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Study of the impact of structural parameters on the dynamic response of an electronic fuel injector

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ABSTRACT

The study concentrates on the effects of structural parameters of an electronic fuel injector on its dynamic response (the opening delay and the closing delay). The injector was developed for a marine medium-speed diesel engine. The dynamic response from the start of the control signal to the end of the needle valve closing were investigated. Firstly, a complete and detailed model of the electronic fuel injector was built and integrated into an optimisation model, where a MOGA was applied. Secondly, the importance and effects of main structural parameters on dynamic response were examined, as were their interactions. Finally, a Pareto optimum was obtained through scattering charts and comparisons were made between the baseline design and the optimal design. Results show that the control piston diameter, fuel oil inlet passage diameter, fuel oil outlet passage diameter and their interactions are influential factors to the opening delay, while the fuel oil inlet passage diameter has the dominant effect on the closing delay. A small control piston diameter together with a small fuel oil inlet passage diameter contribute to a short opening delay, however, they lead to a significant increase in the closing delay. Moreover, a small closing delay prefers a large fuel oil inlet passage diameter. The selected Pareto optimum achieved a significant reduction in both the opening delay and the closing delay under three different rail pressures.

1. Introduction

Nowadays, the HPCR system has gained significant attention and application as one of the most promising technologies for the control of internal combustion engines. The electronic fuel injector, one of the key components of HPCR systems, is of particular interest to researchers. Many studies have already been carried out around the injector nozzle area, and on the influences of nozzle types and nozzle numbers on the internal flow and cavitation performance, for example, Molina et al. [1] investigated the inner nozzle flow and cavitation development of elliptical orifices, in that study, four nozzles with different major axis orientation and eccentricity value were compared with each other and also with the standard nozzle. Benajes et al. [2], Payri et al. [3], and Han et al. [4] focused on nozzle orifice types for electronic fuel injectors, comparisons were made between a cylindrical nozzle and a conical one. He et al. [5], Moon et al. [6] and Salvador et al. [7] studied the effects of different nozzle hole arrangements and needle lift movements on the initial flow and cavitation development inside diesel injectors. However, to date, little attention has been paid to the influence of the nozzle parameters on dynamic response, i.e. the opening delay and closing delay.

Few studies were found in the literature which considers the impact of electronic fuel injector structural parameters on the dynamic response. Salvador et al. [8] compared the influences of a standard diesel fuel and biodiesels on the dynamic behaviour of a solenoid-operated injector. A change of the fuel oil outlet passage diameter from 0.246 mm to 0.27 mm was proposed to eliminate the needle lift and injection rate deviations between the two fuels. The deviations were caused by a higher viscosity of the biodiesel fuel comparing to the regular diesel fuel. Results showed that the opening delay of the biodiesel fuel was reduced significantly under low injection pressure to match that of the standard diesel fuel. Additionally, some related studies are also worth mentioning. Wang et al. [9] investigated the influence of control valve parameters on the flow and cavitation inside the control valve. Stefano Beccari et al. [10] predicted the mass injected by a gaseous fuel solenoid injector for spark ignition engines, with special attentions paid to a gas injector and to the complex needle motion during the opening and closing phases. Cheng et al. [11] investigated the impact of drive strategies on the power losses and dynamic

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Nomenclature

1D	one dimensional
2D	two dimensional
ARMOGA	adaptive range multi-objective genetic algorithm
CPD	control piston diameter
Compact RIO	a real-time embedded industrial controller made by National Instruments
DOE	design of experiments
ECU	electronic control unit
GA	genetic algorithm
HIL	hardware in loop
HPCR	high pressure common rail
IPD	fuel oil inlet passage diameter
I/O	input/output
LABCAR	a flexible test system developed by ETAS Company
MOGA	multi-objective genetic algorithm
NSGA-II	non-dominated sorting genetic algorithm II
NZD	nozzle orifice diameter
NZN	nozzle orifice number
OPD	fuel oil outlet passage diameter
PLC	programmable logic controller
PID	proportional-integral-derivative
RSM	response surface method
SPF	spring preload force
SS-ANOVA	smoothing spline analysis of variance algorithm
μGA	micro-genetic algorithm

Functions and variables

M	objectives number
f	function
j	variable
K	a specific objective
$\vec{x}^*$	Pareto design
$\vec{x}$	arbitrary design

Units

mm	millimetre
MPa	mega Pascal
ms	millisecond
N	Newton

response of a solenoid injector. As it can be seen that these studies focused on the dynamic response of the needle motion itself rather than on the opening delay and closing delay, and also left structural parameters such as the control piston diameter, fuel oil inlet passage diameter, fuel oil outlet passage diameter and the spring preload force at the needle valve out of their scope. Salvador et al. [12] investigated the impact of fuel temperature on injection dynamics, especially during the opening stage and closing stage. The delays were considered, but the structural parameters were still not included.

