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QUALIFICATION WORK OF THE MASTER

In specialty 151- Automation and computer-integrated technologies

on the topic:

Modeling of internal combustion engine control processes

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ABSTRACT

Today, the technical, economic, and environmental requirements for internal combustion engines (ICE) and their control systems are increasing. In this study, the initial focus is on understanding an engine model, specifically modeling engine components that significantly impact idle speed dynamics. To improve a process such as an engine control requires a mathematical model that adequately reflects its dynamic properties. In modern literature, a limited number of works consider internal combustion engines from control theory. All modern internal combustion engines operate under electronic engine control (ECM) systems based on microprocessor control systems (MCS). Various control techniques have been developed to decrease idle speed while meeting the noise, vibration, and harshness specifications. A PID controller is developed and tuned for this purpose. Through this intelligent technique, we can define control parameters for the engine model's Idle Speed Control and air-fuel ratio system. The controller operates using feedback from Exhaust Gas Oxygen (EGO) sensor situated in the exhaust manifold.

Master's work contained 73 pages of printed text consists of an introduction, Conclusion, future work, and applications. The work contains 2 tables, 28 figures, formulas.

Object of research is a gasoline engine equipped with electronic control system.

The subject of the research is gasoline engine management internal combustion.

The purpose and objectives of the research. The aim of the work is to decrease emissions on internal combustion engine by controlling the air/fuel ratio and Idle speed control. In order to fulfil this, the following objectives were set up.

Objectives of the study:

- Develop and use an air fuel ratio controller that combines both feedforwards and feedback based on exhaust sensor measurements.

- To tune the parameters of nonlinear plant model into linearization condition for stable equilibrium.

- To be able to define control parameters for Idle speed control and air fuel ratio control system of the engine model.

- Simulation PID control investigates exhaust gas oxygen sensor (lambda) and Idle speed control and shows responses changes when disturbances are inserted in the system.

- compute the desired actuator output by calculating PID responses.

Research methods are based on the main provisions of the various theory control strategies of air fuel ratio control and Idle speed control and PID controller powerful method for controlling a variety process.

Key words: Engine Model, PID Control, AFR control, Idle Speed Control, internal combustion engine, tuning

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List of Figures

Nomenclature

ICE – Internal combustion engine;

IICE– injection internal combustion engines

ECM – electronic engine control;

MCS – microprocessor control systems;

PID – proportional-integral and derivative;

MPC– Predictive model Control

MAP– Manifold absolute pressure

W*– desired vehicle speed

M*– desired engine torque

W – speed

TWC– Three-Way Catalyst

EGO – Exhaust Gas Oxygen EGO

AFR– air/fuel ratio

μ_{fi} – the amount of injected fuel

HC– Hydrocarbon

NOX– Nitrogen Oxides

a_{ign} – ignition timing

W_{cyl}– the mean value of air introduced into the cylinders

η_v – is the volumetric efficiency of the engine condition

v_d – is the engine displacement

n_e– the engine speeds

P – the manifold pressure

T – the intake manifold temperature
m_a– mass of air
m_f – mass of fuel

Introduction

Motivation

The internal combustion engine remains the first choice for personal transportation due to its relatively low production cost, proven durability, and compactness. New technologies such as fuel cells or lithium-ion batteries combined with permanent magnet electric motors have been introduced as possible successors to the internal combustion engine. However, they are still far too expensive to be considered real competitors. Therefore, the internal combustion engine will remain the primary means of transportation for many years.

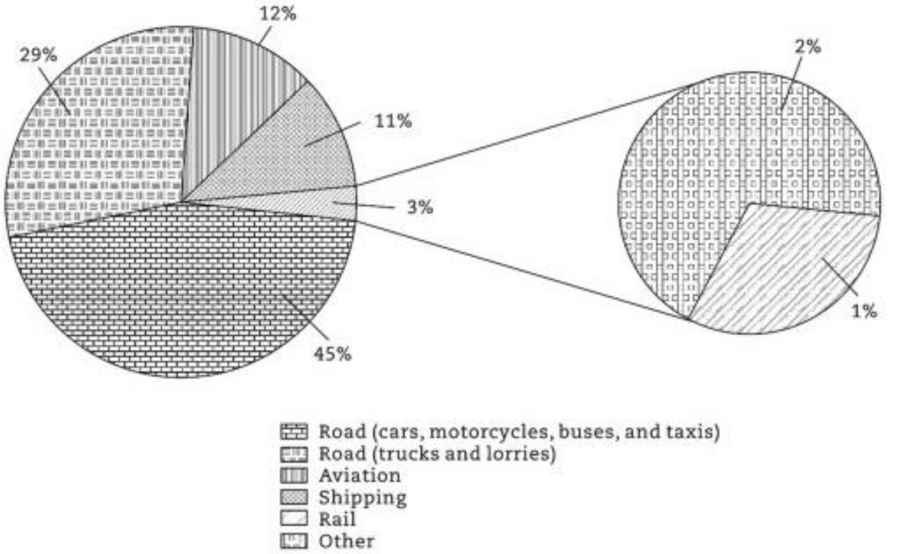


Figure 1. Global CO2 emissions from transportation [1]

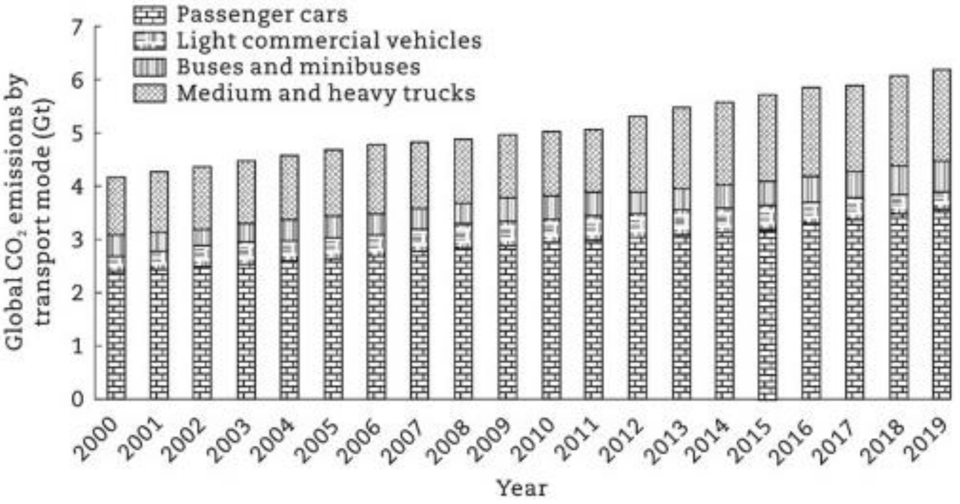


Figure 2. Global CO2 emissions by transport mode, 2000–2019 [1]

However, the continued use of the internal combustion engine has in the last couple of decades become more and more an environmentally important issue - and thereby has awakened severe political interest. Figure 1 illustrates a Global CO2 emission from transportation, and figure 2 shows Global CO2 emissions by transport mode, 2000–2019. The heavy environmental burden coming from road transportation is clear.

In order to make less pollution from road transport, the government has taken varied initiatives to motivate the automotive industry to invest in research into environmentally friendly vehicles for more than two decades now. One of the essential improvements initiated by the legislation is the general use of catalytic converters.

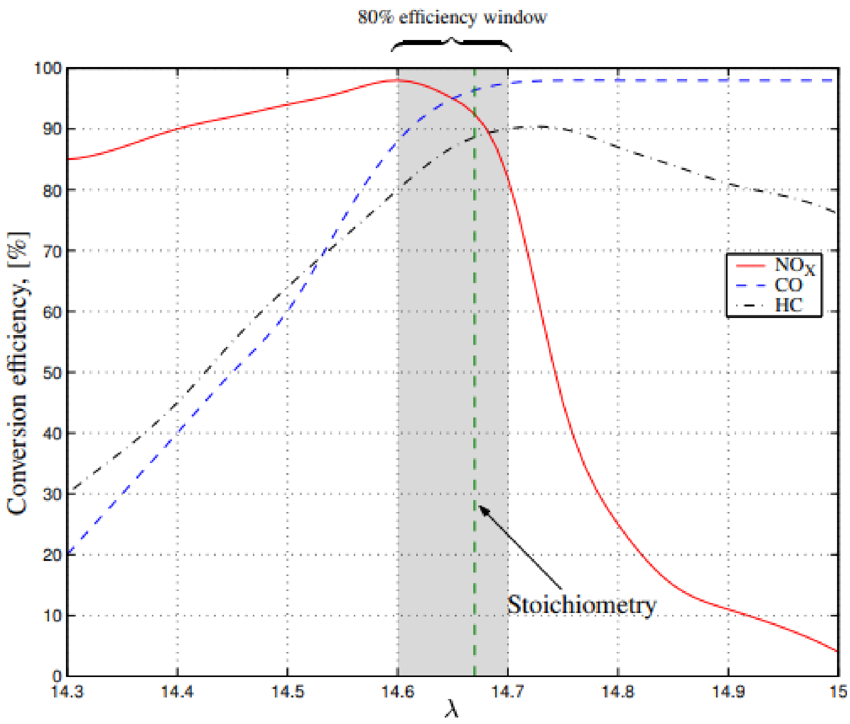


Figure 3. Typical efficiency of a Three-Way Catalyst [2]

The first family of catalysts offered in series was of the oxidation type, reducing CO (carbon monoxide) pollution by about 80%. The TWC (Three-Way Catalyst) and the toxic components of the exhaust gases CO, HC (Hydrocarbon), and NOX could be transformed into harmless emissions for the environment. However, the TWC could only be used with gasoline engines and required precise control of the AFR (air/fuel ratio) around the stoichiometric level while the engine was running in a transient and stable state. Even small excursions outside the 1% window around the stoichiometric level reduce the effectiveness of TWCs. A typical picture of the efficiency level of the TWC is graphically illustrated in Figure 3.

Research topic and Scope

Regarding all the above, this thesis aims to construct a closed-loop control scheme to sufficiently regulate the air-to-fuel ratio and idle speed controller. The first part of this work involves obtaining a proper dynamic model of an internal combustion engine and setting up a corresponding simulation in MATLAB. The second part involves building the closed-loop scheme by tuning a PID controller.

Dissertation organization

The dissertation is divided in four main chapters:

The first chapter introduces briefly Features of internal combustion engine as control objects and the main approaches and methods for constructing control systems for such engines and their tasks arising in the development.

Chapter 2 discusses the engine modelling and a comprehensive review on the basic control modules in the engine management systems and understanding of the control system architecture for the future developing with higher performance and fewer emissions. This chapter is the introduction to and the motivation behind the rest of dissertation.

In chapter 3 discusses developing of the air fuel ratio control and idle speed control strategy system for ensuring that engine model could work around optimal states during all operations at the range of fuel economy, drinving comfort and emissions by engine control system.

Chapter 4 closes the dissertation with final conclusions and recommendations for future work.

Chapter 1. Features of internal combustion engine control

From a control point of view, an internal combustion engine is a complex object, the characteristics of which have significant nonlinearity. The internal combustion engine operates in several modes. There are usually five such modes:

- engine start mode;
- mode of limiting the minimum speed (mode idle move);
- partial load mode;
- full power mode;
- engine braking mode.

Control strategies and algorithms for each of the modes may differ significantly. It is also necessary to consider the transient processes, which make up most of the operating time of a classic ICE. The exception here is power plants, in which the engine provides the operation of an electric current generator.

This chapter will consider the features of internal combustion engines as control objects and the main approaches and methods for constructing control systems for such engines.

1.1 Injection engine as a control object:

The internal combustion engine is the main power plant in automobiles today. Thus, controlling the speed and acceleration of the car is reduced to controlling the power that the internal combustion engine gives out, considering external influences.

While driving, the driver changes the position of the accelerator in order to change the speed of the vehicle. Therefore, the purpose of controlling the closed system "driver-car" is to stabilize the desired vehicle speed W*. However, this process is not straightforward since a change in the accelerator's position first causes a change in the torque developed by the engine. In turn, the difference between this moment and the moment of the external load determines the acceleration and, ultimately, the vehicle's speed. Therefore, based on the difference between the desired W* and the actual W speed, we can assume that the driver determines the required motor torque M*. Thus, the position of the accelerator can be interpreted as the desired engine torque M*. The following control loops can be distinguished in the engine control system (Fig.4).

1. Loop with torque feedback (main feedback); for a given loop, the purpose of control is to stabilize the desired value of the motor torque M* (or maintain the desired law of change in the torque M*(t)), determined by the position of the accelerator; the control signal in this circuit is the throttle opening angle damper α, and the reference value is the position of the accelerator.

2. Air/fuel ratio feedback loop (slave feedback); the control aims to stabilize the desired air/fuel ratio for a given circuit. The so-called stoichiometric ratio of 14.7: 1 is optimal for gasoline [1, 3]. This means that for complete combustion, one kilogram of gasoline needs 14.7 kilograms of air. To quantify the deviation of the engine operating mode from the optimum point, coefficient X is introduced, which shows the ratio of the mass fractions of air and fuel entering the cylinder during the operating cycle to the reference one. In the domestic literature, this coefficient is known as the "excess air ratio." The desired value of this coefficient is P = 1. The control signal for this circuit is the amount of injected fuel μ_{fi}.

3. Ignition timing feedback loop (optimizing feedback); for a given contour, the goal is to control is to increase the efficiency of the engine by minimizing the ignition timing, taking into account the elimination of detonation; the control signal, in this case, is the ignition timing a_{ign}.

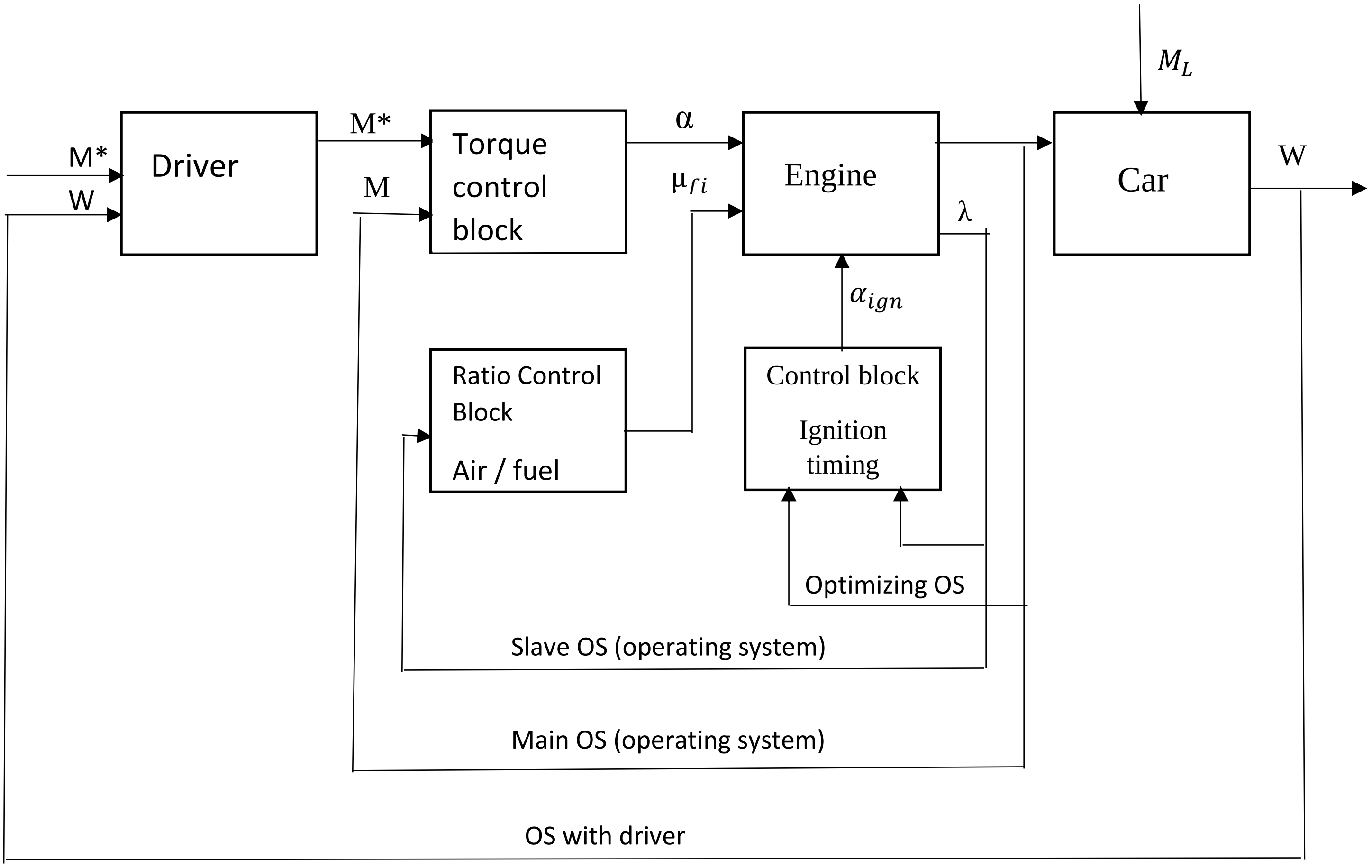


Figure 4. Vehicle dynamics control system

Thus, the following main tasks can be identified when developing control systems for an injection engine:

1. Torque control is a task of tracking or stabilization in conditions of external disturbances. In this case, the signal of the reference, which is being monitored, is the position of the throttle valve, which is interpreted as the desired value of the torque, and external disturbances are changes in the load torque caused by road irregularities (uphill, descents), air resistance, wind strength, and speed, as well as changes in road conditions

(acceleration, braking). It should be noted that the control object is significantly nonlinear, and the lack of the possibility of direct measurements of the torque value makes it necessary to use estimation algorithms for the magnitude of the moment.

