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THE EVOLUTION OF INTERNAL COMBUSTION ENGINE CONTROL SYSTEMS: A MECHATRONICS PERSPECTIVE REVIEW

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Abstract

This article discusses the evolution of engine control systems, particularly in Internal Combustion Engines (ICE), which have undergone a significant transformation from purely mechanical systems to integrated mechatronic systems. This development is driven by demands for fuel efficiency, lower emissions, and optimal performance. The research method used is a systematic literature review of recent studies in the last ten years discussing the integration of electronic components, sensors, actuators, and control units in engine management. The review results show that the mechatronic approach, embodied in systems such as Engine-by-Wire, electric Variable Valve Timing (VVT), and turbochargers assisted by electric motors, has revolutionized the precision and speed of engine control responses. The conclusion of this article affirms that the integration of mechatronics not only extends the lifespan and competitiveness of ICE in the electrification era but also serves as a crucial foundation for developing more efficient hybrid powertrains in the future

Keywords: Engine Control, Mechatronics, Engine-by-Wire, Efficiency, Internal Combustion Engine (ICE).

INTRODUCTION

The internal combustion engine (ICE) control system has been the heart of motor vehicles for over a century. Initially, this system relied entirely on mechanical components, such as carburetors and mechanical distributors, which had limitations in precision and adaptability (Heywood, J. B. 2018). However, global demands to reduce exhaust emissions and improve fuel efficiency have forced the automotive industry to innovate. In recent decades, the digital revolution and advances in electrical engineering have introduced a new approach: mechatronics.

Mechatronics, as a discipline that integrates mechanical engineering, electronics, computer engineering, and intelligent control, has become a catalyst for the evolution of engine control systems (Alciatore, D. G 2019). This integration enables more precise combustion process management, dynamic valve regulation, and smarter energy management, which are impossible to achieve with conventional mechanical systems. Modern mechatronic systems in engines consist of a network of sensors, sophisticated Electronic Control Units (ECUs), and fast, accurate actuators.

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Theoretical studies and previous research (Robert Bosch GmbH. 2014; Zhao, H.2010), illustrate this evolutionary journey, starting from purely mechanical systems like carburetors described by fluid flow equations, towards integrated electronic systems. Recent research focuses more on optimizing existing mechatronic systems, such as improving control algorithms in ECUs and integration with higher vehicle electrical systems.

Based on this background, this article aims to comprehensively review the evolution of engine control systems from a mechatronics perspective. The review will focus on the development of key technologies such as Engine-by-Wire, electric variable valve systems, and electric turbocharging, as well as analyze their impact on engine performance, efficiency, and emissions. By understanding this evolution, it is hoped to provide insight into how mechatronics not only saves ICE from obsolescence but also positions it as a strategic partner in the transition towards the electrification era, while opening opportunities for further research in intelligent control and hybrid integration.

METHODOLOGY

This research uses a systematic literature review method. This type of research is descriptive qualitative with a literature study approach. Primary literature searches were conducted on leading scientific databases such as IEEE Xplore, Science Direct, and Scopus. The main keywords used in the search include: "mechatronic engine control", "engine-by-wire", "electric VVT", "48V mild-hybrid", and "internal combustion engine evolution".

The inclusion criteria applied were: (1) articles in the form of international journals or conference proceedings; (2) published within the timeframe of 2014 to 2024 to ensure the freshness of findings; (3) explicitly discuss aspects of mechatronics, electronics, or intelligent control in internal combustion engine systems. The selection process was carried out by reviewing the title, abstract, and then the full content of the articles to ensure relevance.

The data analysis technique used was content analysis. Data and findings from the collected literature were grouped based on emerging mechatronic technology themes, such as throttle control systems, valve systems, turbochargers, and emissions. The analysis results were then described narratively to identify trends, advantages, and impacts of each technology, as well as their relationship with overall engine performance improvement.

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RESULTS AND DISCUSSION

Based on the conducted literature review, the following are the main findings regarding the evolution of engine control systems through the mechatronic approach.

