Research, Design, and Manufacture of a Model Frame Integrating Electronic Fuel Injection and Ignition Systems for Modern Automobiles

Vu Thi Phuong, Do Thi Khanh Hoa

***Abstract*— This paper presents the research results, design, and fabrication of a frame model integrating an electronic fuel injection and ignition system for automotive engineering education. The development of electronic engine management systems requires training equipment that allows learners to simultaneously observe the hardware structure, signal pathways, and control relationships among the ECU, sensors, and actuators. Based on an analysis of pedagogical and structural requirements, the authors selected a welded box-steel frame solution, developed a 3D model using Inventor, evaluated strength and stiffness using ANSYS R19.5, and carried out fabrication and assembly of the experimental model. The results show that the frame ensures sufficient rigidity and convenience for arranging the ECU, fuel injectors, ignition coils, sensors, and electrical circuit boards. After assembly, the model enables direct observation, measurement, and simulation of the fuel injection–ignition process in a visual manner. The model demonstrates good applicability in teaching, diagnostic practice, and research on modern gasoline engine control systems.**

***Index Terms*— Electronic fuel injection system; electronic ignition system; model frame; ECU; automotive engineering education**

I. INTRODUCTION

In recent years, gasoline engines in modern automobiles have developed significantly toward electronicization, intelligent control integration, and emission optimization. In this control architecture, the electronic control unit (ECU) receives signals from sensors such as crankshaft position, camshaft position, coolant temperature, throttle position, oxygen content in the exhaust gas, and many other operating parameters in order to determine the appropriate fuel injection quantity and ignition timing for each engine operating condition. Accurate control of these two fundamental parameters plays a decisive role in engine power, fuel economy, operational stability, and emission levels [1]–[3].

However, the increasing level of integration in engine management systems also creates significant challenges for training activities. In real vehicles, many components are arranged within a confined engine compartment, electronic signals vary rapidly and are difficult to access, while disassembly and direct measurement require specialized equipment, high cost, and strict safety requirements. As a result, learners may find it difficult to visualize the relationships between input signals, ECU processing stages, and actuator responses when studying only through theoretical materials or observing complete vehicles [2], [4].

Therefore, training models play an important role as a bridge between theory and practice. A well-designed model should not only reproduce the system structure but also allow learners to observe wiring layouts, sensor and actuator installation positions, perform signal measurements, and simulate typical engine operating conditions. Some previous studies have developed direct ignition models or individual control system models for teaching purposes, thereby confirming the effectiveness of visual training methods in the field of automotive electrical and electronic engineering [4].

Nevertheless, most existing models mainly focus on a single subsystem or are limited to electrical circuit training boards, and therefore do not fully represent the integration between electronic fuel injection and ignition systems within a complete model frame. This gap is particularly evident in requirements related to spatial arrangement, mobility, visualization level, measurement convenience, and structural rigidity when multiple device assemblies are installed simultaneously. Consequently, research on an integrated frame with a sound structural design basis and suitability for pedagogical objectives is necessary.

Based on these requirements, this paper focuses on solving two main groups of problems. The first concerns mechanical design: selecting structural solutions, materials, dimensions, and spatial layout to ensure the frame is sufficiently strong, rigid, compact, and convenient to use. The second concerns system integration: arranging the ECU, fuel injectors, ignition coils, sensors, and electrical panels so that simulation, observation, and diagnostic processes can be performed clearly, safely, and effectively.

The objective of this study is to design and fabricate a model frame integrating electronic fuel injection and ignition systems for modern gasoline engines for teaching and research purposes. The model is oriented as a practical training device that demonstrates operating principles, supports signal measurement, and enables students to directly access the structure of gasoline engine control systems.

To achieve this objective, the study investigates training requirements, selects a welded box-steel frame solution,

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develops a 3D model using Inventor software, performs strength and stiffness simulations using ANSYS, organizes fabrication and assembly, and evaluates the applicability of the completed model. The main contribution of this paper is the proposal of an integrated model frame solution with high practical and pedagogical value, suitable for current automotive engineering education conditions.

II. SCIENTIFIC BASIS FOR MODEL FRAME DESIGN

2.1. Functional Analysis and Structural Options for the Frame

In training models of engine control systems, the frame is the primary load-bearing structure used to mount the ECU, fuel injectors, ignition coils, sensors, electrical panels, and auxiliary components. In addition to its supporting function, the frame directly determines stability, safety, visibility, and convenience in practical operations. From the perspective of machine design, an effective frame structure must simultaneously ensure strength, stiffness, and the ability to maintain installation geometry under static loads as well as vibrations generated during operation [5], [6].