2. Maintaining an optimal air/fuel ratio is a stabilization problem with compensation for disturbances. In this case, the stabilized value is the air/fuel ratio. The disturbing influences are the variable airflow, changes caused by pressing the accelerator pedal by the driver, the outside air temperature, its uneven rarefaction, and changes in atmospheric pressure. The features of this task include:

- multimodality, expressed in significant changes in the mathematical model of the engine, depending on the conditions of his work;

- uncertainty of the mathematical model;

- the need to maintain high accuracy of optimal air / fuel ratio, since its smallest fluctuations (within 3%) lead to a sharp increase concentration in exhaust gases of such components as CO and CH [4].

3. Prompt correction of the ignition timing is an optimization problem in which the optimized value is the ignition timing, the value of which can vary depending on the engine operating mode (idle, cold start).

We can also highlight particular (consumer) tasks focused on ensuring the engine's operation in unique modes. Successful solution of these tasks will lead to increased efficiency and environmental friendliness of the engine:

- Idle mode - depletion of the working mixture and stabilization of the speed at the minimum in idle mode in order to increase the efficiency of the car. A distinctive feature of this mode is that the throttle valve is completely closed at idle speed, and air enters the intake manifold through a special idle speed regulator, metering the amount supplied air.

- Cruise control is the task of automatically maintaining a given speed by the car. The mode is necessary for highway driving modes, on the highway, when it is necessary to move for a long time with any fixed speed (speed limits on the highway, subjective feelings of the driver). The system operates as follows. Using the onboard computer, the driver sets the desired speed value. After that, the system, taking into account the current speed of movement, the curb weight of the car, the moment of resistance caused by the unevenness of the road, as well as by the features of the road surface, automatically brings the car to the set speed and keeps it at it, taking into account the changes in all the above parameters in real-time. This problem is a tracking problem, as well as a problem of compensating for external disturbances.

• Reducing the number of toxic emissions during the cold start of the engine. Since platinum catalytic converters used in the modern automotive industry begin to effectively burn out unburned fuel particles only when the working surfaces up to 900 - 3000 C, the principal amount of harmful emissions falls on the first 2-5 minutes of cold engine operation [5]. At the same time, in technically developed countries, the toxicity standards of automobile emissions are becoming stricter every year [6]. Reducing the number of toxic emissions during a cold start of the engine can be posed as an optimization problem.

The above analysis makes it possible to single out the following features of an injection internal combustion engine as a control object [6, 8]:

- Lack of an accurate mathematical model; the existing mathematical models describing the injection engine have many inaccuracies and assumptions. Accurate no model describes this type of engine.
- Substantial nonlinearity of the mathematical model and the dependence of its parameters on the engine operating modes.
- Most of the measurements carried out in an internal combustion engine are made using dynamic sensors, which, while not being inertial links, introduce significant amplitude and phase mismatches into the input signal spectrum.
- Most of the disturbing influences affecting the operation of the engine are described by nonlinear functions.
- The belonging of the parameters of the system to the previously known numerical sets.
- There are connections between constant values of input signals and the state space of controlled variables, expressed by static characteristics. Thus, when synthesizing algorithms control of injection internal combustion engines, the problem arises development of a control system operating in conditions parametric and partially structural uncertainty, continuously exposed to external disturbances, as well as carrying a multi-mode concept.

1.2. Automatic control methods for internal combustion engine:

This section discusses control techniques for internal combustion engine. Their classification and features are given.

1.2.1 Brief Historical Overview:

The first works devoted to the application of the classical theory of automatic control to solving problems of controlling an internal combustion engine appeared in the 70s of the last century. Basically, the works of that time are devoted to justifying the feasibility of using the theory of automatic control as applied to the control of internal combustion engines [9, 10]. It was these works that marked the main paths of research in this area. For the first time, controlled and control variables were identified, the use of approaches such as stochastic estimation of unmeasured quantities, static and dynamic optimization and multiscriptual control.

In early works on this issue, the authors predicted the widespread use of microprocessor control systems, which had just appeared at that time, and we are just beginning to replace transistor technology gradually. However, most of the works of that time were of a more survey-analytical than applied nature. This is first and foremost was due to the lack of adequate from the point of view of the theory of automatic control of mathematical models describing the internal combustion engine.

Such models were developed in the mid-seventies [11]. These were the so-called averaged models. Such models operate with average values over the entire measurement interval of external and internal variables that dynamically change over time. The time scale for calculations is chosen significantly larger than one operating cycle of the engine but much smaller than that required to warm up a cold engine (less than 1000 cycles). With this choice of time scaling, an acceptable accuracy is achieved when describing the average values of changes in the most rapidly changing variables of the engine operation. [12, 13]. This method made it possible to bypass the essential nonlinearities of the control object; however, it negatively affected the quality of the control algorithms synthesized on its basis.

The averaged models described the dynamics of engine operation (crankshaft rotation speed, change in the mass of fuel injected into the cylinder) and the process of forming the air/fuel ratio in the cylinder. Also, dynamic models described the process of fuel deposition on the walls of the intake manifold. The presence of models describing the processes occurring in the engine with an acceptable degree of reliability made it possible to apply control theory approaches to solving problems of increasing the efficiency of the engine and its control in unique modes. Work on this issue was also carried out in our country [14]. However, the main emphasis was placed on the control of engines rather than a highly technical direction. (tractor, tank, and ship internal combustion engines), rather than car engines.

The first generation of electronic engine management systems, internal combustion, developed based on the principles and approaches of control theory, was applied in practice more than 20 years ago to reduce the toxicity of exhaust gases. The main task of the developers was to effectively interface the engine with a three-chamber catalytic neutralizer [15]. These systems were based on static dependences of the engine operation and open models of its dynamics. The implemented algorithms were also static and open-ended. The fact that the engine is a set of interconnected non-linear multidimensional systems with a wide scatter of operating ranges significantly reduced the accuracy of such algorithms. In addition, algorithms based on static methods did not consider the effect of engine wear, which significantly affects the characteristics of its operation, especially after a car has driven 100-120 thousand kilometers.

Gradually, with the development of the automotive industry and the advent of more sophisticated internal combustion engines equipped, for example, with oxygen sensors, control methods have also changed. It became possible to close the control loop since before the appearance of lambda probes, cars were not equipped with sensors that provided information about the processes inside the engine, and the control systems were open. The introduction of feedback made it possible to complicate and improve control algorithms and move away from outdated static open-loop models and go to more advanced dynamic and closed linear models. Since an injection internal combustion engine is a complex dynamic object operating in various modes, it is advisable to use control methods such as adaptive, self-adjusting control, and control in sliding modes [16, 17]. Thus, the next stage in developing control algorithms is nonlinear, adaptive, and self-adjusting control. In addition, some of the variables required for motor control cannot be measured due to the design features of the control object, which motivates the use of identification methods [18] and the use of neural networks [19.20].

In parallel with the development of engine control methods, the improvement of its mathematical model took place. From averaged models [21], which do not give a detailed idea of the processes in the engine at any given time, there is a transition to the so-called instantaneous models [22], which more accurately reflect the processes occurring in the engine and are more convenient for digital control of the system. A feature of instant (step-by-step) models is that they describe the operation of the engine step-by-step, cycle by cycle. This allows you to get a complete picture of the change in the vector of the state of the engine and increases the accuracy of the automatic control system. However, it complicates the calculation part of the algorithms and makes the model more cumbersome. Currently, there are both separate software packages (SIEM (Spark lgnition Engine Modelling Environment), Virtual Engines) and additional modules for widespread simulation environments (Matlab, Simulink) that allow you to simulate internal combustion engines. However, despite already entirely accurate models describing the dynamic processes occurring in the engine, most automakers considered it expedient to introduce the methodology into production. Motor control using the so-called tuning tables. The essence of this method is that the control variables are not calculated in real-time but are entered into the memory of the control microcontroller at the stage of engine manufacture and calibration. Thus, each combination of input action values is associated with a particular set of control variables issued by the microcontroller. The technique has proven itself well due to its reliability and simplicity; however, the tabular control method does not provide a high-quality and flexible approach to engine control with modern requirements for injection internal combustion engines. The introduction of fuzzy logic and neural networks into engine control systems begins [23].

Thus, summing up the brief historical review, the following stages in the development of ICE control systems and their mathematical modeling can be distinguished:

- **1st stage (the 60s-70s of the XX century):** the appearance of the first works on mathematical modeling of engines, the experimental determination of the static characteristics of the engine, the construction of static regulators on their basis, the dynamics of the system is not taken into account. Possible ways of further development of control systems are determined. For the first time, there is a mention of the possible application of systems based on adaptive and robust algorithms [24]. The first passenger cars equipped with fuel injection systems are produced (Mercedes-Benz, Volkswagen, SAAB).

- **2nd stage (80s-90s of the XX century):** the emergence of control systems, equipped with feedback, considering the dynamics of the object management. The emergence of linearized models [21]. The emergence of nonlinear models, the first steps in the field of nonlinear motor control [25]. The parallel development of computer technology makes it possible to widely use computer modeling in the design of automobiles. An increasing number of car manufacturers produce models equipped with fuel injection systems.

- **3rd stage (the 90s-2000s of the XX century):** the creation of self-adjusting control systems using methods of identification of unmeasured quantities, direct adaptation, as well as the use of neural networks for motor control. Cars are produced, equipped with fuzzy logic controllers (Audi, Toyota). Widespread replacement of carburetor power systems injection circuits. Introduction of the first fully computer-engineered car (Ford Focus). The first works on the creation of cars on hydrogen fuel, and cars are working on fuel cells.

1.2.2 Classification of methods for constructing ICE control systems:

Based on the analysis, the following classification of modern methods for constructing automatic control systems for internal combustion engines is proposed (Fig. 5). The main difference in the principles of building control systems for injection internal combustion engines (IICE) consists of the use of either experimental synthesis methods or analytical ones. In the experimental design of the control system, the rich engineering experience of designers is used, and many development tests are conducted on unique stands. With a more modern analytical method of synthesis, most calculations are performed on a computer; mathematical modeling is widely used IICE. Initially, the experimental method was used by all car manufacturers, but gradually, with the tightening of market requirements and the introduction of new environmental standards, most car manufacturers switched to analytical methods of synthesis. In addition, the development of analytical methods themselves was stimulated by the same factors. For example, with the introduction of the EURO-1 environmental standard in Europe in 1989, most car manufacturers abandoned open-loop control systems. Moreover, they switched to the use of closed systems.

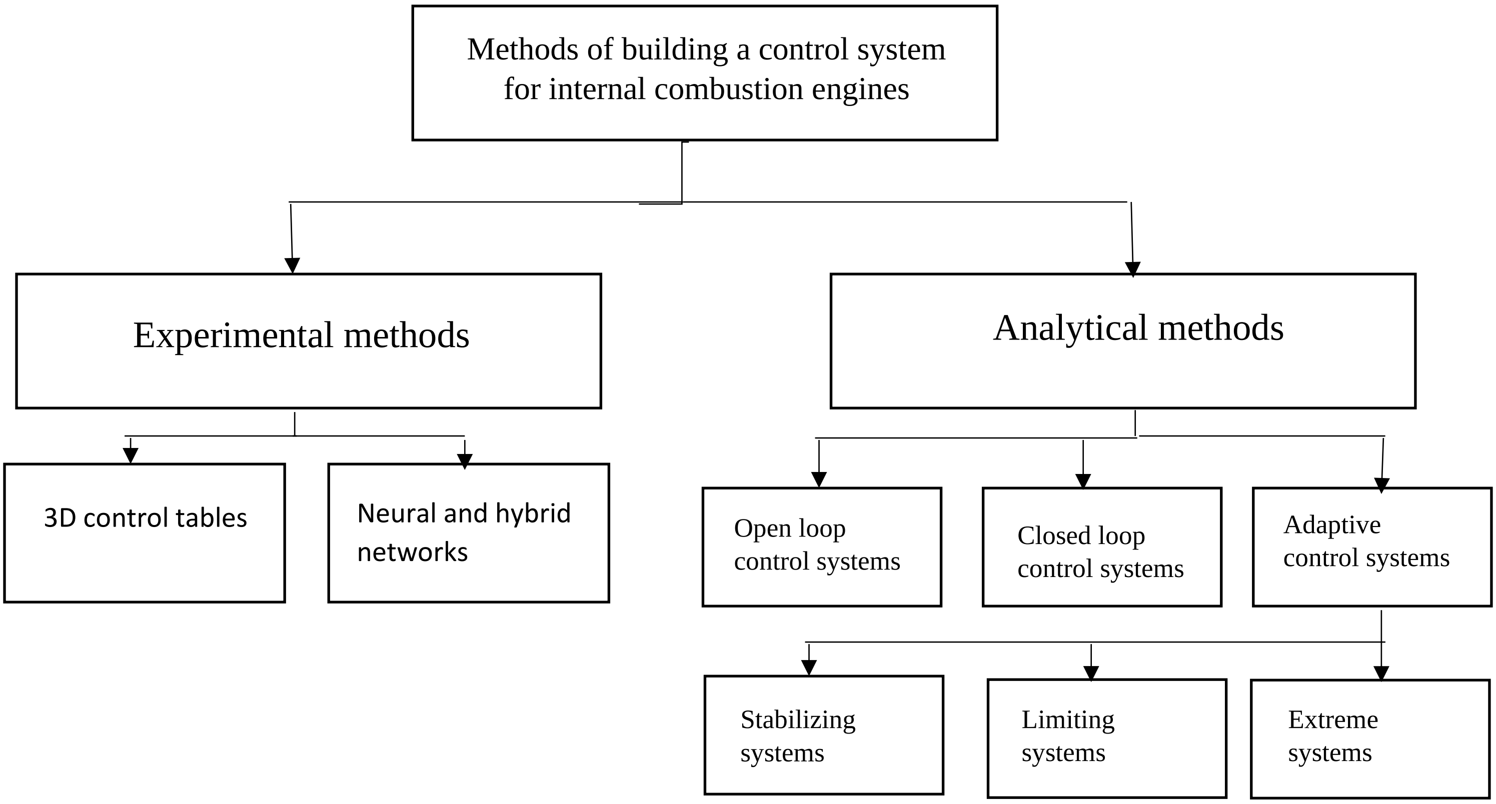


Figure 5. classification of modern methods of building automatic engine control systems internal combustion.

In systems using feedback control, the controlled output parameter is measured, and, based on the analysis of its value, new control actions are calculated. In this case, the disturbances acting on the control object are not considered. Such systems allow for more precise control.

At present, adaptive systems are understood as systems that can change the system's parameters and/or structure and possibly control actions based on the current information to achieve a specific, usually optimal, state of the system with initial uncertainty and changing operating conditions [25].

Learning circuits in a control system can be used to solve several problems:

1. maintaining the controlled value at a certain level (stabilizing systems);

2. limitation of the maximum or minimum value-controlled parameter (limiting systems);

3. ensuring the optimal value of the controlled parameter (extreme systems).

The first task can be solved entirely using closed-loop control. It is also possible to use an observer model to construct feedback.

In some control loops, it is necessary to provide control with the fulfillment of certain restrictions. Usually, they are constructed in the form of locally closed contours according to the limited parameters.

The first two functions can be successfully implemented in conventional closed-loop control loops based on feedback in steady-state conditions. However, under conditions of rapidly changing engine operating modes, in some cases, in such circuits, it is necessary to introduce a dynamic control correction, which should change depending on the object's state and when disturbances appear. In other words, it is required to readjust the dynamic correctors during operation, which is difficult to quantify. Foresee in advance. Therefore, in many loops, it is necessary to be able to self-adjust the control.

Sometimes it is desirable to ensure the most efficient work according to specific criteria. For example, to provide the best fuel economy or toxicity. Systems of excessive regulation can solve these problems. They are, by definition, self-adjusting. When constructing such systems, two problems usually arise the need to find the possibility of obtaining information about the value of the quality criterion and the lack of time to search for the optimum, considering the engine's operation at unsteady modes. Due to the complexity of their implementation, such circuits have not yet become widespread on serial internal combustion engines.