The Engine-by-Wire Revolution

One of the most tangible manifestations of mechatronics is the Engine-by-Wire concept. This system eliminates the direct mechanical link between the accelerator pedal and the throttle body, replacing it with a pedal position sensor and an electric motor actuator on the throttle body (Ulsoy, A. G.2017). The ECU receives signals from the sensor and calculates the optimal throttle opening based on load conditions, engine temperature, and driver input. The result is smoother engine response, more efficient fuel consumption, and lower emissions. Similar technologies have also developed in Brake-by-Wire and Steer-by-Wire systems.

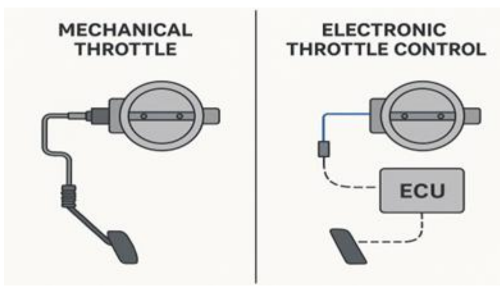

ILLUSTRATION 1. Sistem throttle mekanis (kiri) dan *electronic throttle control* (kanan)

Electric Variable Valve Timing (VVT) Systems

Conventional VVT systems use oil pressure to regulate valve timing, which is slow to respond and less precise at low engine speeds. Electric VVT systems use an electric motor (mechatronic actuator) to control valve position directly Anderson, (M. K., et al. 2017). This allows for a very wide and fast variation in valve lift and duration, significantly improving volumetric efficiency and engine power, while reducing particulate emissions.

Integration with 48-Volt Systems and Electric Turbocharging

In the context of mild-hybrids, mechatronics serves as a bridge between the internal combustion engine and the electrical system. The Motor-Generator Unit (MGU) connected to the 48-volt system can function as a starter, alternator, and power booster (boost). Furthermore, the MGU can be used to drive the turbocharger electrically (e-turbo) before the exhaust gases are strong enough to spin the turbine, thus eliminating turbo lag (Burkhard, P. L., et al.2019). The

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engine torque equation with an e-turbo can be simplified as: Te = Tice + Tmgu - Tloss. This integration demonstrates the convergence of disciplines that is the essence of mechatronics, where mechanical systems (engine, turbo), electrical systems (MGU, 48V battery), and control systems (ECU) merge to solve traditional performance problems.

Mechatronics-Based Emission Control Systems

Modern emission control systems rely entirely on a mechatronic approach. Electronically controlled Exhaust Gas Recirculation (EGR) systems are capable of regulating the flow of recirculated exhaust gas with high precision based on engine operating conditions (Guzzella, M.2010). Similarly, Selective Catalytic Reduction (SCR) systems use ECU-controlled urea injectors to spray reductant accurately, ensuring optimal NOx conversion. Latest generation NOx sensors and oxygen sensors provide real-time feedback to the ECU for continuous adjustment, which is a typical implementation of a closed-loop feedback control system.

CONCLUSION AND SUGGESTIONS

Based on the literature review conducted, it can be concluded that the integration of mechatronics has revolutionized internal combustion engine control systems. The evolution from mechanical to mechatronic systems has resulted in significant improvements in fuel efficiency, emission reduction, responsiveness, and overall engine performance. Technologies such as Engine-by-Wire, electric VVT, and electric turbocharging are clear evidence of the success of this disciplinary convergence. Mechatronics not only maintains the relevance of ICE amidst electrification pressures but actually enables its smoother and more optimal integration into future hybrid powertrains, by serving as an intelligent and precise control foundation.

The implication of this research is the need for increasingly multidisciplinary approaches in engineering education and training, covering mechanics, electronics, and programming. A limitation of this review lies in its focus on technical control aspects, whereas economic aspects, long-term reliability, and recycling of mechatronic components could be explored further. Therefore, for future research, it is suggested to conduct a more in-depth study on the role of Artificial Intelligence (AI) and the Internet of Things (IoT) in engine mechatronic control systems, as well as an analysis of the durability and reliability of complex mechatronic systems in the long

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term. Suggestions are also directed towards exploring control strategies for deeper integration between ICE and electrical systems in hybrid vehicles.

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