In terms of structural options, common frame types include box frames, truss frames, and rigid frames. Truss frames have advantages in terms of mass reduction but are complex to manufacture and difficult to arrange continuous mounting surfaces. Box frames and rigid frames offer the advantages of simple construction, ease of fabrication, convenient welding and assembly, and the ability to provide relatively flat mounting surfaces, which are suitable for training models requiring high visualization. For an integrated EFI–ignition system, a welded box-steel frame is an appropriate solution because it satisfies load-bearing requirements while facilitating the arrangement of component assemblies and electrical wiring [5], [6].

In addition to load-bearing capacity, vibration and oscillation characteristics of the frame must also be considered. When the frame stiffness is insufficient, local vibrations at cross members or joint areas may cause installation misalignment, loosen connections, and affect signal measurement quality. Studies on supporting frame structures for equipment indicate that stress distribution, deflection, and vibration characteristics should be evaluated to avoid instability or resonance during operation [7]–[9].

From the above analysis, a welded box-steel rigid frame structure was selected for the model. This solution offers relatively high stiffness, ease of fabrication using common workshop technologies, reasonable cost, and flexibility for expanding or modifying equipment layouts for teaching and research purposes.

2.2. Model Frame Design Requirements

The first requirement for the model frame is the ability to withstand the load of all equipment assemblies mounted on the structure without excessive deformation. This load includes the weight of the ECU, electrical panels, fuel injector assemblies, ignition coils, sensors, wiring, brackets, and fastening components. Therefore, the frame must be designed so that the resulting stresses remain below the allowable limits of the material, while deflection at the primary bending members does not affect installation positions or model performance [5], [8].

The second requirement is stiffness and stability during operation. Training models are frequently moved, assembled, disassembled, and observed from different positions; therefore, the frame must minimize vibration and ensure that equipment assemblies do not shift, loosen, or collide. In addition, the structure must provide an appropriate installation space that allows learners to clearly observe each element, conveniently access electrical connectors, and perform signal measurements without obstruction.

In addition to mechanical requirements, the frame must also satisfy pedagogical and operational requirements. Specifically, the structure should be compact, easy to move within the laboratory, and capable of accommodating suitable wheels or support legs. Frame surfaces and edges must ensure user safety, and component assemblies should be easy to disassemble, replace, and maintain. These criteria are important to ensure that the model not only meets technical requirements but also has long-term applicability in training.

2.3. Model Frame Design

Based on the identified requirements, the material selected for the frame is 40×40×1.2 mm box steel. This material offers advantages in load-bearing capacity, relatively high stiffness, ease of cutting and welding, good machinability, and cost suitability for practical training models. The frame was designed using Inventor software to determine overall dimensions, load-bearing member arrangement, electrical panel installation positions, and locations of system component assemblies.

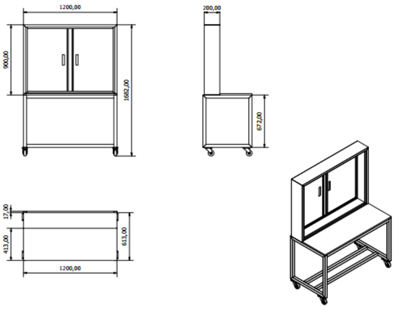
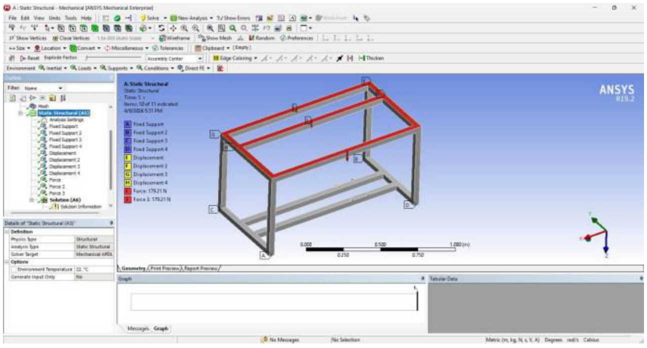


Figure 1. Detailed drawing of the model frame

After completing the geometric model, ANSYS R19.5 was used to simulate the structure under static working conditions. The evaluation procedure included determining the loads acting on the frame, analyzing the equivalent stress distribution, calculating deflection, and verifying the structural strength condition. This approach enables rapid assessment of the feasibility of the design solution before actual fabrication.



