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Performance analysis of a Miller cycle engine by an indirect analysis method with sparking and knock in consideration

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ABSTRACT

In this paper, a full-factorial design of experiment was applied to thoroughly investigate the effects of compression ratio, intake valve closing retardation angle, and engine speed on the fuel consumption performance and power performance of the Miller cycle engine based on a quasi-dimensional simulation model. A new indirect analysis method based on formula derivation and main effect analysis was proposed to simplify the complex relationship between the design factors and the performance parameters. The definition of effective compression ratio was modified to take account of the actual mass of mixture trapped in the cylinder. The results show that the distributions of brake mean effective pressure and brake specific fuel consumption can be regarded as the re-organization results from the distributions of volumetric efficiency and indicated efficiency. The intake valve closing retardation angle has a strong negative correlation with volumetric efficiency. The modified effective compression ratio is the approximate product of the compression ratio and the volumetric efficiency, and makes obvious effects on the distribution of the indicated efficiency. Therefore the combustion process is co-evolved with the intake process in a Miller cycle engine. The further improvement of brake specific fuel consumption is mainly limited by four factors, i.e., the back flow loss, the exergy loss, the incomplete expansion loss, and the combustion loss. The improvement of fuel consumption performance is at a cost of power performance, and the trade-off between the both essentially results from the knock constraint. The engine speed makes obviously effects on both volumetric efficiency and indicated efficiency, resulting in increasing the nonlinearity of the variation of the performance parameters. However, the nonlinearity provides a possibility for a Miller cycle range extender to improve the fuel consumption performance and power performance at same time by optimizing the controlled speed.

1. Introduction

With the growth of population and the development of industry, the demand for energy in the transportation sector increases rapidly. The fossil fuel was overused in recent decades, resulting in anthropogenic greenhouse gas emission and air pollution. Accordingly, the related regulations have been introduced to limit the CO_2 emission. In Europe, according to the new amendment (Regulation EC No. 333/2014) [1] released in the year 2014, by the year 2021, the target for the fleet average CO_2 emission of all the new cars is set as 95 grams per kilometer, which is a big challenge for OEMs. One of the available strategies to meet the strict emission regulations of CO_2 is the gradual electrification of the vehicle [2]. However, at present, due to the capabilities of battery, the overall range of Electric Vehicle (EV) is limited compared to an equivalent gasoline or diesel fuelled [3]. Thereby, the Hybrid Electric Vehicle (HEV) is a good solution for the aforementioned limitation.

The efficiency of engine makes significant effects on the fuel economy of HEV, especially for the series HEV [4]. As a result, Miller cycle was adopted to improve the efficiency of range extender. The design concept of the Miller cycle was proposed by Ralph Miller [5]. As compared with the Otto cycle, the Miller cycle achieves higher efficiency due to the longer expansion stroke [6]. The longer expansion stroke is realized by enlarging the (geometrical) compression ratio; meanwhile, the late Intake Valve Closing (IVC) strategy is employed to reduce the effective compression ratio in order to avoid knock [7]. A study by Ribau et al. [2] showed that the series HEV equipped with the Miller cycle engine was the most efficient option during the charge sustaining operation and in global annual combined cycle due to the higher efficiency of the Miller cycle engine in comparison with the HEVs equipped with Wankel engine and microturbine.

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Nomenclature

M_e	entrained mass into the flame front
ρ_u	unburned mixture density
A_e	flame surface area
S_T	turbulent flame speed
S_L	laminar flame speed
M_b	burned mass
τ	characteristic burning time
λ	Taylor microscale of turbulence
α	temperature exponent
β	pressure exponent
ϕ	equivalence ratio
I	induction time integral
τ_k	instantaneous induction time
η_{it}	indicated efficiency
η_{et}	effective efficiency
η_v	volumetric efficiency

Acronyms

BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CR	compression ratio
DOE	Design of Experiment
ECR	Effective Compression Ratio
FMEP	Friction Mean Effective Pressure
IMEP	Indicated Mean Effective Pressure
IVC	Intake Valve Closing
IVO	Intake Valve Open
KITI	Knock Induction Time Integral
MBT	Maximum Brake Torque
SA	Sparking Angle

The definition of the design factors is an important step in the development of new Miller cycle engine, thereby, it is necessary to investigate the effects of design factors on the Miller cycle engine performance. Al-Sarkhi et al. [8] derived the relations between the thermal efficiency, the compression ratio and the expansion ratio for an air-standard Miller cycle based on finite time thermodynamics. Wang and Hou [9] investigated the performance of the Miller cycle at the maximum power condition and the maximum power density condition. Hou [10] investigated the performance of the Miller cycle with heat transfer in consideration.

