenario requirements. The following section describes the relevant air motor (actuator) literature.

Padian et al. [7] modeled a control-oriented van-type air motor. Simple air pressure dynamics and mechanical dynamics were established. However, the study did not address the variation of key variables and geometric shaft angle relationships in detail. Most of the published literature has focused on scroll-type air motors because such pneumatic actuators offer higher performance than hydraulic and electrical motors. Chen et al. [8,9] modeled scroll compressors and developed the inner geometric relationships of the chamber volumes at various operation modes. The study derived nonlinear differential equations by using lumped-parameter flow dynamics. Orbiting-angle dynamics were thus investigated. Similarly, Wang et al. [10,11] proposed a mathematical modeling study of scroll air motors. Wang et al. [10] first derived the spiral equations, chamber volume calculation, and driving torque. Wang et al. [11] conducted dynamic process modeling and an energy efficiency calculation. Dov and Salcudean [12] built a pneumatic actuator model based on adiabatic process and perfect gas assumptions. The study mainly stressed the mass flow dynamics between valves and cylinders. Compared to [7] and [12], this study fully constructs the nonlinear dynamics of flow and mechanical components with respect to geometric variation.

To achieve motor or actuator control, Dov and Salcudean [12] used a frequency-domain feedback compensator to enhance system performance after deriving the plant transfer function. An experimental assessment was then conducted to verify the close-loop control or plant system. Takemura et al. [13] proposed a hybrid pneumatic-electric motor. A small electric motor was used with vane-type air motors. A simple second-order dynamic model of the rotational angle was used to implement sliding mode control and trajectory control. Experimental results showed that the motor and control were effective. Wang et al. [14] developed position control of servo pneumatic actuator systems. A PID controller was designed for accurate position control, and the experimental system conducted transient behavior.

Using pneumatic power as a vehicle power source has attracted attention in the last 5 years. Huang et al. [15] developed a hybrid pneumatic-power system for optimizing the thermal efficiency of the powertrain. The engine drives the compressor to propel the air motor at a fixed operation point at high efficiency. Waste engine heat is also sent to drive the air motor. A simple model simulation showed that overall system efficiency increased by 20%. Huang et al. [16] integrated the concept described in [15] with vehicles in standard test modes. Experimental verification and analysis showed that system efficiency improved by recycling waste engine energy to compensate for the weaknesses of pneumatic power. Huang et al. [17] mathematically analyzed the innovative hybrid pneumatic power system mentioned in [15,16]. Constructing performance maps of the engine (BSFC contour) and air motor (torque–speed curves) increased vehicle efficiency from 15% to 33%. Fazeli et al. [18] proposed a novel compression strategy for air hybrid engines to enhance regenerative braking efficiency and energy storage capacity. Experiments showed that energy storage capacity during the regenerative braking process improved by 125%.

Shen and Hwang [19] developed an air-powered motorcycle. A motorcycle was equipped with a vane-type air motor, air tank, and other accessories. A fuzzy logic PI control scheme was designed to manage the dead zone and hysteretic behavior and to enhance