Details of "Static Structural (A5)"

Definition

Physics Type: Structural

Analysis Type: Static Structural

Solver Target: Mechanical APDL

Options

Environment Temperature: 22. °C

Generate Input Only: No

Figure 2. Representation of loads acting on the frame

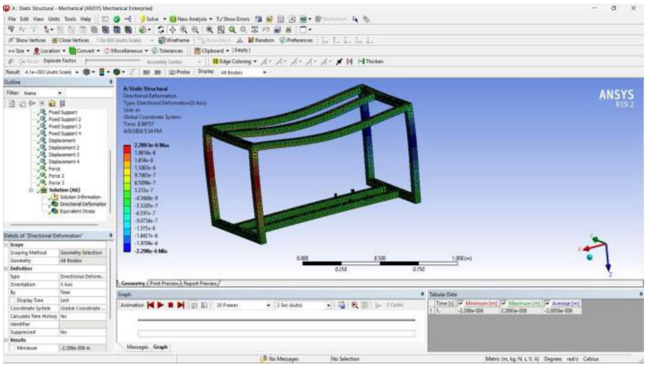


Figure 3. Equivalent stress distribution on the frame

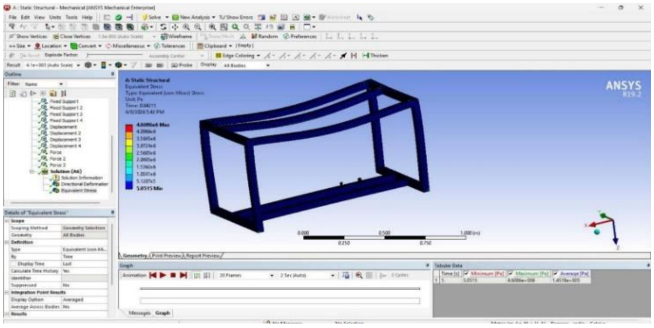


Figure 4. Deflection distribution of the frame

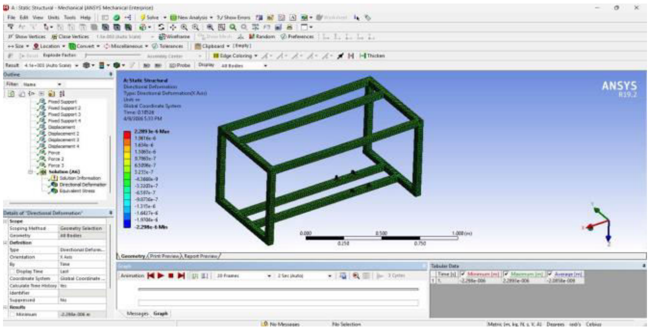


Figure 5. Strength verification results of the model frame

Load determination

The loads in the model were determined from the masses of the equipment assemblies mounted on the frame and their actual installation positions. In the simulation, these loads were converted into forces applied at the corresponding supporting regions of the frame, while also considering the boundary conditions at the frame supports. Correct identification of load locations and directions provides a realistic representation of the structural working condition.

Stress analysis

Simulation results indicate that equivalent stress is mainly concentrated in geometric transition regions, joints, and load-bearing connection areas. This distribution pattern is consistent with the working characteristics of welded steel frames, in which intersections between vertical members, horizontal members, and supports are typically locations prone to stress concentration. Identifying unfavorable stress regions provides a basis for reinforcing the structure or adjusting equipment layout when necessary.

Deflection analysis

Frame deflection reflects the level of geometric deformation under working loads. Simulation results show that the maximum deflection occurs primarily at the spans of horizontal members and directly loaded regions; however, the deformation distribution is generally continuous, with no indication of local instability. This demonstrates that the structural design adequately satisfies stiffness requirements for the training model.

Strength verification

Based on the stress and deflection results, the model frame satisfies the strength requirements under the considered loading conditions. The small deformation magnitude, reasonable stress distribution, and absence of critical failure-prone regions indicate that the proposed design can be implemented for fabrication. These results also confirm that the selection of welded box steel for the model is appropriate from both technical and economic perspectives.