If the classification is carried out based on the assigned tasks, all internal combustion engine control systems can be separated into three main types:

1. Software;
2. Software-adaptive;
3. Responsive.

By software systems, we mean systems were exercising control according to a rigidly laid down program.

By software-adaptive systems, we mean systems capable of changing the operation control programs according to clearly laid down algorithms.

By adaptive systems, we mean systems that can learn not only by changing the parameters but also the structure of the control system itself and systems that can build a new controller based on the analysis of the collected information.

Based on this classification, we can conclude that software and software-adaptive circuits are mainly used in modern systems. Examples of software loops control loop ignition advance angle in terms of crankshaft rotation speed in START mode, the control circuit of the Ignition timing at idle speed (XX) depending on the coolant temperature, and crankshaft speed, fuel supply correction circuit based on the coolant temperature, etc. The program-adaptive circuits include the learning circuit of the matrices for correcting the readings of the mass airflow sensor based on the signal from the free oxygen sensor in the exhaust gases. Modern and future requirements for an auto-tractor engine and a car cannot do without the use of learning systems.

1.3 Features of microprocessor control systems internal combustion engines:

Microprocessor control has become an integral part of the modern internal combustion engine [26], making it possible to significantly increase its fuel efficiency and fulfill very stringent legal requirements for emissions of toxic substances with spent gases from cars. The use of microprocessor control systems (MCS) has opened new opportunities for the further improvement of motors due to a complex coupled multi-parameter control of working processes of engines and their systems. This, in turn, required the complication of control systems, an increase in the number of sensors used, and the creation of new actuators [27].

An internal combustion engine is a multidimensional non-linear non-stationary control object. It consists of many subsystems that are interconnected with each other and form a single whole. To ensure the high performance of such a system, it is necessary to solve the problem of optimal control. The solution consists in finding such control from the range of permissible values at which the quality indicator reaches an extreme value [28]. To solve this problem, at the stage of system development, it is necessary to carry out many experiments to obtain a priori information. The task becomes more complicated with an increase in the number of control actions.

During operation, a change in engine performance is possible due to the wear of the engine itself and elements of the control system, the formation of deposits, and other factors. The motors coming off the assembly line also differ, which is associated with the peculiarities of the process production. They may differ in the cleanliness of the treated surfaces, gaps in the mates, assembly and adjustment errors, etc. In addition, the engine is subject to internal and external disturbances such as environmental parameters, properties of the fuel, oil, etc. [29, 30].

Thus, for the best work results engine, it is necessary to ensure the adaptation of the control program to each engine coming off the conveyor and correct its operation throughout the entire service life of the engine. Solving this problem requires significant experimental research. The task becomes more complicated because anticipating all possible changes in the object control and disturbing external influences is impossible. Therefore, it is challenging to ensure optimal engine performance. In addition, there remains an unresolved issue of adjusting the control program for each specific engine.

To meet the requirements for suitable motors, it is necessary to ensure not only the exact execution of the specified controls in the main modes but also optimal control of the engine in the modes of starting, heating, in transient processes, etc., as well as to maintain such control during long-term operation of the car.

The following are used in modern MCS ICEs with spark-ignition: programmed control for the reference action, programmed compensation for disturbances, and closed-loop control in local control loops. They implement the principles of software and—software-adaptive control. For two decades, the MCS ICE passed a long way of development and has reached high excellence. Along with this, modern MCSs have at least three drawbacks [31]:

- an increase in the number of control actions and the desire to programmed control to consider the maximum of possible disturbances led to a significant complication of systems, their software, and the need to use many sensors;

- determination of control programs (calibration) of such MCS is a complex and very time-consuming process;

- Despite these complications, modern MCSs do not provide automatic control correction considering the individual characteristics of the engine and the vehicle, their changes during operation, and in the event of several external disturbances.

These disadvantages limit the possibilities for improving the performance of engines and cars. It is possible to overcome these disadvantages by using self-adjusting control systems. In this case, the control system independently receives the missing information during operation and adjusts to the operating conditions of the control object. This approach is more sophisticated. It allows you to achieve the best performance of the engine and significantly reduces the research work. Several foreign firms have started work on creating such control systems, but they have been introduced so far only concerning individual local circuits. This is due to the complexity of their development and implementation. There are also problems associated with the choice of informative and straightforward quality criteria that can be measured on board the car, the predominant operation of the engine at unsteady modes, and the complexity of compliance in the process of adjusting the restrictions imposed on the operation of the engine (toxicity, efficiency, stability of operation).

1.4. Actual problems of ICE control:

Problems arising in the management of internal combustion engines can be divided into two groups: general problems and particular problems [32]. General ones refer to the entire engine as a single system, private ones - to separate units, elements, or engine operating modes. Common problems include [33] :

- Uncertainty of the mathematical model of the engine. Several processes occurring in the engine do not have an accurate analytical description. For example, the process of fuel deposition on the intake manifold walls and the process of generating torque have not yet been accurately described. Mathematically. Some variables are not available for direct real-time measurement (torque, cylinder pressure, cylinder air/fuel ratio). This motivates the use of self-adjusting control algorithms [34, 35, 36].

- The presence of many particular engine operating modes. Depending on the operating mode (cold start, idle, acceleration, partial load, and full power modes), various control actions are optimal. Stable operation of the engine under these conditions should be ensured by the methods of logical and hybrid ICE control [37].

- Noise and distortion of the measured signals. The overwhelming majority of sensors used in the automotive industry are dynamic devices, which, due to their design features, introduce amplitude and phase mismatches into the spectrum of the input signal. In addition, in modern engine building, the problem of filtering noisy input signals is acute, which motivates the use of modern methods of observation, identification and filtration.

The particular problems of controlling an injection engine include:

- Uncertainty of the mathematical description of the process of fuel deposition on the walls of the intake manifold. Part of the sprayed fuel is deposited on the walls of the intake manifold, forming a film [6, 33]. This film accumulates and delivers fuel to the cylinder as a result of the process of evaporation. Thus, fuel from two sources enters the cylinder: injected by the nozzle and evaporated from the manifold walls. No exact analytical model describes this process.

- The problem of torque control [38], generated by the inability to measure the controlled variable directly. In engine building, special torque sensors are used that determines the value of braking and torque. However, due to their bulkiness (each sensor is a laboratory bench), they cannot currently be used on a passenger car. Therefore, for obtaining information about the magnitude and dynamics of the change in torque on the motor shaft, it is relevant to use methods for identifying an unmeasured variable.

- The problem of compensation for the parasitic dynamics of oxygen sensors is caused by the nonlinearity of the sensors themselves and the dynamics of changes in input signals. Modern Achunds, which are equipped with cars, are dynamic devices. In the presence of noise in the signal spectrum, the sensors amplify them many times due to their design features, which negatively affect the operation. Control algorithms [39].

The current level of development of control theory (adaptive, robust, self-learning, logical and hybrid control) makes it possible to successfully solve problems of this type.

1.5 Conclusions:

- The features of control of internal combustion engines are considered. The general and special tasks arising in the development of ICE control systems are highlighted.
- The analysis and classification of ICE control methods have been carried out. The features of microprocessor control systems for internal combustion engines are considered.
- Revealed the actual problems of ICE control

Chapter 2. Literature review

2.1 Introduction

During the former three eras, significant progress has been made in improving the efficiency of automotive engines and the fuel economy and exhaust emissions. Part of this progress is due to the ability of the researchers to model the machines to examine and test possible innovations. Thanks to the research and development by engineers, numerous rising technologies are driven by the impending energy climacteric and the more and more strict emission limitation of vehicles and legislation of fuel economy. The appearance of these new technologies has significantly increased the complexity of the internal combustion engine system.

2.2 Engine Modeling

When considering engine modeling, there are two main approaches:

- the cylinder-by-cylinder engine approaches: The first describes each cylinder individually and generates a torque signal for each combustion pulse present derived from engine geometries, which is useful for improving and optimizing the development of engine performance.

- the mean-valued engine method: The last method - the mean-value engine model defines several cylinders as one, which occupies the entire displacement volume. Its main aspects are speed, engine torque and pressure build-up in the intake and exhaust manifolds. The average value over one cycle is used to model the fluctuating flow.

These methods and differents approaches are both in terms of precision and structure for describing reality through a model. Hence, this modelling chosen depends on above all on the field of application.

Engine modeled by the zero-dimensional mean value method are used diffusely for the development of control contours due to their simplicity and low simulation throughput. As the subsystem is influenced more by the reciprocating motion of the piston than by the combustion process, for the dynamics of the crankshaft and the air intake engine system, the use of the average value models is sufficiently precise. The drawback is that it does not provide the knowledge of the combustion that has occurred, for example, the gas pressure in the cylinder, the temperature of the gas in the cylinder, and the indicated signals for ionization. The latter would be a critical parameter used in controlling closed-loop combustion, while the pressure build-up in the cylinder is an Important indicator for developing knock control by detecting engine knock.

As with other modeling approaches, many methods can determine the model. The most common method is the physical equation, which theoretically describes the system by creating a general model that will work for many areas of operation. Another method used in common is entirely measurement-based. The measured data is stored as two, sometimes three or more, dimensions, depending on the input signals. The exact results are usually provided by the measurement method that the engine's physical model could directly and initially generate.

2.3 Engine management system

Engine research has two main objectives: promotions to develop and increase fuel consumption performance and reduce emissions. In order to meet pressing emissions regulations and claim better fuel performance, progressive control techniques for engine control are developed. It is crucial to reduce emissions and improve fuel consumption performance while compromising reliability and relieving driving problems. The engine design stage should always affect the control design, as this is one of the most complicated problems in the system [40]. An efficient envelope of automotive engines with the leading soul of mechatronic systems could provide improved emissions levels, fuel economy, and performance through an abundance of sensor, actuator, and electronics applications and control systems based on a microprocessor.

The classical mechanical approach has been replaced by the new engine control missions achieved by ECU (electronic control systems). In this case, the control strategies established in the system involve the performance of the engine, including:

- fuel,
- torque,
- consumption,
- horsepower,
- emissions

The driver makes an action to control the vehicle based on the demanded output. The engine management system is designed to provide the required value of the engine's working condition. The parameters, such as sparking, air-fuel ratio, the speed at idle state, and other variables like valve timing or other complicated parameters, are desired to be controlled. By controlling these characteristics, the emissions could be reduced, and the efficiency and performance of the engine could be enhanced.

Regarding the modules within the system, some modules accomplice with the module used for torque control would impact:

- the air-fuel ratio (AFR) module;
- slow motion;
- electronic accelerator;
- ignition timing;
- hit;
- diagnostic, etc.

There are different types of sensors with actuators inside the engine management system. The real-time engine achieved parameters are investigated by the electronic device and sensor involved in engine operation, such as a spark, throttle valve, and the fuel injector controlled by the actuators.

Therefore, to produce the output indicators desired by the driver especially the other modules which operate in parallel, which is called the torque control module.

Some other modules would be recognized as other sections of the control modules in an actual production vehicle engine management system (EGR, Turbocharger, Camshaft). To achieve the global torque reference value, it is necessary to manipulate several parameters, such as the injection duration and ignition time. For achieving the global torque reference value, it is necessary to manipulate several parameters, such as the injection duration and ignition time. The motor output obtains the torque control module, and other coordinate modules are obtained by the motor output (to generate the requested torque).

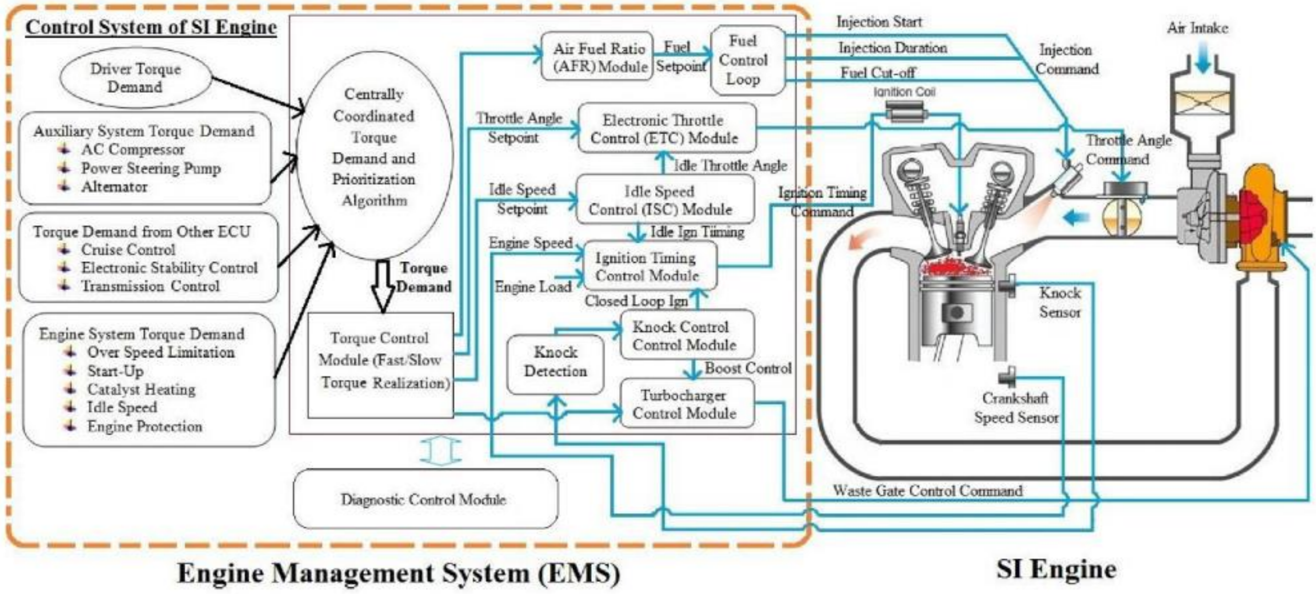


Figure 6. Schematic representation of the EMS control system in an SI engine [40].

2.3.1 Torque engine control module:

The control strategy based on the engine torque is suitable to meet the increasingly complex integration of the vehicle and engine control system. It can easily interact with torque interfaces of external systems, like transmission, traction control. This control module of the engine management system can transform all inputs into the engine torque variable. The torque variable is recognized as the main connector between the engine control unit and other functions of the vehicle control system [41]. The engine torque control module gives engine actuators suck as throttle position, cam phase positions, spark advance, an opportunity to realize torque demanded. The driver or vehicle subsystem could determine the demanded torque.

When the driver changes torque demand by changing the accelerator pedal, the torque value is transformed as a set point of torque throughout the transcriber, the interface between the driver and the control unit. The target of it is to translate the demand produced by changing the position of the accelerator pedal. The potentiometer in the accelerator pedal produces an electrical signal, and this electrical signal equals to the demands of torque from the driver decision.

A pedal map stores the torque request from the driver. From that map, the values could be interpreted into a demanded torque request and considering the other external demand, depending on the position signal of the speed sensor signal and accelerator pedal. The response of the vehicle corresponding to the pedal position can be offhandedly influenced by changing the pedal map as the torque demand is the only interface between the accelerator pedal position and the engine control strategies [42].

The system of engine torque control is composed of feed-forward and feedback subsystems. The system offers performance control in both steady-state and transient states. The first subsystems could calculate the desired actuator positions, in which the engine can generate torque as demanded. While the last subsystem could use the estimated torque to rectify the feed-forward subsystem. The friction, accessory loads, and pumping losses are subtracted from working torque during the conversion from desired torque by torque control module block. The look-up table is used to import the torque loss, which relies on engine speed and the temperature of the engine. The pumping loss is also recognized by a form relying on intake charge as well as engine speed. In consequence, the caused torque as requested is alternated as functional torque-impacting control parameters according to control modules, such as injection time as well as injection deviation in case of torque reduction, the variation of throttle angle, last but not least, waste-gate bypass valve used for turbocharger control, if equipped. It should be noticed that the throttle system should be considered as electronic throttle controlled.

As to the set-point of torque, the subsystem modes of the control system, such as air-fuel ratio and ignition, use their algorithms to determine fuel amount injected, air mass flow rate, and optimum spark advance to acquire torque as desired. Then the relevant signals are transferred to the modules used to control actuators, which is recognized as the driver circuit. Actuators receive activation signals from the driver circuit. The activation signal must actuate the needed actuators like a spark plug, fuel injectors, and intake air throttle [43]. Therefore, to accomplish the torque as required, the different actuators, such as throttle, spark plug, injector, need to be managed, respectively.

