Applied Energy 92 (2012) 492–502

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Design and optimization of an Atkinson cycle engine with the Artificial Neural Network Method

Jinxing Zhao, Min Xu *, Mian Li, Bin Wang, Shuangzhai Liu

National Engineering Laboratory for the Automotive Electronic Control Technology, Shanghai Jiao Tong University, 800 Dongchuan Rd., Shanghai 200240, China

ARTICLE INFO

Article history:
Received 24 February 2011
Received in revised form 18 October 2011
Accepted 23 November 2011
Available online 21 December 2011

Keywords:
Atkinson cycle
Fuel economy
ANN
LIVC
Optimization
Hybrid vehicle

ABSTRACT

The Atkinson cycle engines have larger expansion ratio, thus higher thermal efficiency, which are more suitable for the hybrid fuel-electric vehicles than the conventional Otto cycle engines. Larger expansion ratio in an Atkinson cycle engine can be realized by increasing the geometrical compression ratio. Late Intake Valve Closure (LIVC) strategy is adopted to reduce the effective compression ratio to avoid the knock. However, the LIVC operation would reduce the effective displacement of the engine hence decrease the power density. There is a tradeoff between the thermal efficiency and Widely Open Throttling (WOT) torque/power. Computation-efficient nonlinear models for the baseline engine were built based on the Artificial Neural Network (ANN) technique. The ANN models were trained and tested using the data computed by a precisely calibrated GT-Power engine simulation model. Interactive effects of the LIVC, geometrical compression ratio, spark timing and air-to-fuel ratio on the fuel economy, WOT torque, knock intensity and exhaust temperature were deeply investigated. Optimization of the geometrical compression ratio and operating parameters was conducted based on the optimum ANN models. The optimization objective is to maximize the fuel economy, under the restriction conditions of WOT torque reduction percentage, knock intensity, and exhaust temperature. The optimum geometrical compression ratio was finally determined as 12.5. Experimental results obtained from the actual engine tests have validated the excellent prediction accuracy of the ANN models. Significant fuel economy improvement, of 6–13% at most WOT operating conditions, is obtained for the Atkinson cycle engine with acceptable compromise in the WOT torque.

1. Introduction

Due to mass production of the hybrid vehicles, the Atkinson cycle engines [1] have been given more and more attention nowadays. The first Atkinson cycle engine was invented in 1882 named after its inventor, James Atkinson [1]. Comparing to the traditional Otto cycle engines, the Atkinson cycle engines can realize larger expansion ratio, which lead to higher thermal efficiency [2–9]. The first Atkinson cycle engine utilized a complex linkage mechanism to separate the compression and expansion stroke. This technique realized larger expansion ratio than the conventional Otto cycle engines while maintaining comparative compression ratio. However, this complex linkage mechanism was impractical for mass production in the automotive industry. Refs. [2–4] report a type of Otto–Atkinson cycle engines. The Otto–Atkinson cycle engines operate on the Otto cycle at full load, for good power density, and on the Atkinson cycle at part loads, for reduced fuel consumption. However, these engines need a variable clearance volume design (i.e., variable compression ratio), whose response is slower than required and expensive for mass production.

Recently, the realization of the Atkinson cycle engines becomes much easier due to the application of Variable Valve Timing (VVT) devices. The electric control VVT devices can easily perform the Late Intake Valve Closure (LIVC) operation [3–5,7–11] to reduce the effective compression ratio (ECR) to avoid the knock due to the larger geometrical compression ratio (GCR). In this way, a modern Atkinson cycle engine can realize larger expansion ratio to enhance the thermal efficiency level. Ref. [7] investigates into the effects of different expansion ratio and different compression ratio on the thermal efficiency of a single cylinder SI engine. Its experimental results indicate that, the effect of the expansion ratio on the thermal efficiency is as 10 times as that of the compression ratio and the thermal efficiency can be increased up to 13% with the increase in the expansion ratio from 11 to 23.9. Ref. [8] reports that the thermal efficiency can be improved by 3% through enhancing the expansion ratio from 11.5 to 15.

However, the LIVC operation would reduce the effective displacement, thus decrease the power density of the Atkinson cycle engines [1,5,10,11]. When used in the hybrid fuel-electric vehicles, the electric motor can provide part of power at full load work

* Corresponding author. Tel.: +86 21 3420 6670.
E-mail address: mxu@sjtu.edu.cn (M. Xu).