III. FABRICATION AND ASSEMBLY OF THE MODEL

3.1. Frame fabrication

Based on the selected design solution, the frame manufacturing process was carried out through the stages of material cutting, positioning, welding, surface cleaning, and protective coating. Each stage directly affects geometric accuracy, joint strength, and the aesthetic quality of the model; therefore, the fabrication process was organized in a logical sequence with controlled tolerances.

The box steel material was cut according to the designed dimensions using a table cutting machine in order to ensure member length accuracy, cross-sectional perpendicularity, and uniformity among components. After cutting, the bar ends were cleaned to remove burrs, inspected for dimensional accuracy, and arranged into component groups to facilitate assembly positioning and frame welding.

After preparation, the components were positioned on the assembly surface and joined using the arc welding method. During this stage, controlling parallelism, perpendicularity, and welding sequence plays an important role in minimizing thermal deformation and ensuring the overall geometry of the frame. After welding, the joints were visually inspected to eliminate surface defects and ensure sufficient connection strength before proceeding to the finishing stage.

Figure 6. Welding of the model frame

After welding, the frame was ground to remove excess weld material, sharp edges, and surface areas that could negatively affect operation during use. This process not only improves safety during practical training but also enhances surface flatness, smoothness, and the overall aesthetic quality of the model.

Finally, the frame was coated with protective paint to improve corrosion resistance, extend structural service life, and create a visually clear appearance for the model. The paint layer also helps standardize color, allowing clear distinction between the mechanical frame and the electrical–electronic components mounted on it.

Figure 7. Frame after finishing paint

The fabrication results show that the model frame achieves the required assembly accuracy, ensures sufficient stiffness, and is suitable for equipment arrangement requirements. This serves as an important foundation for implementing the integration of the electronic fuel injection and ignition systems into a complete training model.

3.2. Model installation and completion

After completing the frame, the model's equipment assemblies were arranged according to the principles of clear observation, convenient operation, and rational signal routing. The ECU was installed in a central position to shorten wiring length and facilitate connection inspection; the fuel injectors, ignition coils, sensors, and electrical panels were arranged according to functional groups in order to clearly demonstrate the relationship between input elements, processing stages, and actuators.

The electrical wiring system was connected, bundled, and securely fixed onto the frame. Continuity testing, power supply verification, and initial trial operation of the model were then carried out after installation. Preliminary operational results show that the model enables intuitive observation of the system's working process, effectively supporting the explanation of fuel injection and ignition control principles, as well as basic measurement and diagnostic training exercises.

Figure 8. Model after complete assembly

IV. RESULTS AND DISCUSSION

The research results show that the objective of designing and fabricating a model frame integrating the electronic fuel injection and ignition systems has been successfully achieved. From the mechanical perspective, the frame constructed from welded box steel demonstrates good load-bearing capacity, stable geometry, and a rational spatial arrangement for component assemblies. Simulation results obtained using ANSYS R19.5 indicate that stress and deflection are distributed in a manner consistent with the structural configuration, with no unfavorable indications regarding strength under the investigated loading conditions. From the system integration perspective, the assembled model fully represents the main components of the gasoline engine management system, allowing learners to directly observe installation positions, the relationships between sensors, ECU, and actuators, as well as the control signal transmission process.

From an educational perspective, the model has high practical value because it reduces dependence on complete vehicles, improves safety during training, and provides favorable conditions for instructors to organize lessons on operating principles, component identification, signal measurement, and basic diagnostics. The mobility of the frame structure, clear visual arrangement, and ease of maintenance are also important advantages for laboratory environments. However, the current model mainly focuses on basic simulation and functional demonstration; future studies may integrate parameter display interfaces, fault-generation functions, real-time data acquisition, or diagnostic software connectivity to further enhance training and research effectiveness.

V. CONCLUSION

This paper presents the research, design, and fabrication process of a model frame integrating electronic fuel injection and ignition systems for modern automobiles. Based on an analysis of technical and pedagogical requirements, a welded box-steel frame solution was selected, a 3D model was developed using Inventor, and the structure was validated through ANSYS R19.5 simulation before actual fabrication. The results show that the model frame satisfies requirements regarding strength, stiffness, stability, and equipment arrangement capability.

The completed model effectively supports teaching and practical training in courses related to gasoline engine control systems, particularly topics involving electronic fuel injection systems, ignition systems, signal measurement, and basic diagnostics. The study provides a foundation for developing more advanced training models in the future, with enhanced interactivity, fault simulation capability, and integration with modern diagnostic tools.

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