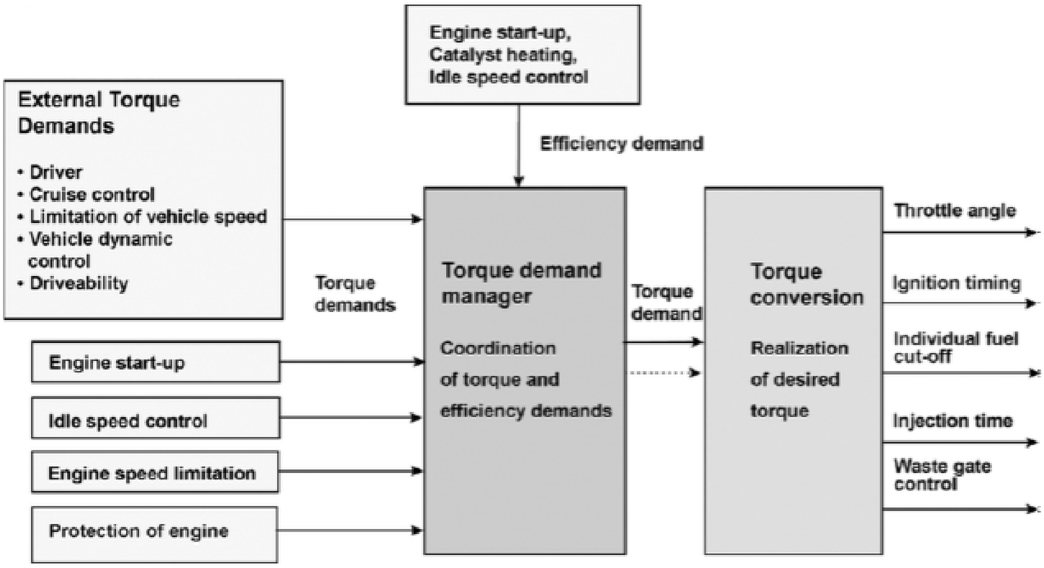


Figure 7. Torque Based engine control System [44]

2.3.2 Air-fuel ratio control module (AFR control module):

Air fuel ratio (AFR) is one of the main control modules in the engine management system and by considering engine demands such warming up of catalytic, vehicle requirement and air conditioning. The three-way catalytic (TWC) achieves the ideal efficiency physical and chemical processes in the engine and the AFR usually keeps changing the torque, like cruise control and transmission control [45].

The principal elements of the AFR shown in figure 8, are Fuel film compensator, mass airflow estimator, air-fuel ratio observer, and corresponding controller are the significant components of the Air-fuel ratio control system. These components make use of all the information sensed and generate the suitable pulse width of injectors.

- ❖ Mass Air Flow Estimator is used to measure the correct mass of air inducted in the cylinders and measure the correct amount of fuel due to the necessary amount of fuel required to maintain stoichiometric combustion based on flow and inlet pressure. Nevertheless, in general, two types of sensors are used to estimate the fair quantity of an SI engine: the manifold absolute pressure sensor abbreviated MAP and the mass airflow sensor abbreviated MAF. To calculate the intake airflow introduced into the cylinders and calculate fuel demands, the manifold absolute pressure sensor applies the speed-density method..

This method relates the intake pressure collected by the sensor and the temperature of the charged air with the volumetric efficiency of an engine, which is known from the lookup table. The density of the intake airflow is estimated via the intake air temperature and the manifold pressure; therefore, since the intake charge density is a given number, the air-fuel ratio mode could obtain the expected fresh charge amount under the engine operating conditions specified by the speed and the MAP according to the equation [46] :

$$W_{cyl} = \eta_v \frac{n_e}{2} v_d \frac{P}{RT} \quad (1)$$

Where

- W_{cyl} is the mean value of air introduced into the cylinders.
- η_v is the volumetric efficiency of the engine condition.
- v_d is the engine displacement
- n_e is the engine speed.
- P is the manifold pressure
- T is the intake manifold temperature.

This calculation must be carried out in the form of volumetric efficiency and stored in the control unit in the form of a card after calibration. In the mass airflow sensor method, the airflow is estimated directly into the intake manifold because the mass airflow sensor is usually a hot wire anemometer, which could measure the flow in the cylinder with high precision only under controlled conditions [47]. An additional estimator to correct the input could be introduced during the transient operation to correct the final value obtained when the airflow is introduced into the cylinder.

- ❖ The fuel film compensator is part of the air-fuel ratio control system. This compensator balances the amount of fuel stored and released in the oil film by changing the amount of fuel injection. It should be used inside the port fuel injection system because some fuel does not immediately enter the cylinder when injected at the intake port. The fuel would sink into the port side wall, upside-down of the intake valve, where a fuel film would form. This fuel film causes diversity between the fuel injected and the fuel induced in the cylinders [48]. If a difference did not compensate for this offset, there would be significant peaks in the air-fuel ratio response. Because when the intake valves are open, the injected fuel is not entirely in the gaseous state, so it is necessary to describe the model of the mass flow rate of the fuel in the cylinder. The mass balance of the fuel is estimated by the refueling model based on the mass ratio of the inlet injection fuel and the fuel flow-induced into the cylinders as a liquid at the outlet, as a compensating action to balance the fuel flow mass of the fuel film.

- The air-fuel ratio observer acquires information from control circuits regarding the air-fuel ratio in the respective cylinder, making real-time observation of the air-fuel ratio. Most of these observation methods rely on the upward growth of a simplified model for different aspects. These aspects involve the delay of the exhausting traffic, the sensors' dynamic effect, and the appearance of the air-fuel mixture. In this air-fuel ratio watcher, the communication requirement is the equivalence air-fuel ratio of a single cylinder. Therefore, the exhaust gas oxygen sensor signal provides the fundamental measurement, abbreviated as the EGO sensor. The essential compensation operation will be executed for the time shift, the characteristics of the sensor, and the phenomena of the air-fuel mixture by a suitable type for the EGO sensor. This EGO sensor provides feedback on the air-fuel ratio control information as part of closed-loop control, which is then periodically converted to injection time rectification after the information.

- The air-fuel ratio controller is introduced to calculate the injector's pulse width by observing the airflow. The pulse width is determined by the absolute pressure of the manifold or mass airflow sensor relative to driver demand and engine speed [49]. The controllers are based on designing anticipatory and feedback control modules, establishing lookup tables, estimating the air path dynamics, and a refueling system with a good repair. The typical air mass determines the amount of fuel, which must be induced into the cylinders to achieve the advanced indicated air-fuel ratio for the required torque. The fuel filler system model estimates the required injector pulse width control based on fuel vaporization, injector characteristics, fuel pudding dynamics, and driving dynamics. The stoichiometric air-fuel ratio could be achieved in whole throttle operation by applying the refueling strategy if the air intake system and the refueling system models are accurate. However, the core part of the controllers of the fuel injection systems in the actual production vehicle is comprised of either closed-loop or open-loop control. Open-loop control uses a lookup table. Closed-loop control is feedback with the PID controller. The proportional-integral-derivative controller operates based on a programmed gain approach with a simple structure, few tuning parameters, no system model, and robust performance among the wide range of operating conditions [50].

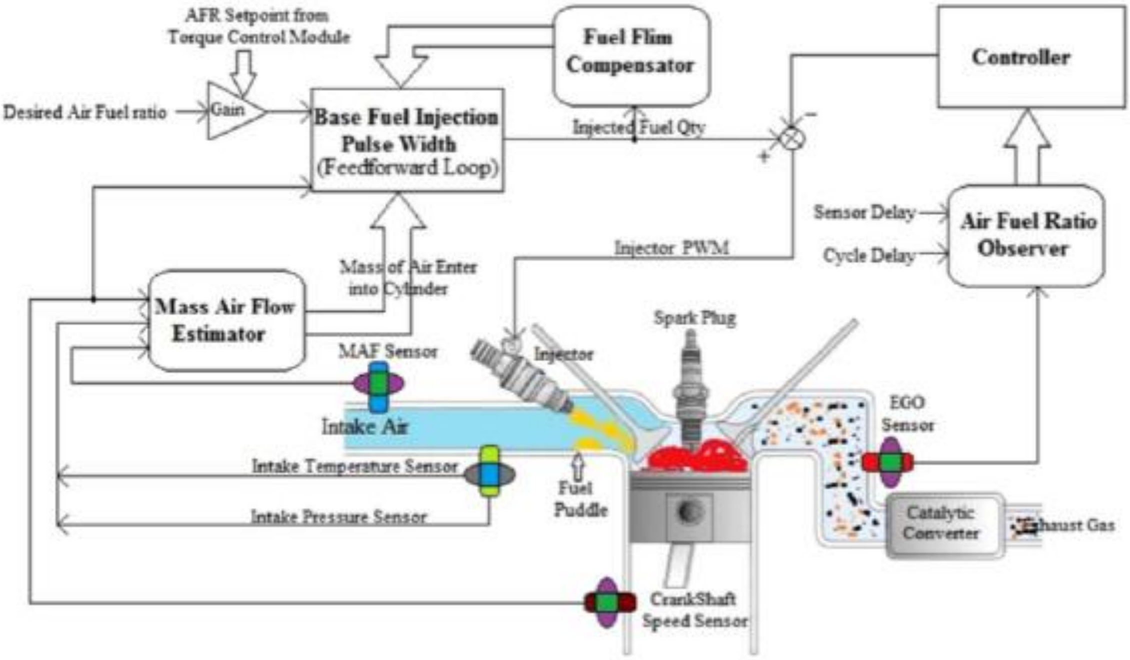


Figure 8. Air-fuel Ratio control System [51]

2.3.3 Electronic throttle control module (ETC module):

The intake flow is introduced into the cylinders of the spark-ignition engine; the throttle valve in the intake system controls the airflow into the engine and, thereby, the cylinder charge. The cylinder load determines the engine's output power and torque. The throttle valve, assumed a mechanical butterfly valve, is directly linked to the accelerator pedal. Therefore, the driver operates the control device according to the need for torque and power. In this case, the idle air control intake bypass valve could be controlled very small using a stepper motor in the engine management system is accomplished by the engine management system.

The electronic throttle system has replaced the conventional mechanical throttle control for many technical benefits, as shown in figure 9, also known as drive-by-wire (DBW). Within the injection electronic controlled system, the throttle valve is controlled electronically; thus, in such a system, the accelerating pedal is not mechanically linked to the throttle. Only facilitate the driver via an accelerating pedal sensor to the engine management system torque request from the engine. The intake valve stays unchanged with this different servo motor operating the butterfly valve. The engine management system based on the torque control module for the torque demand controls the throttle opening angle on the strength of the torque control mode as the required signals from the accelerating pedal position sensor and requirements of other systems. Furthermore, the position sensor of the throttle is combined into the throttle subsystem to determine the throttle valve's actual position. Based on the signal from this throttle position sensor, the electronic throttle retains the closed-loop control to achieve the the throttle opening angle demand from the torque control mode.

The torque demand could be generated by driving action and other additional external subsystems (cruise control, traction control, etc.). The required torque values are made as a set point for the engine by controlling the torque mode. The desired intake mixture charge needs to be determined initially to obtain the resulting value and the caused value, which demand the required cylinder charge. This value indicates the intake mixture charge as the target, which is essential to the required torque [52].

Based on the engine speed, as for the represented setpoint of torque, it is necessary to discuss desired air and recirculated exhaust amounts. Therefore, the intake air system control could be divided into air mass control (wastegate and throttle valve), and the predefined lookup table calculates the recirculated exhaust gas mass control to determine the required intake flow mass. The setpoint of throttle position is calculated for achieving the intake mixture charge based on a divided physical model of intake system function. Then the information is transferred from the position of the accelerator pedal to different relevant actuators by the electronic throttle control to operate the throttle opening or closing independently [53].

An understanding ETC control module always consists of a controller. The throttle control system determines the necessary voltage to control the motor using the pulse width modulation (PWM) signal. As a result, this throttle receives the signal and the DC motor with a brush or a gear mechanism, producing the needed torque to move the throttle plate for the setpoint angle. For fail-safe reasons, the performance of the ETC module is deteriorated because of friction in the servo motor in small-signal operating conditions, causing a slow response. Controllers extend to demanded friction to improve the performance under the small-signal division working method. A PID controller in the vehicle engine management system must be used to enable high validity and accurate control performance [54].

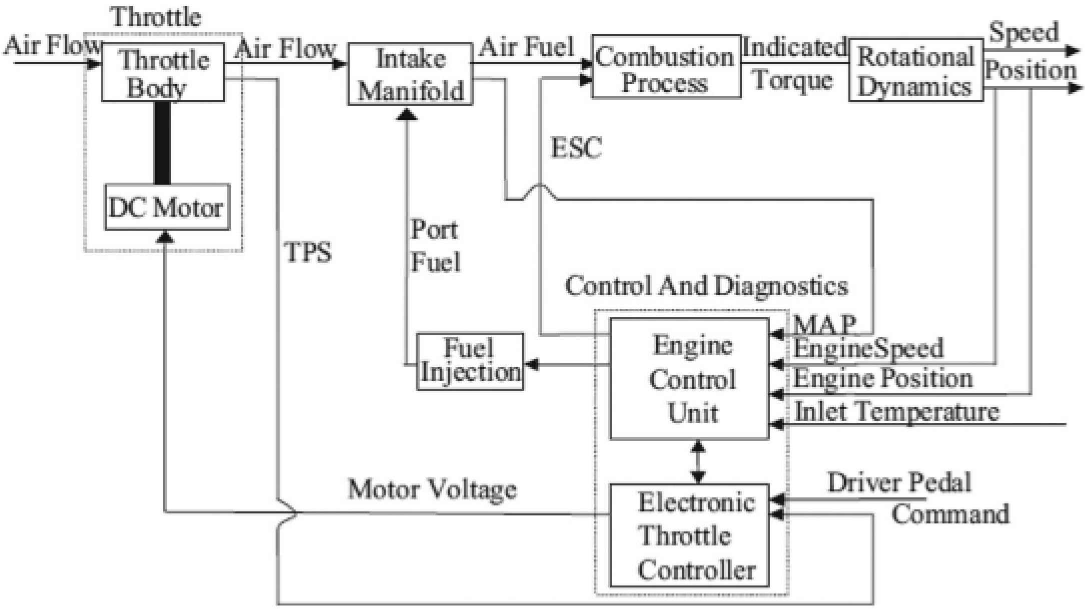


Figure 9. Electronic Throttle Control Module [55].

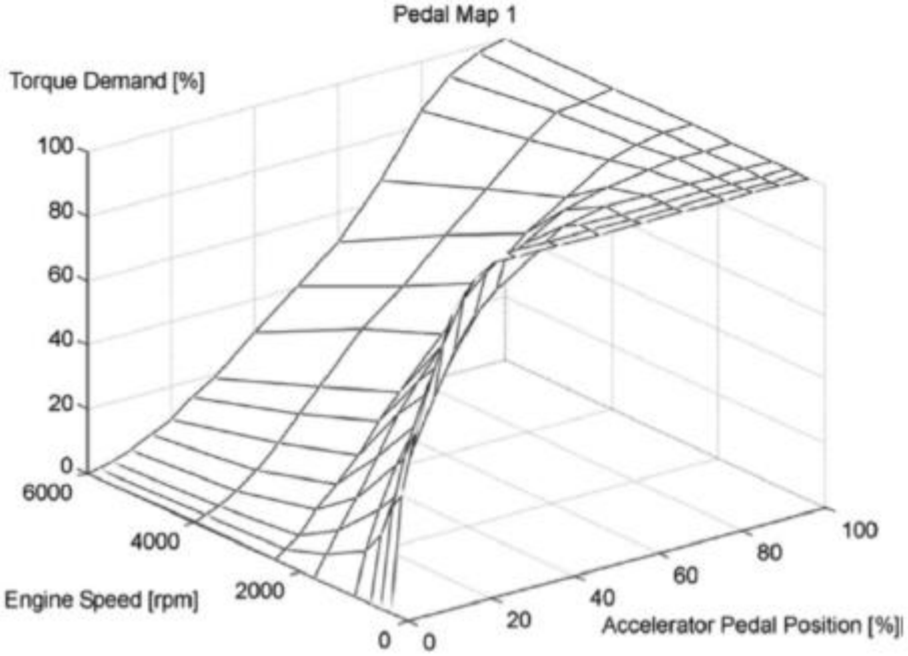


Figure 10. Pedal Map Example [55]

2.3.4 Idle speed control module:

The idle speed control maintains the engine speed to the defined value (selected target idle speed), preventing the motor from stalling while interference load is added or subtracted. The torque disturbance is due to the use of devices powered by the engine and could be caused, for example, power steering, electric windows, air conditioning, and headlamp that affect the engine speed at idle speed operating conditions. the controller controls just the fuel, air, recirculated exhaust gas and sparking time [56].

The intake flow and ignition timing influence the idle speed mainly because two main factors control the engine speed: the throttle, which manages the air-fuel mixing and charge amount and sparks advance. The control process utilizing the spark advance system has a quicker response than utilizing the intake air system. Therefore, spark advance is usually used as core input for controlling [57]. Subsequently, when the intake input starts to govern the engine speed, the timing value of the spark advance returns to a numerical value. To simplify this control strategy, the two control signals are used parallel and should be aware of each other.

