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Comparison of in-cylinder combustion and heat-work conversion processes of vehicle engine under transient and steady-state conditions

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ABSTRACT

To improve the actual performance of internal combustion engine (ICE), the transient behaviors of in-cylinder combustion and heat-work conversion processes of ICE were investigated and an optimization method was proposed. Based on an advanced turbocharged gasoline direct injection (TGDI) engine, the steady-state bench test, load-step test at constant-speed and vehicle road test were carried out. On this basis, the in-cylinder combustion and heat-work conversion processes of vehicle engine under load-step and vehicle driving conditions were compared with the steady-state results. By this means, the deviations of ICE transient performance from their steady-state values were demonstrated and also their impacts were revealed. The research results show that there is a satisfactory consistency of ICE performance especially the ignition advance angle under load-step and steady-state conditions. However, under vehicle driving conditions, the operating and control parameters gravely deviate from the steady-state values with large fluctuations, e.g., ignition advance angle is retarded largely under the sharp deceleration conditions. When the IMEP is below 4 bar, the ignition advance angle seriously deviates from the steady-state values, which results in large fluctuation of combustion characteristic parameters and finally leads to the decrease of heat-work conversion efficiency. Moreover, the fluctuation of excess air coefficient is one of the main reasons for the instability of ICE transient performance. To accurately control the ignition timing under low load and decrease the fluctuation of excess air coefficient is an effective way to improve the ICE performance under vehicle driving conditions.

1. Introduction

Along with rapid socio-economic development and the constant advance of industrialization, countries around the world are facing two major challenges of energy crisis and environmental pollution [1–4]. In terms of transportation industry, it requests the vehicle to continuously increase fuel efficiency and reduce pollution emission. In order to meet the increasingly rigorous emission and fuel consumption regulations, various kinds of advanced technologies (such as GDI, VVT, EGR) [5–7] and new combustion concepts (HCCI, RCCI) [8,9] for ICE were proposed and studied in recent decades. Although the previous studies showed that ICE fuel efficiency can be effectively improved by using these advanced technologies, it is difficult to ensure the improvement of vehicle actual fuel efficiency. This is because in most cases the vehicle operates under transient conditions rather than steady-state conditions, and the transient behaviors of ICE are usually different from its steady-state performance. In other words, the steady-state performance of ICE tested on bench cannot represent its actual level under vehicle driving conditions. Therefore, only by improving the working performance especially the thermal efficiency of ICE under transient conditions, can it ensure the vehicle has satisfactory actual fuel efficiency.

Under vehicle driving conditions such as FTP-75 cycle, in most of the time ICE operates under transient conditions. The random fluctuation of intake and exhaust pressures due to the sharp change of vehicle operating conditions causes the variation of ICE gas exchange performance from cycle to cycle, including in-cylinder trapped intake mass, air-fuel ratio (AFR), residual gas fraction (RGF), etc., and also the changes of speed and load make it difficult to accurately control the ignition timing. Finally, the operating parameters of ICE deviate from the desired values (steady-state calibration values), and the in-cylinder combustion processes are more unstable with large cyclic variations and

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Nomenclature

V_h	cylinder displacement [m^3]
p	pressure [Pa]
η_{HP}	high-pressure cycle efficiency [–]
H_u	low heating value [J/kg]
m_{fue}	fuel-injection quantity [kg]

Abbreviation

ICE	internal combustion engine
TGDI	turbocharged gasoline direct injection
IMEP	indicated mean effective pressure
GDI	gasoline direct injection
VVT	variable valve timing
EGR	exhaust gas recirculation
HCCI	homogeneous charge compression ignition
RCCI	reactivity controlled compression ignition
AFR	air-fuel ratio
RGF	residual gas fraction
ECU	electronic control unit
TDC	top dead center

combustion instabilities [10–12]. For these reasons, the actual ICE performance under transient conditions is usually worse than the steady-state level [13]. Since the ICE performance is directly determined by the in-cylinder combustion and heat-work conversion processes, it is significant to study the internal relations and effects of in-cylinder combustion processes under transient conditions for improving the actual performance of ICE [14].