A number of valuable researches based on the finite time thermodynamics model were performed to investigate the Miller cycle performance. However, the conclusion drawn from the previous studies cannot effectively guide the design of practical engine due to the wide gap between the finite time thermodynamics model and the practical engine. Thereby, further investigation needs performing based on advanced combustion model (i.e. zero-dimensional, quasi-dimensional, and multi-dimensional model).

When the adopted combustion model shifts from thermodynamics model to advanced combustion model, the investigated object transforms from a white system to a grey one. Therefore, the statistical Design of Experiment (DOE) was applied in this investigation to capture the behavior of a physical system instead of an analytic method. When the DOE is applied, the simulation model is required to respond to the variations in the control factors. In addition, the statistic analysis re-builds the engine's characteristic based on a large number of simulation cases. Accordingly, the computational demand of the simulation model should be taken in account [11]. The quasi-dimensional model, which is developed to bridge the gap between zero- and multi-dimensional model [12], is a desirable option for reasonably fast and accurate predictive simulations [11].

In this work, a full-factorial DOE was implemented based on a quasi-dimensional model. The DOE thoroughly investigates the variation trends of Miller cycle engine performance with the variation of the key design factors (i.e. compression ratio, IVC retardation angle, and controlled engine speed), and finds out the factors limiting the further improvement of the engine performance. At each test point on the DOE matrix, the SA was optimized based on multi-island genetic algorithm to obtain locally optimum performance. As the spark ignition engine obtains optimum performance in the critical knock state, a phenomenological knock model was adopted in this paper to take the knock constraint in account.

As well known, there is a nonlinear relationship between design factors and performance parameters, resulting in more difficulties in analyzing the effects of design factors on the engine performance. Accordingly, a new indirect analysis method was proposed in this paper, and it transformed the complex relationship between the both into two simple relationships based on formula derivation and main effect analysis. The details on the indirect analysis method were discussed in Section 4.

2. Modeling

The 1-D simulation model was established in the GT-POWER code environment developed by Gamma Technologies Inc. [13] to calculate the engine performance characteristics, e.g., volumetric efficiency, indicated efficiency, Indicated Mean Effective Pressure (IMEP), Brake Mean Effective Pressure (BMEP), Brake Specific Fuel Consumption (BSFC), brake power, and brake torque. The main equations related to combustion model and knock model are listed in Table 1.

A quasi-dimensional combustion model was applied as the combustion model in this work. The quasi-dimensional combustion model is a predict combustion model, and it means that the burn rate is calculated based on an empirical flame model instead of an experimentally fitted Wiebe function [11]. As a result, this combustion model can take the combustion chamber geometry and several flow-field parameters (e.g., spark timing, compression ratio, and air fuel ratio) in account [12].

The burn rate submodel proposed by Morel et al. [14] was adopted in this work. The mass entrainment rate and the burn rate are governed by Eqs. (1)–(7). For typical gasoline, the temperature exponent α and pressure exponent β can be written by Eqs. (8) and (9) [15]. The simplified k–ε turbulence submodel and the flame front propagation submodel were applied to close the aforementioned equations, and the details are explained in Ref. [14].

As well known, the spark ignition engine obtains optimum performance in the critical knock state. Although a number of studies have been performed to optimize the performance of the Miller cycle engine, limited studies have taken the knock in account to prove that such optimization is reasonable. Thereby, the predictive knock model is necessarily adopted in the simulation model. Even though no complete fundamental theory explains the knock phenomenon over the full range of operating conditions, it is generally agreed that knock is caused by auto-ignition in the end-gas region [16]. Livengood and Wu [17] proposed empirical induction-time correlation (Eq. (10)) to describe the auto-ignition delay time,