The desired setpoint value is relative to the spark advance. Therefore, during the changing in other loads, it is possible to implement the idle speed control by adjusting the air-fuel mixture introduced into cylinders.

During idling mode, The idle speed desired depends on the different torque disturbances to the engine. Only predictable torque as the load is related through the feed-forward, which consists of multiple lookup tables of various interruptions and disturbances because the engine control unit is aware that predict the load due to the accessories are switched on after estimating the load torque by the estimated interfaces, by defined spark timing. Moreover, for fixed AFR ratio and spark need to maintain at the fixed setpoint the engine speed.

Over the years, feedback idle speed control systems have been adapted in the literature. Therefore, the scope for providing a high performance by tackling changes in operating conditions and time delay in the idle speed control module. However, during idling mode and to meet the emission targets, the robust control system developed can be improved.

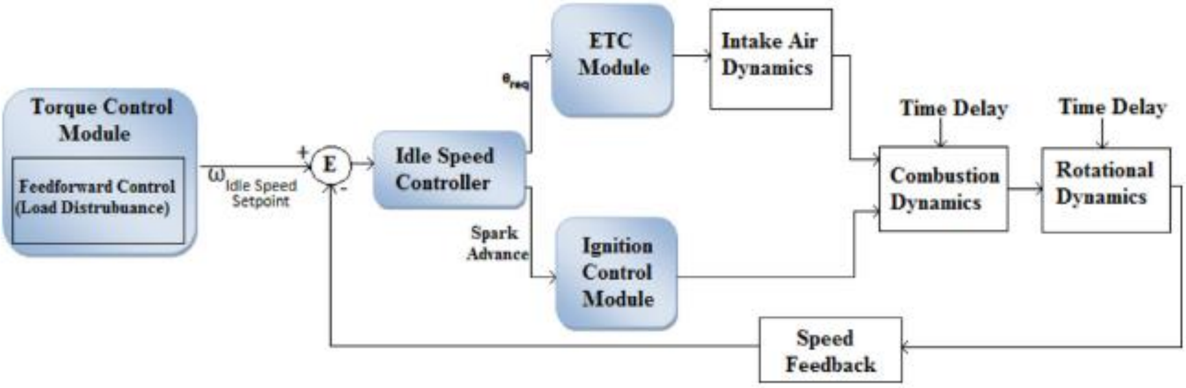


Figure 11. Idle Speed Control Module [58].

Chapter 3. Engine Modeling and control strategy simulation in Simulink

1.1 Introduction

The first step of this project was to study the available literature on engine model, Idle speed control and fuel-ratio control. According to the facts, in the automotive industry, in the field of internal combustion engines, is carrying out various research aimed at achieving technological innovations which will result in both lowering the engine production and maintenance costs and reduced fuel consumption. The goal is to allow the engine to idle as low as possible while preventing the engine from rough running and stalling when power-consuming accessories, such as air conditioning compressors and alternators, fail. light up. some issues are going to be addressed in relation to speed control like engine stalling at all operating conditions. Primarily in the production and operation of an engine, the amount of air controlled by a throttle bypass valve (to open as soon as the expander inlet valves start to close) rotates air from the intake manifold to the closed primary throttle plate. The bypass system function requires immediate opening of the bypass control valves in the event of rejection at partial or full load. The air-controlled path is considered relatively slow due to the intake multiple dynamics and subsequent seizure of power issues. Therefore, a much faster actuation path is determined by the spark control.

Typically, the control strategies available in the automotive literature solve the problem of controlling the idle speed acting both on the throttle position and on the ignition advance. The engine is not only the most bottom-line component for automotive performance; its performance in terms of emissions also truly changes the environment. Engine control systems may carry fuel injection control (i.e., air-fuel ratio control), ignition or ignition control, knock control systems, idle control, EGR control, and transmission control.

Essentially, the engine idle speed control is a non-linear, time-varying, complex, uncertain dynamic control problem, including the now-widespread use of classic control, modern control, and intelligent control like LQ, H, μ for synthesis and development-based methodologies. For the convenience of neural networks and fuzzy-logic-based control systems, several control systems can work with the same plant dynamics phenomenon to select an idle speed Control design model.

Engine models were designed to control and keep the idle speed conditions of an automobile [59]. The fundamental engine model for Idle Speed Controller design was designed by many developers [60-62]. Therefore, these models must be derived from the first principle, physical law, and many identification techniques. Therefore, to start our model-developed work, we need first a nonlinear descriptive engine combustion torque dynamic. To develop the engine's idle speed, there are some models, like a nonlinear engine model [63], for use to determine the engine's response and arrange acceptable data. In these models, some tuning is created of the pre-calculated model parameter range due to the given assumptions, such as linear model structure and constant air/fuel ratio [64].

Thus, for effective control of the idle speed to improve the fuel economy of the vehicle, the improvement of the driving comfort of the vehicle and the reduction of emissions has tremendous importance; there are diverse types of control techniques that exist for controlling an engine such as feedback control for the spark loop, proportional-integral-derivative (PID) control offers the simplest and yet most efficient solution to many real-world control problems. It used a PID, multiple anticipatory control, which uses accessory charge information control technique to adjust the parameters of a linearized model of engine idle speed for stable equilibrium conditions. A sensitive-guided design was mentioned as a better way to tune idle PID controllers [65]; on the other hand, due to its simplicity and simple design, proportional-integral-derivative (PID) control is acceptable and has been widely applied in many practical applications.

In order to build robust control systems, H methods and LQ techniques were also applied [66]. In the case of system sensitivity and excess actuator Efforts, some error adjustments were made on the frequency weighting functions. The conclusion offered a frequency-shaped PI controller and a PD controller.

However, the engine with this technique was unstable when the ignition advance was under high stress. Hrovat and Zheng [67] tried to eliminate this problem by applying the Predictive model Control (MPC) technique.

The modern optimization techniques have adjusted the early model into a simple and more refined model to solve the problem. Therefore, we can improve the fuel economy and reduce the vehicle's emissions by regulating the idle speed regulator via the PID control loop.

Also, this chapter is devoted to the brief history of the evolution of engine control with specific attention to engine modeling and air-fuel ratio control strategies. The use of modern mathematical control techniques in engine engineering has advanced in recent years, and some of the control-oriented models are identified and addressed with specific focus air-fuel ratio for port fuel injection engines. This review demonstrates the importance of AFR control [68].

The designed AFR controller has been divided into two parts. The first part is the desired AFR tuning controller, which must be adaptable according to the operating conditions of the engine of a vehicle. The second part is the ideal AFR controller, which controls the fuel injection according to the ideal AFR setting. The advantages of this control scheme are the desired AFR tuning controller focuses on the best AFR analysis desired; The ideal AFR controller can focus on improving transient control performance [69]. For AFR PID control, the engine is first assumed to be operating under stabilizing conditions, and the baseline ideal AFR is set based on fuel output. The variation is corrected using the PID controller [70].

3.2 Geometric Model

The primary plant model for an Idle Speed Control (ISC) and air fuel ratio is justified in this part. The control input is a throttle angle in degrees, and the output is an engine speed per minute (rpm). The modeling is discussed below [71]:

3.2.1 Throttle mass flow:

The mass airflow over the idle throttle opening can be modeled using the throttled flow equation:

$$m_{th} = A_{th} \frac{Pa}{\sqrt{(2RT)}} \quad (1)$$

Where,

- A_{th} is the effective area of throttle
- Th is the air mass flowrate passing through throttle opening.
- Pa is the ambient pressure
- R is the universal gas constant.
- T is the ambient temperature

The throttle area is a non-linear function of throttle position, but given that while idling, the throttle movement is minimal, hence a linear relationship will be assumed between the throttle position and throttle effective flow area.

3.2.2 Engine Air mass Flow:

The mean value of fuel-air mixture flow rate getting the engine cylinders can be using the following equation:

$$\varpi_{mix} = \eta_v \frac{Pn}{RT_n} \frac{V_d \varpi e}{4\pi} \quad (2)$$

Where,

- η_v is the volumetric efficiency
- V_d is the displacement volume
- ϖ is the engine speed in radians-per-second.

Air mass flow rate entering the cylinders can be found using the formula:

$$\varpi_{eng} = \frac{\varpi_{mix}}{[1+\phi\,(\frac{F}{A})_s]} \quad (3)$$

Where,

- $(\frac{F}{A})_s$ $and\ \phi$ represent the stoichiometric fuel-to-air ratio and fuel-to-air ratio normalized by the stoichiometric fuel-to-air ratio, respectively.
- Φ is referred as equivalence ratio.

3.2.3 Intake Manifold:

Based on the isothermal conditions, the pressure dynamics can be modeled as:

$$P_m = \frac{PTm}{Vm} (m_{ai} - m_{a0}) \quad (4)$$

Where,

- Pm= Rate of change of manifold pressure (bar/s)
- R= Specific gas constant, (287j/kg-k)
- T= Temperature (K)
- Vm = Manifold volume m^3
- m_{ai} = Mass flow rate of air out of the Manifold (g/s)

The mass rate, m_{ai} is a function of the manifold pressure and the engine speed.

3.2.4 Torque Generation:

The torque generation is a non-linear function of engine speed, engine cylinder mass flow, similarity spark advance, and ratio:

$$T_e = f(N, \varpi_{mix}, \phi, SA) \qquad (5)$$

Where,

SA= show the ignition advance. Note that the power induction delay (IP) enters the system dynamics through the raised equation because the torque focuses on the delayed value of the mass flow in the engine's cylinders.

3.2.5 Engine Rotational Dynamics:

The equation of engine rotational dynamics is as follows:

$$\frac{d}{dt}\varpi_e = \frac{1}{J}(T_e - T_1) \quad (6)$$

Where,

- J is the inertia of engine in neutral state
- T1 is the load torque on the engine including internal engine friction.

3.3 Air/Fuel ratio control

3.3.1 The Air-Fuel Ratio

Thermal engines use fuel and oxygen (from air) to produce energy through combustion. To guarantee the combustion process, certain quantities of fuel and air need to be supplied in the combustion chamber. A complete combustion takes place when all the fuel is burned, in the exhaust gas there will be no quantities of unburnt fuel [72].

Air fuel ratio is defined as the ratio of air and fuel of a mixture prepared for combustion. For example, if we have a mixture of methane and air which has the air fuel ratio of 17.5, it means that in the mixture we have 17.5 kg of air and 1 kg of methane.

The ideal air fuel ratio, for a complete combustion, is called stoichiometric air fuel ratio. For a gasoline engine, the stoichiometric air fuel ratio is around 14.7:1. This means that, in order to burn completely 1 kg of fuel, we need 14.7

kg of air. The combustion is possible even is the AFR is different than stoichiometric. For the combustion process to take place in a gasoline engine, the minimum AFR is around 6:1 and the maximum can go up to 20:1.

When the air fuel ratio is higher than the stoichiometric ratio, the air fuel mixture is called lean. When the air fuel ratio is lower than the stoichiometric ratio, the air fuel mixture is called rich. For example, for a gasoline engine, an AFR of 16.5:1 is lean and 13.7:1 is rich.

3.3.2 Air fuel ratio formula

In the context of internal combustion engines, air fuel ratio (AF or AFR) is defined as the ratio between the mass of air m_a and mass fuel m_f , used by the engine when running [73]:

$$AFR = \frac{m_a}{m_f} \quad (7)$$

The inverse ratio is called fuel-air ratio (FA or FAR) and it’s calculated as:

$$AFR = \frac{m_a}{m_f} = \frac{1}{AFR} \quad (8)$$

3.3.3 Calculation of stoichiometric air-fuel ratio

In order to understand how the stoichiometric air fuel ratio is calculated, we need to look at the combustion process of the fuel. Combustion is basically a chemical reaction (called oxidation) in which a fuel is mixed with oxygen and produces carbon dioxide (CO2), water (H2O) and energy (heat). Consider that, for the oxidation reaction to occur we need an activation energy (spark or high temperature). Also, the net reaction is highly exothermic (with heat release) [74].

Fuel + Oxygen → Carbon dioxide + Water + Energy

For a better understanding, let’s look at the oxidation combustion of gasoline. This is a pretty common chemical reaction. Considering that gasoline is made up from iso-octane $C_8\mathrm{H}_{18}$, calculate the stoichiometric air fuel ratio for gasoline.

- First, we write the chemical reaction (oxidation):

$$C_8H_{18} + O_2 \longrightarrow CO_2 + H_2O$$

- Balance the Equation:

$$C_8H_{18} + 12.5\, O_2 \longrightarrow 8\; CO_2 + 9\, H_2O$$

- write down the standard atomic weight for each atom:

Hydrogen= 1,008 uma ; Carbon =12.011 uma; Oxygen = 15.999 amu

- Calculate the mass of fuel, which is 1 mol of iso-octane, made up from 8 atoms of carbon and 18 atoms of hydrogen and the mass of oxygen, which consists of 12.5 moles, each mol made up from 2 atoms of oxygen.
  m_f = 8·12.011 + 18·1.008 = 114.232 g

  m_o= 12.5·15.999·2 = 399.975 g

- Calculate the necessary mass of air which contains the calculated mass of oxygen, considering that air contains around 21 % oxygen.

$$m_a = \frac{100}{21}\, m_o \;=\; \frac{100}{21}\, 399.97 = \; 1904.64\, g \qquad (9)$$

- Calculate the air fuel ratio using equation (10)

$$AFR = \frac{m_a}{m_f} \; = \frac{1904.64}{114.232} = 16.67 \qquad (10)$$

Again, the calculated stoichiometric air-fuel ratio for gasoline is slightly different from that provided in the literature. Thus, the result is acceptable since we made a lot of assumptions (gasoline contains only iso-octane, the air contains only oxygen at a rate of 21%, the only combustion products are carbon dioxide and water, combustion is ideal).

3.3.4 Exhaust Gas Oxygen (EGO) air fuel ratio (Lambda)

We have seen what is and how to calculate the stoichiometric (ideal) air fuel ratio. Internal combustion engines do not work exactly with ideal AFR, but with values close to it. Therefore, we'll have an ideal and an actual air fuel AFR ratio. The ratio between the actual air fuel ratio (AFR actual) and the ideal/stoichiometric air fuel ratio (AFR ideal) is called equivalence air fuel ratio or lambda (λ).

$$AFR = \frac{AFR_{actual}}{AFR_{ideal}} \quad (11)$$

The lambda parameter is a ratio that indicates how far from stoichiometry the mixture is. Its value is given by

$$AFR = \frac{AFR_{actual}}{AFR_{ideal}} \quad (12)$$

For a value of 1, the mixture, is stoichiometric, above, the mixture is lean (excess of air), and below, it is rich (excess of fuel).

Depending on the value of lambda, the engine is told to work with lean, stoichiometric or rich air fuel mixture [75].

Equivalence factor	Air fuel mixture type	description
$\lambda < 1$	Rich	There is not enough air to burn completely the amount of fuel; after combustion there is unburnt fuel in the exhaust gases.
$\lambda = 1$	Stoichiometric	The mass of air is exact for a complete combustion of the fuel; after combustion there is no excess oxygen in the exhaust and no unburnt fuel.
$\lambda > 1$	Lean	There is more oxygen than required to burn completely the amount of fuel; after combustion there is excess oxygen in the exhaust gases.

The Lambda Sensor block, which simulates the behavior of a binary lambda sensor whose output signal will depend on the ratio between the air flow and the fuel flow (its two inputs).

- **Simulation:**

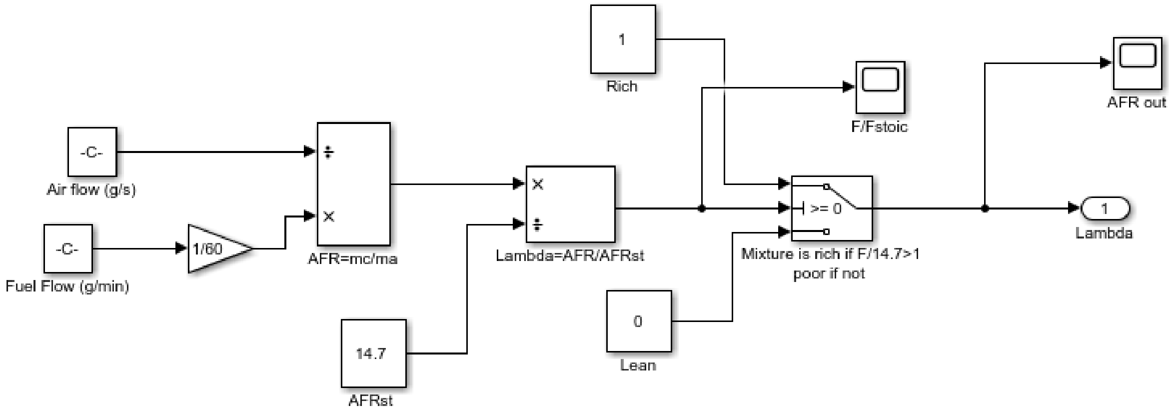


Figure 12. Exhaust Gas Oxygen (EGO) simulation

- The air flow, in grams/sec, which indicates the quantity of air pumped by the engine from the intake manifold.