In this paper, the impact of the structural parameters of an electronic fuel injector on injector dynamic response of the opening delay and closing delay are carefully investigated, and the opening delay and closing delay are the two objectives to be minimised. Firstly, a complete and detailed 1D electronic fuel injector model was built in AMESim and was validated by using injection quantity data and average steady-state mass flow rate obtained from a HIL test rig. Then, an optimisation model was built in the modeFRONTIER software, where the 1D fuel injector model was included and a MOGA was applied for optimisation. Besides the impacts of the structural parameters, the interactions of them were also studied. Scattering charts were used for selecting Pareto designs and the sensitivity of the important parameters and interactions on the delays were examined using RSM.

One-dimensional (1D) models have frequently been built and adopted in many studies to predict the performance of electronic fuel injectors. Payri et al. [13] used a 1D model of a solenoid-driven common rail ballistic injector to study the influences of the inlet fuel temperature on injection rate. Seykens et al. [14] built a 1D model of an injector to analyse the elasticity of the injector needle valve and nonlinearities caused by the impact of the needle valve when it returns to its seat. Rahim et al. [15] implemented a 1D model to study the effect of temperature on diesel engine performance. The detailed modelling of a solenoid fuel injector and a third generation piezo injector were demonstrated by Payri et al. [16] and Salvador et al. [17] respectively.

Since two objectives are involved in this study, it is naturally a multi-objective problem. GA is born for solving multi-objective problems. It is based on the idea of the natural selection which obeys the law of “survival of the fittest”. It can continually improves the average fitness level of a population by means of inheritance, mutation, selection and cross-over, eventually leading to an optimal design [18–20]. MOGA is the modified version of the classic GA which can find a set of multiple non-dominant solutions in a single run [21]. NSGA-II, one of the genetic algorithms, proposed by Deb et al. [22], was proven to have better performance of finding a diverse set of solutions and converging near the true Pareto front. Thus, in this paper, the NSGA-II algorithm is applied. The NSGA-II algorithm employs an elite-preserving strategy and an explicit diversity-preserving mechanism. According to the objectives, elitism is given to the corresponding designs. Designs with a higher elitism have priority to be selected. If two designs have the same elitism, the one with less crowding distance (proximity to other Pareto solutions) is assigned with a higher priority.

Pareto optimums are often adopted in multi-objective optimisation occasions, as shown in Fig. 1. Cases A-D can be considered as Pareto optimal cases due to the fact that none of them is outperformed by other cases. These cases can be grouped together to form a Pareto frontier [23]. The Pareto optimality can be defined as follows: for all designs and the corresponding M objectives $f_k(\vec{x})$, where, $K = 1, 2, \ldots, N$. The Pareto design $\vec{x}^*$ is defined as follows: for an arbitrary design j, there exists at least one objective, k, meets the condition $f_k(\vec{x}_j) \geqslant f_k(\vec{x}^*)$. MOGA's mission is to find the Pareto frontier while maintaining diversity in the results.

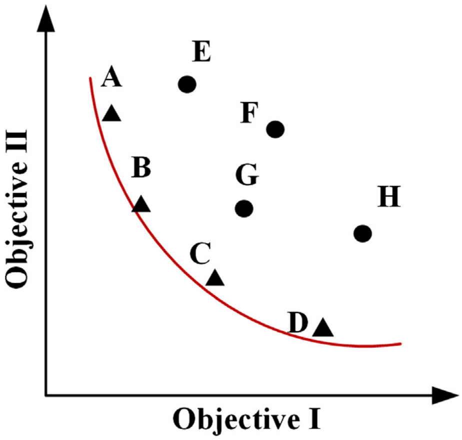

Fig. 1. Definition of Pareto optimums.