At present, the performance development, optimization and calibration for ICE operating and control parameters, are usually conducted by steady-state bench test. However, in most cases the vehicle engine operates under transient conditions, thus there comes a gap between ICE actual behaviors under vehicle driving conditions and steady-state performance under bench test. In other words, ICE transient performance determines its actual behaviors including power, fuel economy and emissions [15,16]. For the purpose of improving ICE transient performance, many scholars have made unremitting efforts for decades [17–22]. Giakoumis and Alafouzos [23] studied the diesel engine performance and emissions during a transient cycle applying a developed engine mapping-based methodology, and demonstrated the advantages of the proposed methodology. Berglund et al. [24] presented an engine model for using in computer simulation of transient behavior in drivetrain and vehicle systems, and concluded that this model might be a useful tool for heavy vehicle drivetrain simulation. Rackmil et al. [25] followed the same approach for load and speed increase transients and also applied a correction coefficient to account for transient discrepancies based on an earlier phenomenological simulation code. Galindo et al. [26] designed an exhaust manifold to improve transient performance of a high-speed turbocharged diesel engine. Their simulation results showed that exist a potential not only to improve engine transient performance at low engine speeds but also the gas temperature at the catalyst inlet and the steady-state effective torque. Emiliano et al. [27] studied the spark ignition feedback control by means of combustion phase indicators in steady and transient operations, and proved that the combustion phase indicators are suitable for proportional-integral feedback spark advance control, allowing fast and reliable control even in transient operations. Zhang et al. [28] studied the combustion deterioration of an automotive diesel engine under transient operation. Their research results indicated that the notable combustion deterioration was relative to steady-state operation while transient was a function of the delay in the air-supply to the turbocharged engine. Giakoumis and Lioutas [29] developed an engine mapping-based methodology to gain a first approximation of a vehicle's performance and emissions during a light-duty cycle. The procedure is based on a steady-state experimental investigation of the engine with an appropriate vehicle drivetrain model applied so that the cycle vehicle speed data can be transformed into engine speed and torque.

Although lots of research was carried out on both the test and simulation of ICE transient performance, most of them focused on one or several parameters, and lots of studies were conducted under single variable transient conditions (constant-speed or constant-torque) [30,31]. As far as the authors know, none of the earlier research has ever been conducted on comprehensive test and analysis for multiple parameters of ICE under vehicle driving conditions, let alone the difference study on in-cylinder combustion and heat-work conversion processes between transient and steady-state conditions. As a result, the actual ICE performance under vehicle driving conditions and its deviation from the steady-state bench values as well as the influence factors, the evaluation for calibration strategy under transient conditions, etc., are still unknown. The aim of this paper is to fill an apparent gap mentioned above by applying the proposed optimization method for ICE transient performance [16]. To achieve this goal, the in-cylinder combustion and heat-work conversion processes of a gasoline engine under vehicle driving conditions were continuously detected. At the same time, the steady-state and load-step tests were also carried out simultaneously on the bench. On this basis, the differences of in-cylinder combustion and heat-work conversion processes under transient and steady-state conditions were analyzed in detail and the influence factors were revealed, which has provided theoretical basis and data support for the improvements of ICE calibration strategy and actual performance under vehicle driving conditions.

2. Optimization method for ICE performance under transient conditions

When the ICE is running under the actual vehicle driving conditions, usually its operating conditions are not consistent with the calibration points of steady-state bench. Under the circumstances, it is used to determine the operating parameters (such as fuel injection quantity, ignition advance angle) by interpolation calculation according to the steady-state calibration values of adjacent operating points. However, the disturbance of pressure wave from ICE intake and exhaust systems results in the fluctuation of intake mass and AFR, which always causes the interpolation results to deviate from the best level. For this reason, it is necessary to improve the original calibration method so as to make it suitable for the complex vehicle driving conditions and keep ICE transient behaviors close to the steady-state performance. To real-timely detect ICE transient operating and performance parameters is the premise for improving ICE calibration strategy under vehicle driving conditions, while to analyze the differences of tested results between transient and steady-state conditions and reveal the inducements are the basis for adjusting and optimizing ICE transient calibration strategy.

To solve the problems mentioned above, the optimization method for ICE performance under transient conditions is proposed, the workflow of which is illustrated in Fig. 1. As it can be