- The fuel flow, in grams/sec, which represents the total quantity of fuel injected every second.

All this information allows us to deduce that such a sensor can be considered as simple binary sensor which indicates if the mixture is rich or lean. And this type of lambda probes is indeed called binary lambda sensor, on the opposite of proportional sensors which give a signal proportional to the AFR of the mixture. So, in this project, I decided to basically represent the lambda sensor as a simple switch, which will be "on" or "off" depending on if the mixture is rich or lean. This can be seen in detail on Figure 12, which represents the inside of the "Lambda Sensor Simulation"

The two inputs of this subsystem are the mass air flow and the mass fuel flow, which are used to calculate the AFR (block "AFR"). This value is then divided by the AFR at stoichiometry, which is a constant coming from block "AFR stoichiometric", to obtain the value of Lambda. This value is used in the switch to determine which signal to send depending on the mixture: if the mixture is rich (lambda <1), the output will be 1. If not, the output will be 0, meaning a lean mixture. This output is then connected to the ECU, and we will later see how this signal is processed.

❖ Results:

For example:

Air Flow = 23.81 g/s
Fuel Flow = 96.95 g/min

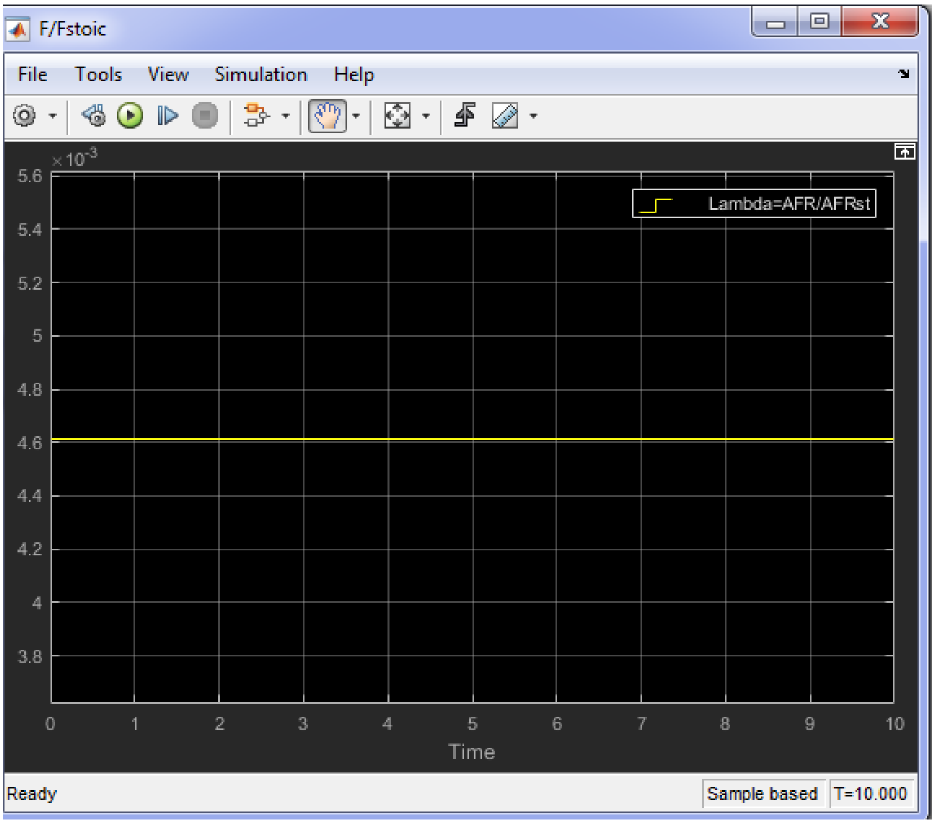


Figure 13. Simulation Lambda AFR/AFRst

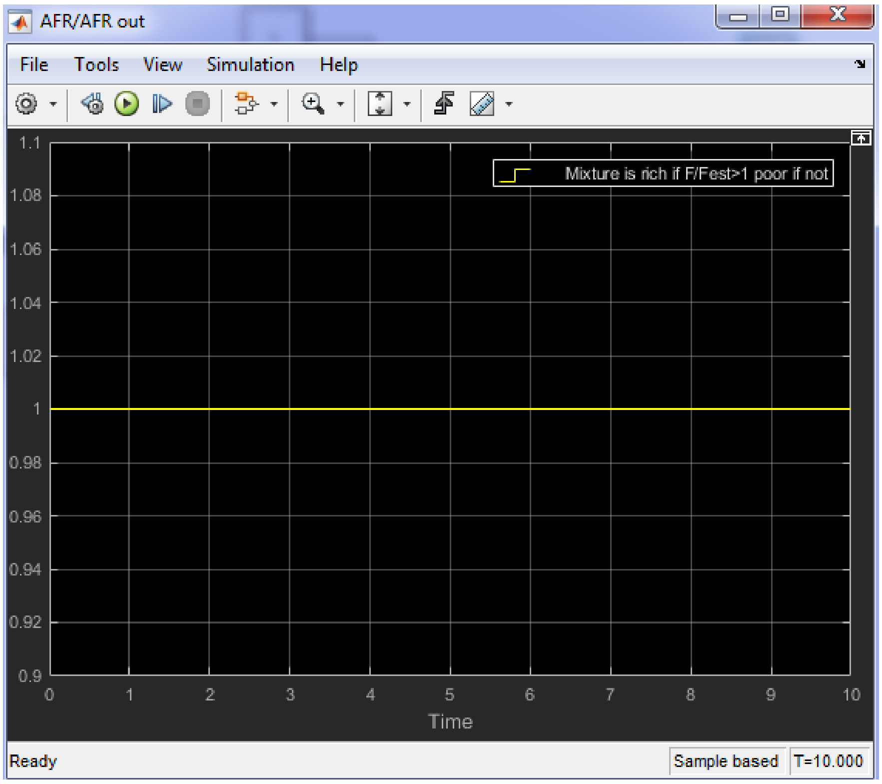


Figure 14. simulation AFR/AFR out

Graphically, λ =1, The mass of air is exact for a complete combustion of the fuel; after combustion there is no excess oxygen in the exhaust and no unburnt fuel.

3.3.5 Air fuel ratio and engine performance

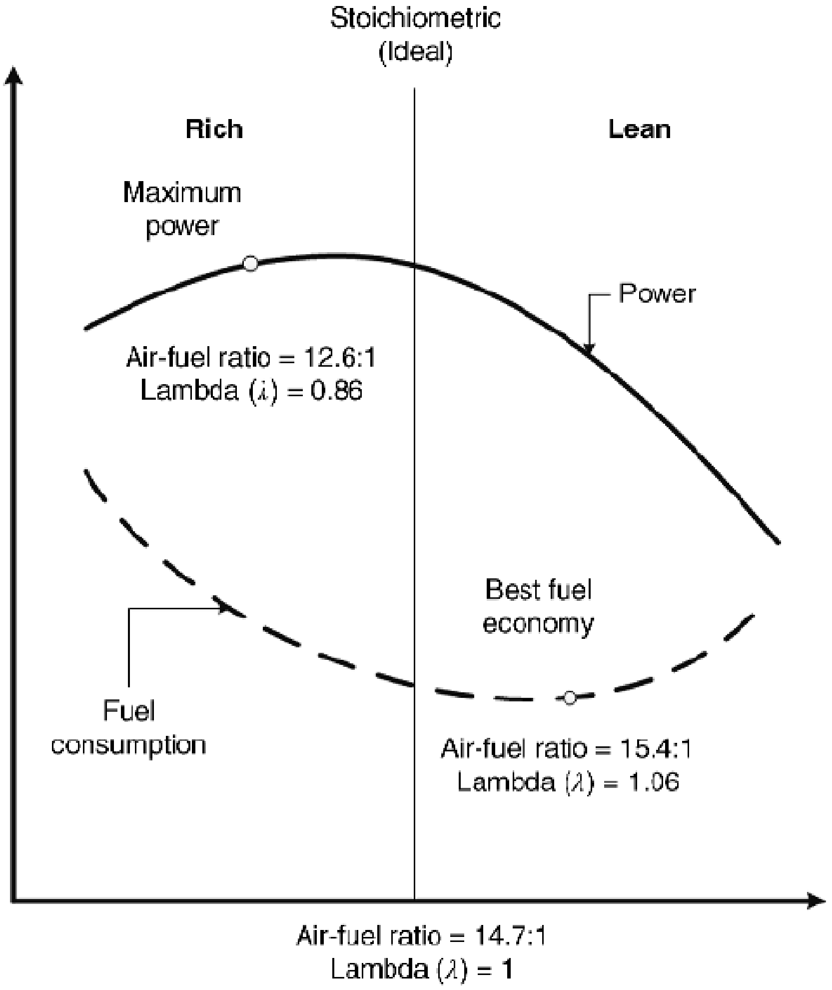


Figure 15. Engine power and fuel consumption function of air fuel ratio [76]

In the figure above we can see that we cannot get the maximum power of the engine and the lowest fuel consumption with the same air fuel ratio. The lowest fuel consumption (best fuel economy) is obtained with lean air fuel mixtures, with an AFR of 15.4:1 and an equivalence factor (λ) of 1.05. The maximum engine power is produced with rich air fuel mixtures, with an AFR of 12.6:1 and an equivalence factor (λ) of 0.86. With a stoichiometric air fuel mixture ($\lambda = 1$), there is a compromise between maximum engine power and minimum fuel consumption [77].

3.3.6 PID Controller

The PID controller with its proportional (Kp), integral (Ki) and derive (Kd) gains is given in the form of a transfer function in Equation. (13) [78].

$$G_{pi} = \frac{u(s)}{e(t)} = k_p + \frac{k_i}{s} + k_D \qquad (13)$$

The closed-loop response influenced by the type of control through the controller and also performs a transformation on the error signal to satisfy criteria includes:

- Steady states errors
- Transient responses
- Disturbance

An Eq. (2), the PID gains need to be properly tuned to obtain the best system performance, i.e, short transient and stability for the closed-loop system, demonstrated in Figure 16 . Ziegler Nichols method has been extensively studied for optimal tuning of the PID controller parameters [79]. However, these parameters need to be manually tuned until prescribed system specifications are met. This motivates us to utilize a global optimization strategy for the PID controller parameters selection over the entire operation ranges.

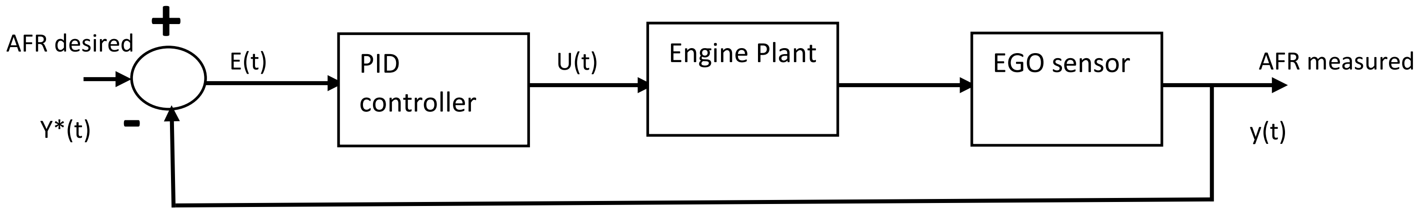


Figure 16. Closed Loop structure

In this study, the designed PID controller aims to optimally improve the dynamic behavior of the closed-loop system. The objective function should include percent overshoot, rise time, settling time, and steady-state control criteria's.

Development AFR controller for our engine model example with a first order transfer function and would have the following form:

$$G(s) = \frac{AFR(s)}{U(s)} = \frac{k_{l,e}}{s+T_{l,e}s}\ e^{-T_{d,e}} \quad (14)$$

Where,
AFR(s)= is the air fuel ratio
U(s)= is the control variable
In order to better understand the performance of a closed-loop system, it is helpful to consider the open-loop response. We assume:

- K=1.1;
- T= 0.07 sec;
- $T_{d,e} = 0.0.5\ sec$;

Now, we will determine P and I gain value to obtain the step response characteristics and construct a block diagram in Simulink.

P= 1, I= 3.7

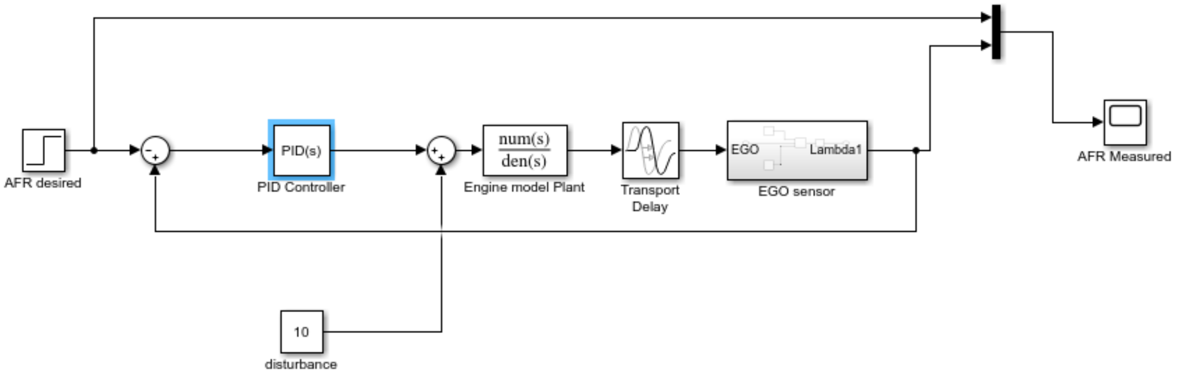


Figure 17. Simulation Closed Loop structure

Using the parameters from this example, its possible to evaluate the response via simulation using MATLAB/ SIMULINK (figure 18).

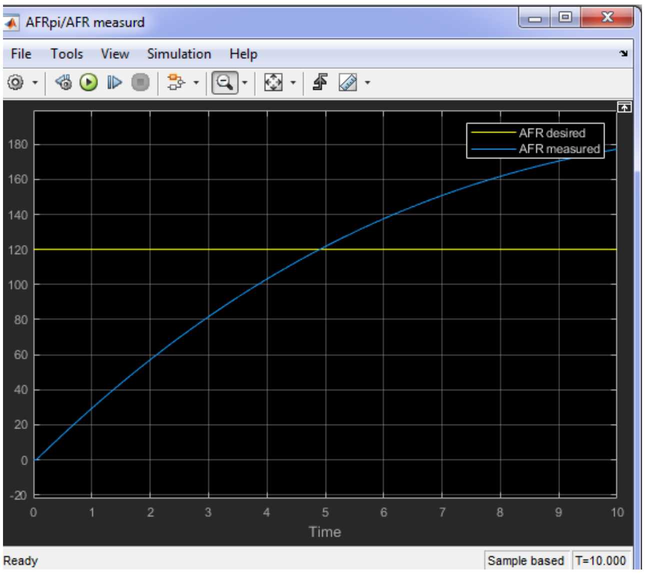
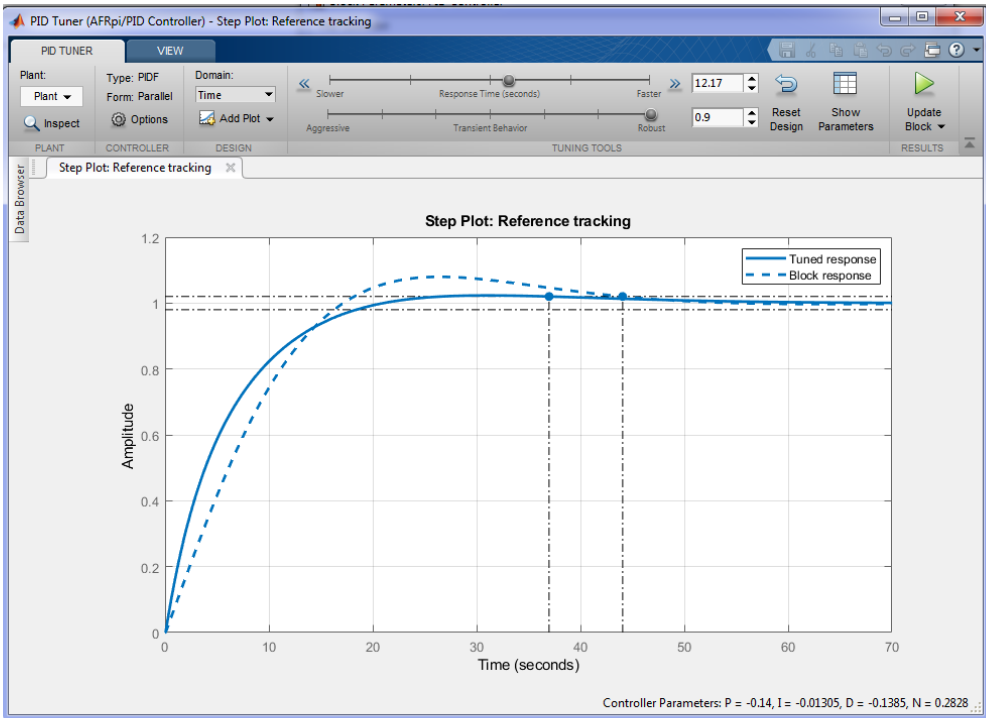


Figure 18. Unit step response of closed-loop system

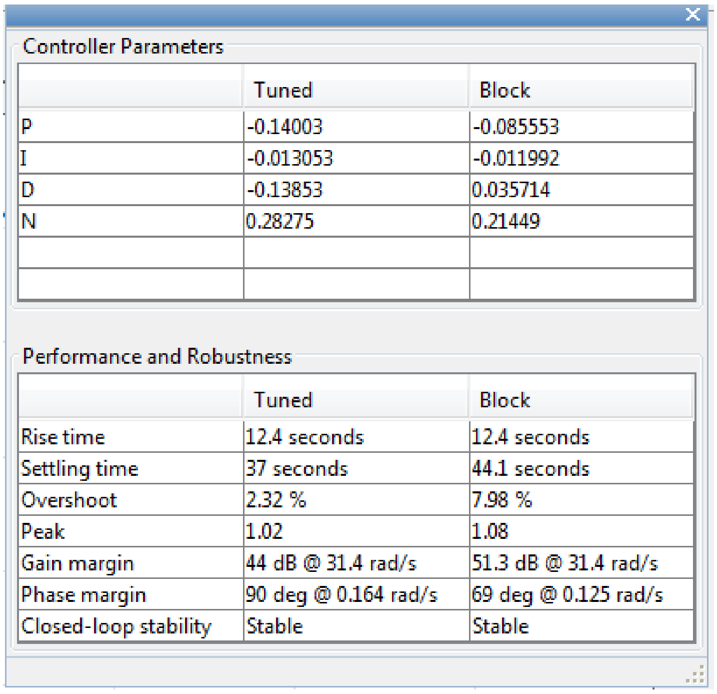
On the PID tuning, which will show the open loop response in dotted line and closed loop (feedback) response in thick line, and we can regulate with the slides on top of this window to get the desired response.