0306-2619/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2011.11.060

Nomenclature

LIVC	Late Intake Valve Closure	BSFC	brake specific fuel consumption
WOT	Widely Open Throttling	ABDC	after bottom dead center
GCR	geometrical compression ratio	BTDC	before top dead center
VVT	Variable Valve Timing	ATDC	after top dead center
ECR	effective compression ratio	IVO	Intake Valve Opening
MBD	model based development	TWC	three-way catalyst convertor
KI	knock intensity	MLP	multi layer perception
ANN	Artificial Neural Network	BP	back propagation
CA	Crank Angle	Temp	exhaust temperature
HRR	heat release rate	SA	spark angle
P–V	pressure–volume	N	engine speed
AFR	Air-to-Fuel Ratio	IVC	intake valve closure
EVO	Exhaust Valve Opening	TDC	top dead center
EMS	engine management system	MPI	multi-point injection

conditions thus compensating the reduced engine power. In this regard, the Atkinson cycle engines are usually used as the preferred power source of the hybrid vehicles considering that the engines often run in the middle to high load range and run at full load is only intermittent [1]. For example, Toyota Prius hybrid vehicle implements an Atkinson cycle engine with the GCR of 13 by using the VVT-i devices [5]. About 8.5% improvement on the fuel economy is reported.

As for the design and optimization of the traditional engines, calibration of the operating parameters of the engine management system (EMS) was often separated from the engine geometrical configuration design. Usually, the engine geometrical parameters, such as the intake runner length, are determined based on simulation results and/or designers' experiences. After the prototype engine is set up with those pre-determined geometrical parameters, experimental calibration of the operating parameters will be conducted. Because the operating parameters for the conventional engines are only a few, the experimental calibration is easy to perform. The engine design objectives are first achieved through the best practice engine design, then further optimized and fine-tuned by EMS control parameter calibration. However, more and more advanced actuators, such as the VVT devices, have been used in the modern engines to increase the degree of freedom of the engine controls. A large number of design and operating parameters have to be optimized to extract the potential benefits of these advanced actuators. If the design targets could not be achieved, designers have to redesign and modify the geometrical configurations and then recalibrate the operating parameters. This procedure will repeat until the design targets are achieved. To the largest extent, this is a process of trial-and-errors, which possibly leads to significant requirement of resources and time. This is because an automobile engine is a highly nonlinear system where the geometrical configurations and operating parameters strongly interacts together to affect fuel economy and performance. Using the Atkinson cycle engine in our work as an example, a too large geometrical compression ratio calls for a more LIVC operation and more delay of the spark timing, which will decrease the WOT torque significantly and contrarily damage the fuel economy benefits of the Atkinson cycle engine. The more LIVC operation, the less air trapped in the cylinder, hence more reduction of WOT torque will be declared. Moreover, the more LIVC operation also allows more advanced spark timing to improve the thermal efficiency. On the contrary, the less LIVC operation, the more spark timing delay will be required to avoid the knock, leading to the degradation of fuel economy. The effects of Exhaust Valve Opening (EVO) timing and Air-to-Fuel Ratio (AFR) on the knock tendency, fuel economy, and WOT torque are also of importance. Therefore, in the design process of the Atkinson cycle engines, those operating parameters, such as spark timing and LIVC, must be optimized together with the geometrical configurations (e.g., GCR) to maximize the fuel economy improvement while maintaining enough WOT torque. The tradeoffs between performance and fuel economy are necessary.

Using model based development (MBD) methods [12,13], we could determine the engine geometrical configurations while initially optimizing the operating parameters. Those optimized operating parameters can be calibrated in physical experiments thereafter. The following advantages could be achieved by applying the MBD methods: (a) significant amount of resources can be saved; (b) the interactions between design parameters and operating parameters can be studied clearly; (c) multi-variable, multi-objective optimization could be conveniently conducted.

The computation of the generally used engine simulation software, such as the GT-Power in this study, is often time consuming, especially when the quasi-3D two-zone combustion model SITurb and the knock intensity (KI) model [14] is adopted. Directly using the GT-Power model to predict the engine performances in an optimization scheme will make the precise optimization of the design and operating parameters time-consuming and inefficient. Therefore, we address a computation efficient surrogate model of the GT-Power model to investigate on the multi-variable interrelations and interactions, and conduct the optimizations. In this study, we use the Artificial Neural Network (ANN) technique to establish the computation efficient surrogate models of the GT-Power [15,16].

The artificial neural network is essentially a mathematical model of the human brain neural network aimed at imitating the learning and memory instinct of the human brain. The ANN is in numerical and nonlinear nature and can learn the complex nonlinear input–output relations implied in a set of experimental or simulation data of the highly nonlinear engine systems. Large amount of researches on applying ANN models in the development of engines have been reported [15–31]. Wu et al. used the ANN as the surrogate models of the high-fidelity simulation model to optimize the cam phasing to maximize the torque output [15] and to improve the fuel consumption and reduce the NO_x emission [16], respectively. Refs. [17–19] trained the ANN models with some experimental data and used the resulted ANN models to optimize the engine operating parameters to reduce the emissions. Generally, collecting all experimental data at every engine operating point is time consuming and expensive. Thus, the ANN can be trained with only a little experimental data at typical engine operating conditions to predict the engine performances at all operating conditions [20–22]. The ANNs have also been applied as