Type: PIDF
Form: Parallel
Domain: Time
12.17
0.9

Controller Parameters: P = -0.14, I = -0.01305, D = -0.1385, N = 0.2828

Figure 19. Step plot response of PID control



Controller Parameters

	Tuned	Block
P	-0.14003	-0.085553
I	-0.013053	-0.011992
D	-0.13853	0.035714
N	0.28275	0.21449

Performance and Robustness

	Tuned	Block
Rise time	12.4 seconds	12.4 seconds
Settling time	37 seconds	44.1 seconds
Overshoot	2.32 %	7.98 %
Peak	1.02	1.08
Gain margin	44 dB @ 31.4 rad/s	51.3 dB @ 31.4 rad/s
Phase margin	90 deg @ 0.164 rad/s	69 deg @ 0.125 rad/s
Closed-loop stability	Stable	Stable

Figure 20. PID control parameters

The PID parameters as shown in the table and both the graphs are shown in the figure.

The PID controller is:

$$C = k_p + \frac{k_i}{s} + \left(\frac{k_d}{Tf\ s+1}\right) \qquad (15)$$

With k_p =-0.0855, $k_i = -0.119$; $k_d = 0.0357$ and $Tf = 0.214$

3.4 Idle Speed Control Model:

3.4.1 AN EXAMPLE OF TRANSFER FUNCTION OF LINEARIZED ENGINE IDLE SPEED MODEL

For the ISC model, a nonlinear engine model established on the above set of models was linearized at a nominal speed of 600 rpm to access a linear plant model. Seeing deviation in throttle position in degrees is input, and deviation in engine speed in rpm is the output for this model. The transfer function [80-86] is:

$$G(s) = K \, \frac{s^2+n_1 s+n^2}{s^3+d_1 s^2+d_2 s+d_3} \quad (16)$$

The delay is a third-order function and a degree one for the plant transfer function. K, s, d1, d2, d3 are the distinct parameters of the heat engine model. Their values are maintained as nominal values under engine operating conditions. The nominal values of the constant parameters are as follows:

- K=30;
- S =1;
- n1 = 50; n2 = 875;
- d1 = 35; d2 = 56.9; d3 = 195.5

The Induction of Power delay at a nominal speed of 600 rpm is 125 ms assuming this delay results from 3600 crank rotation or one revolution of the crankshaft. However, we are getting this revolution only as an approximation because we do not receive maximum torque calculation at the top dead center of crankshaft rotation. Therefore, we receive an overall delay of 150ms by the combination of actuator delay and computational delay.

4. Controller:

Control theory deals with dynamic systems such as internal combustion engines, aircraft, industrial manufacturing, conveyor belts, reading and writing from hard drives, other processes such as keeping satellites in place above the earth, sun-tracking control of solar collectors, etc. last but not least several biological functions. The objective is to control the systems mentioned above sufficiently. This includes a system with good stability, robustness to exogenous disturbances, and minimum oscillations. To achieve this, a controller and a feedback action are necessary.

4.1 Feedback loop

Feedback (closed loop) is a process occurred when the output of a system is returned to a point as an input. This process generates a chain of cause and effect called the feedback.

At its basic form, a feedback control system has three components:

- a system that needs to be controlled which is called a plant
- a controller to alter the plant's input signal
- a feedback loop

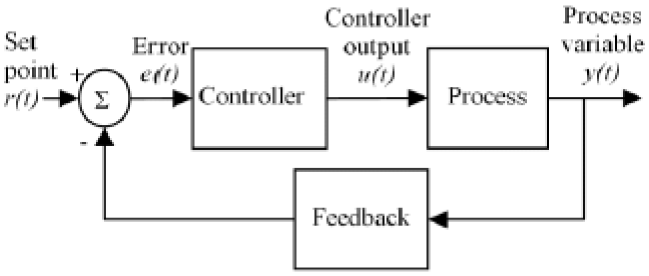


Figure 21. schematic diagram of a general automatic control system [87]

The elements of a closed-loop system are illustrated in Figure 21 Below, we describe these elements and the information, or signals 1, that flow between elements:

- The dependent variable, called output is the quantity or signal of the controlled system that is directly measured and controlled
- The independent variable, called input or desired value is the value that the output variable needs to converge with.
- The output signal of the feedback is a signal of the controlled output which is sent back to the input to be compared with the desired value.
- The error is the difference between the desired value and the controlled output.
- The disturbance is any exogenous change that affects the output signal.

4.2 Control Properties

- Accuracy

  The control system is accurate if the output signal converges (or reaches sufficiently close) to the desired value, or more generally if an actual controlled process is approaching the desired process.

- Robustness

  Most of the time, control systems are subjected to unwanted signals that alter the desired behavior. With the use of a feedback loop, the sensitivity of a control system to these disturbances can be reduced. Robustness is the ability of a closed-loop control system to function correctly when subjected to exogenous disturbances. More specifically, as [88] reports, robustness is the ability of a closed-loop system to sufficiently ignore exogenous noise.

- Stability

  A stable system is a system that produces a bounded output for a given bounded input. Generally, for a stable system, oscillations must die out as early as possible or steady state2 should be reached fast. Stability is typically the first property considered in constructing control systems since unstable systems are not often used.

- Miscellaneous

  If a control system converges quickly to its desired state, it is said to have a short settling time. As defined by Tay, Mareels, and Moore in [89], settling time is the time appropriate for the response curve to influence and stay within a range of a certain percentage (usually 5% or 2%) of the final value. In a control system, overshoot occurs when the output signal exceeds the desired input. As defined by Katsuhiko Ogata in [90], overshoot is the maximum peak value of the response curve measured from the correct response of the system.

4.3 PID design In PID Tuner

We commonly use the PID controller to bring the frequency, voltage, and other parameters to their original value in the power system. However, tuning the PID controller is very difficult. Most of the time, hit and trial methods are used, which is highly time-consuming. Furthermore, despite so much time, it still fails to provide the best response. However, now no need to worry about the PID tuning of any system. MATLAB software in its latest versions has provided the PID Tuner [91].

In this PID Tuner, we just must put the model's response from Simulink, and it will automatically provide the tuned response within a fraction of seconds.

The PID control system is used in this Idle Speed Control problem to address the speed changes in the system for a continuous-time linearized plant model.

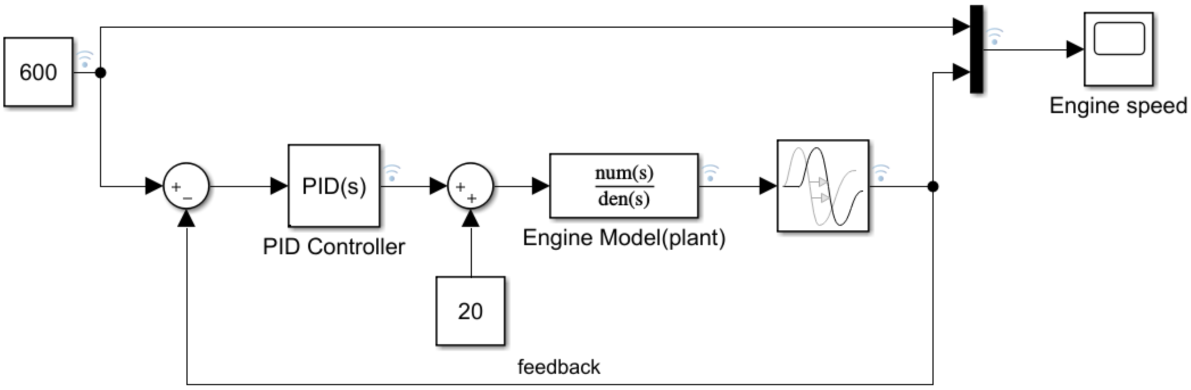


Figure 22. Block diagram of Engine model of Idle Speed Control with PID controller

4.4 Three-Term Functionality design:

A proportional–integral–derivative controller (PID controller or three-term controller) must be individually adjusted or tuned. Based on the difference between these values, a correction factor is calculated and applied to the input. In the case of the PID controller, to achieve a desired performance, the user needs to select carefully the amount of each control action: proportional, integral, and derivative.

- **Proportional**

The “proportional” term is often called the “P” constant; This parameter can also be called “Proportional band” and measured in the unit of percent. For controllers that use the term “Gain,” adjusting this tuning parameter higher may cause more sensitive, less stable loops. Conversely, on controllers with proportional band units, decreasing this tuning parameter affects the loop in the same manner. A control used is directly proportional to control error with controller gain of the system. Proportional control is used as the simplest form of feedback like:

$$U(t)= k\ e(t) \qquad (17)$$

Where ;

- u (t) is the used control;
- K is the controller gain;
- e (t) is the control error.

❖ Integral

The integral term can be different measurements as well; there are “repeat per second,” “second per repeat,” “repeat per minute,” and minute per repeat.” Essentially, regardless of the measurement type, the integral is the sum of all the values reported from the signal, captured from when we started counting to when we completed counting or the area under a plotted curve. This parameter can be called Ki, Ti, or other and the main function of Integral is to determine how fast the steady-state error is removed because of the different measurements. This parameter may not be as intuitive to adjust. In Proportional Control, we notice that control requires a control error in order to have a non-zero control signal. But in the integral controller, a small positive error will always lead to an increased control signal.

$$U_0 = K[e_0 + \frac{e_0}{T}\ t] \qquad (18)$$

Where

- u0 is the control;
- K is controlled gain;
- e_0 is controlled error;
- T is integral time to eliminate error;
- t is a function of control.

❖ Derivative

The purpose of Derivative is used to improve the stability of closed loop in a plant model and predict the change in correction for an error of control. The derivative action acts of the rate of change measured in the process variable and also will predict the error change to controller Td seconds before it can happen in the future (basically means how far in the future we would to predict the rate of change). Initially, the checking starts at Td seconds, but when the Derivative is too large, then it becomes oscillatory.

TABLE I EFFECTS OF INDEPENDENT P, I, AND D TUNING

Closed-Loop Response	**Rise Time**	**Overshoot**	**Settling time**	**Steady-state error**	**Stability**
Increasing K_P	Decrease	Increase	Small increase	decrease	Degrade
Increasing K_I	Small decrease	increase	Increase	Large decrease	degrade
Increasing K_D	Small decrease	Decrease	Decrease	Minor change	Improve

5. Simulation Results

We are practicing some experiments in order to find whether the positions of Proportional, Integral, and Derivative matches correctly to the requirements of the linearized plant model. Since the plant model has a robust behavior hence, we will be practicing PID tuning methods manually on various values to get a linear curve

Case 1:

So, we see that the parameter of P, I and D for our model are 1, 0.25 and 0.28 respectively with Filter Coefficient (N) = 100.

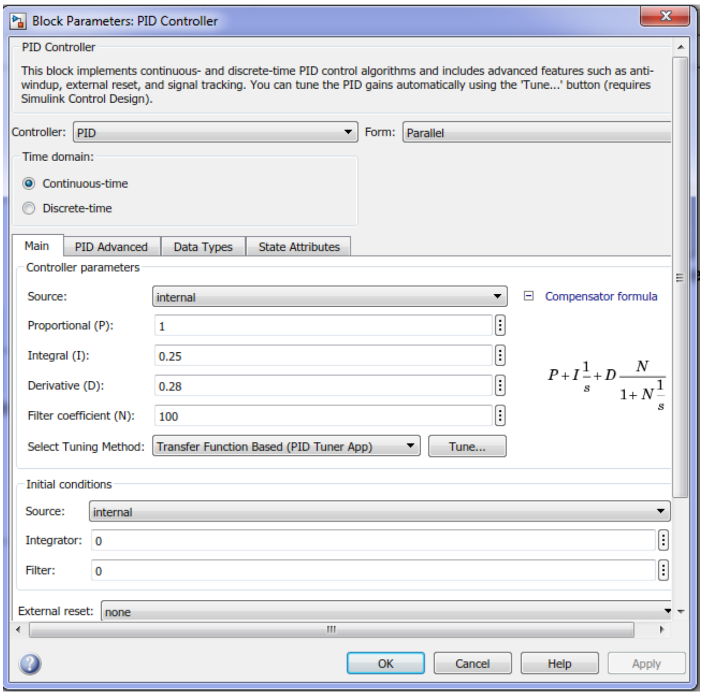
The controller settings are as follows:

P= 1;

I= 0 .25;

D=0.28;

N=100;



Block Parameters: PID Controller

PID Controller

This block implements continuous- and discrete-time PID control algorithms and includes advanced features such as anti-windup, external reset, and signal tracking. You can tune the PID gains automatically using the 'Tune...' button (requires Simulink Control Design).

Controller: PID

Form: Parallel

Time domain:

● Continuous-time

○ Discrete-time

Controller parameters

Source: internal

Proportional (P): 1

Integral (I): 0.25

Derivative (D): 0.28

Filter coefficient (N): 100

Select Tuning Method: Transfer Function Based (PID Tuner App)

Compensator formula

$$P+I\frac{1}{s}+D\frac{N}{1+N\frac{1}{s}}$$

Initial conditions

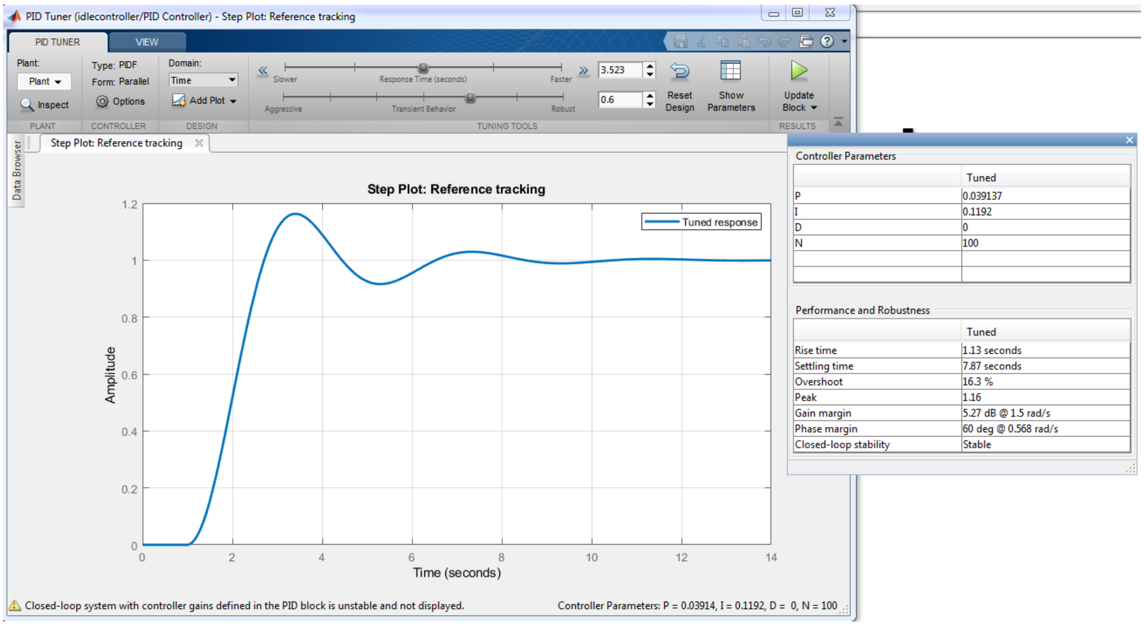
Source: internal

Integrator: 0

Filter: 0

External reset: none

Figure 23. Block parameter: PID controller



PID Tuner (idlecontroller/PID Controller) - Step Plot: Reference tracking

Plant: Plant

Type: PIDF

Form: Parallel

Domain: Time

Response Time (seconds): 3.523

Transient Behavior: 0.6

Step Plot: Reference tracking

Controller Parameters

	Tuned
P	0.039137
I	0.1192
D	0
N	100

Performance and Robustness

	Tuned
Rise time	1.13 seconds
Settling time	7.87 seconds
Overshoot	16.3 %
Peak	1.16
Gain margin	5.27 dB @ 1.5 rad/s
Phase margin	60 deg @ 0.568 rad/s
Closed-loop stability	Stable

Closed-loop system with controller gains defined in the PID block is unstable and not displayed.

Controller Parameters: P = 0.03914, I = 0.1192, D = 0, N = 100

Figure 24. Step Plot Reference Graph with PID control parameters

If we notice the graph, it still contains significant overshoot and a very long settling time. A graph would show more clearly the closed-loop system with steady gains defined in the PID block is unstable and not displayed. The rising response time is 1.13 seconds, settling time is 7.87 seconds, zero error steady-state time is 12.5 seconds at Amplitude one.

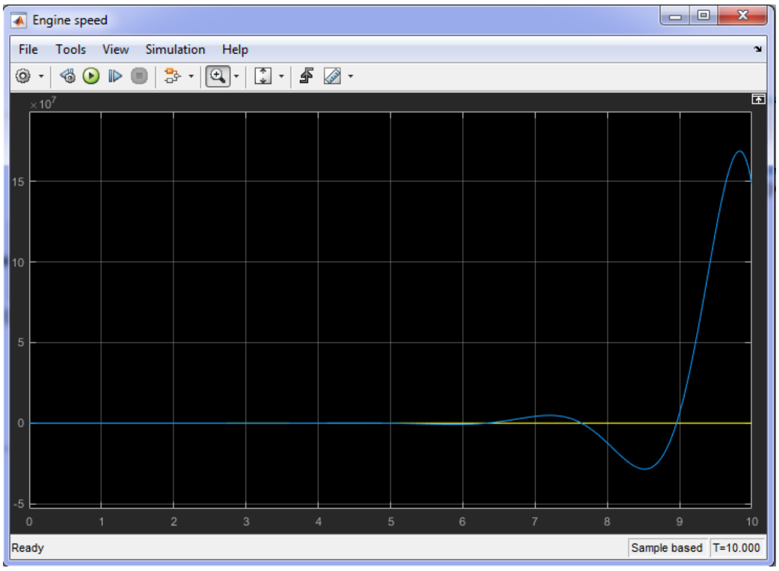


Figure 25. Simulink of Idle Speed Control of Engine

Via Simulink, we receive an unstable curve for Idle Speed control of an engine model. We look for that as the time response increases, the plant model gets highly unstable in a robust control model. Hence, the PID control system of the plant model is not stable at the given points.

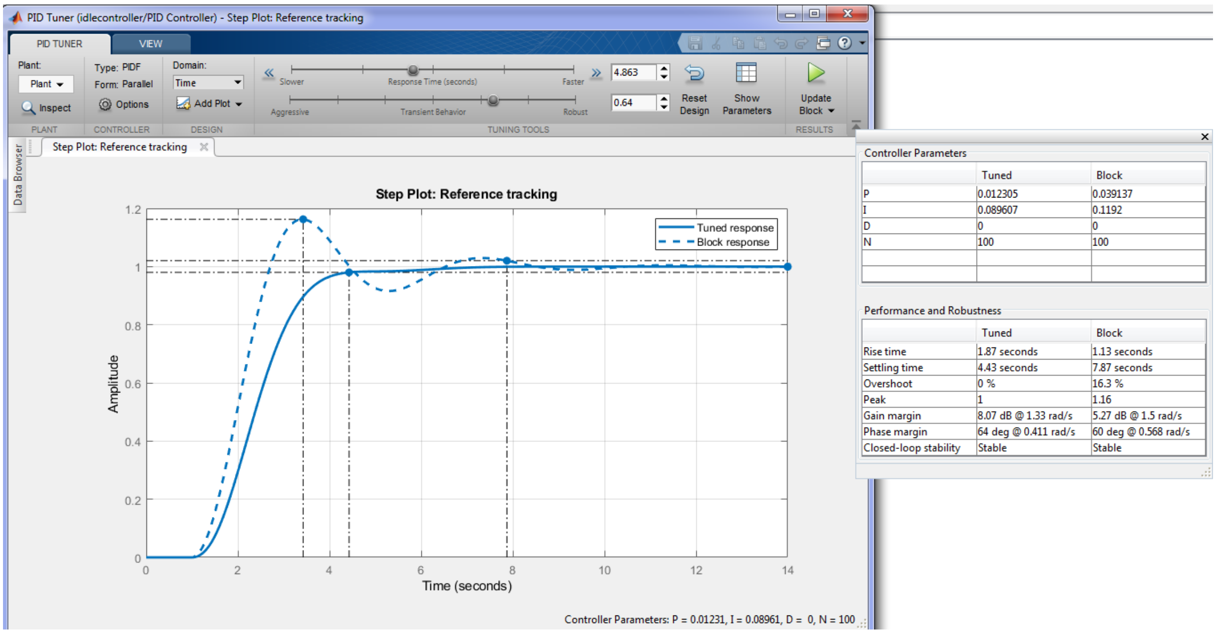
Case-2:

The controller settings are as follows:

P= 0.039137;

I= 0.1192;

D= 0;



PID Tuner (idlecontroller/PID Controller) - Step Plot: Reference tracking

Type: PIDF

Form: Parallel

Domain: Time

Response Time (seconds): 4.863

Transient Behavior: 0.64

Controller Parameters

	Tuned	Block
P	0.012305	0.039137
I	0.089607	0.1192
D	0	0
N	100	100

Performance and Robustness

	Tuned	Block
Rise time	1.87 seconds	1.13 seconds
Settling time	4.43 seconds	7.87 seconds
Overshoot	0 %	16.3 %
Peak	1	1.16
Gain margin	8.07 dB @ 1.33 rad/s	5.27 dB @ 1.5 rad/s
Phase margin	64 deg @ 0.411 rad/s	60 deg @ 0.568 rad/s
Closed-loop stability	Stable	Stable

Controller Parameters: P = 0.01231, I = 0.08961, D = 0, N = 100

Figure 26. Step plot Reference Graph with PID control parameters

Therefore, we will use the PID tuner to tune it properly to have zero overshoot and a short settling time.

Also, we see the different parameter values of both block and tuned response on controller parameters in order to compare their performance. From this comparison, it may notice that the tuned response has a significantly more minor settling as well as smaller overshoot compared to the initial voltage response.

Therefore, for further tuning, The PID tuner has given these two sliders; the top slider is used to make the system response faster or slower by dragging the button. At the same time, a button slider is used to make the system more robust stable.

So, a graph would show more clearly that a closed-loop system with steady gains defined in the PID block is stable before and after the tuning process. The rising time of response is 1.87 sec, settling time is 4.43 sec, zero error steady-state time is infinite sec at Amplitude one.

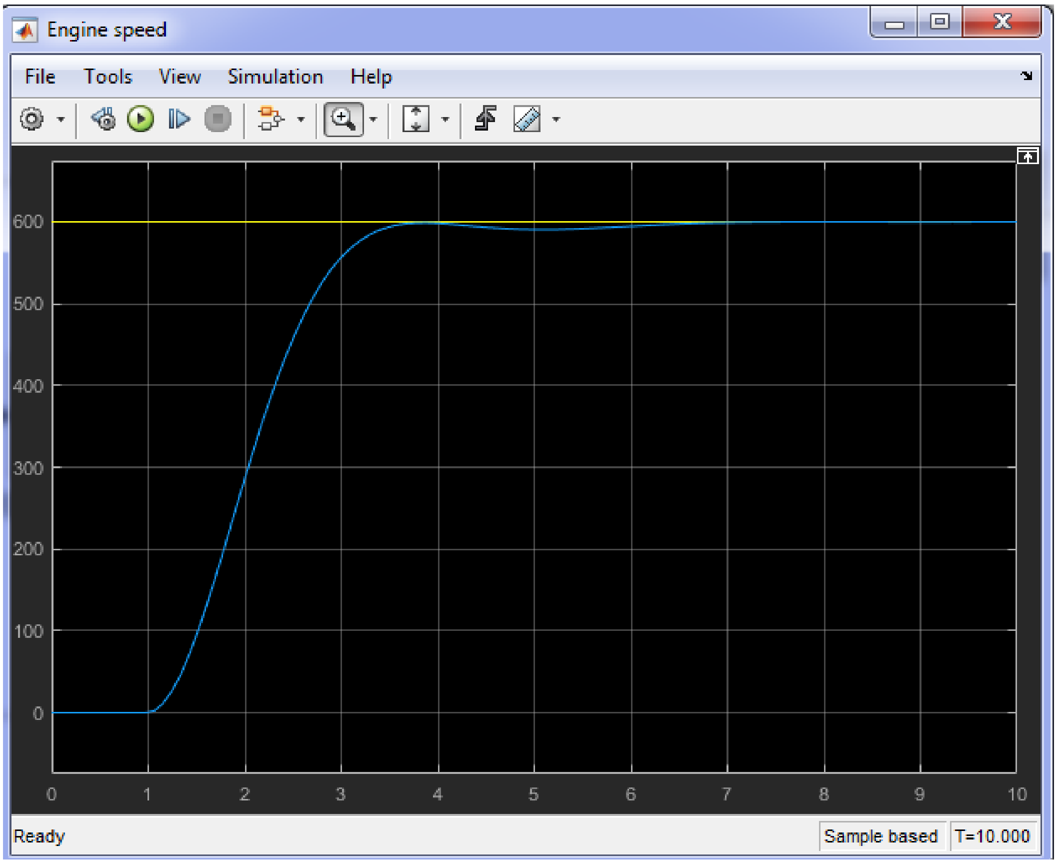
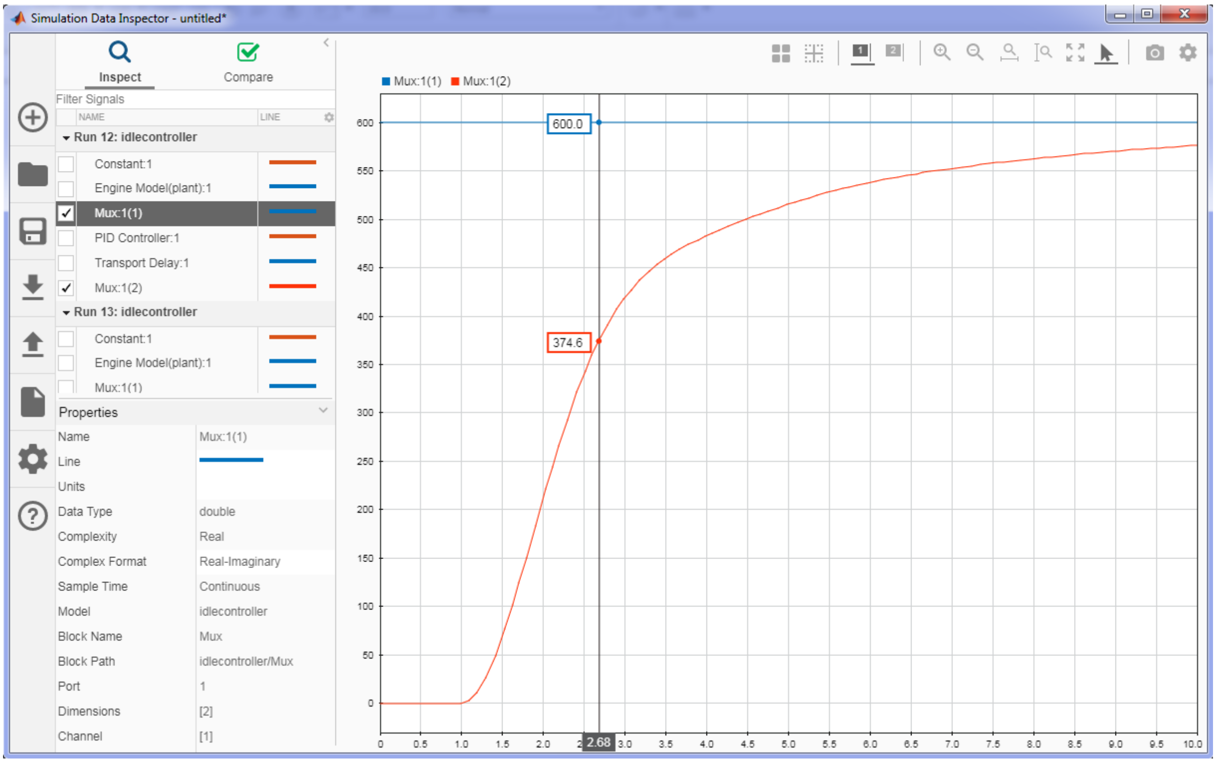


Figure 27. Simulink of Idle Speed Control of Engine

In the final Simulink graph, we receive a stable curve for Idle Speed Control of an engine model. We discover that the time response increase or decrease does not affect the plant model stability in a robust control model. Hence, the PID control system of the plant model is stable at the given points.

At this stage, I would like to highlight another important point; the Simulink simulation data inspector has another good feature to compare the previous response with the new response.



Run 12: idlecontroller
☐ Constant:1
☐ Engine Model(plant):1
☑ Mux:1(1)
☐ PID Controller:1
☐ Transport Delay:1
☑ Mux:1(2)

Run 13: idlecontroller
☐ Constant:1
☐ Engine Model(plant):1
☐ Mux:1(1)

Properties

Name	Mux:1(1)
Line	
Units	
Data Type	double
Complexity	Real
Complex Format	Real-Imaginary
Sample Time	Continuous
Model	idlecontroller
Block Name	Mux
Block Path	idlecontroller/Mux
Port	1
Dimensions	[2]
Channel	[1]

Figure 28. Simulation Data Inspector

6. Conclusion and future work

Conclusion

The control system has been suggested to convert the nonlinear model to a linearized plant model: this control system is called Proportional, Integral, and Derivative (PID). Therefore, we characterized the engine model based on certain aspects and analyzed it accurately to fit in the system. Simulations were performed using the PID controller to regulate and maintain the output response while rejecting any input disturbance.

An engine model of a control system shows an essential role in defining the correct parameters. Hence, Idle speed control is principal of the highest confrontations for the automotive industry and developers as they were addressing many issues concerning engine at rest position and fuel-saving economy.

We keep many experiments with changing values of the PID control system. Through Simulink graphs, we compared different results and were able to find the correct value for the Idle Speed Control of the engine model. Hence, this system control predicts the control change in the system for stable equilibrium. Via manual tuning of PID control parameters, we were able to linearize the plant model and determine the correct parameters of the plant model.

This study also presents an AFR control for the engine model. The main contribution is that AFR regulation is reformulated as a tracking control for the required injected fuel. To obtain a better response, the output measurement is added to a predefined AFR control.

The parameter tuning is straightforward, while better AFR control response and reduction can be achieved compared to the PID control. The AFR control has been studied for internal combustion engines based on the mean value model. The control design method based on nonlinear feedback control and their control performance has been investigated for different cases.

The simulation results show that the controller applying the nonlinear feedback control could give satisfactory AFR regulation performances for our engine model with specific load disturbance.

future work

While a vast amount of research results is published in the literature, there exists a lack of information exchange and analysis. Engine Idle speed and air fuel ratio has gotten lower over the years due to improved design. This has translated to better fuel economy. Automakers are continuing to do significant research in this area, few of which are discussed. So, we will present a modern overview of functionalities and tuning methods in patents, software packages, and commercial hardware modules. many PID variants have been designed in order to increase transient performance, but standardizing and modularizing PID control is desired, although challenging.

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