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Model-Based Development (MBD) for Torque Controls in Spark-Ignition Engines

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Abstract

Spark-ignition (SI) engine torque controls play a crucial role to ensure that vehicle drivability, performance, and emissions compliance goals are met. Engine Control unit (ECU) implements the torque based supervisory controls through the regulation of air, fuel and spark. With the increased complexity of engine controls it is necessary to employ the structured development methodologies to ensure consistent performance. Model Based Development (MBD) methodology for torque generation has been employed, with the framework structured to flow down the stakeholders being decomposed into functional requirements, controls architecture development and executable model implementation. With these controls executable models in place the controls verification and tuning is performed on virtual environment platforms using Model-in-loop (MIL), Software-in-loop (SIL), Hardware-in-loop (HIL) and deployment on the actual engine in a test cell. MBD provides an integrated approach from the Requirement development, controls execution, verification and deployment for the controls development proving to be reliable methodology for the complex multi-input-multi-output (MIMO) controls systems

Keywords: *SI engine, MBD*

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I. Introduction

Conventional powertrains have Internal Combustion Engine (ICE) serving as the primary source of torque generation and SI engines account for the majority of passenger vehicles with as high as 90% in the US market. Torque controls development plays a crucial role along with Emission Driveability (D&E) calibration in ensuring that vehicle emission compliance goals are met.

SI engines, torque is generated with a controlled combustion of premixed air-fuel charge initiated by spark ignition (SI) during the power stroke. The combustion of air-fuel charge generates the thermal energy in the form of the heat, which increases the pressure in the engine cylinder. The generated pressure is applied on the piston head and causes the crankshaft rotation and thus producing mechanical torque. The generated torque is transferred via flywheel, which is on other hand connected to transmission for the eventual transfer of torque to wheels of automobile

Controls perspective of torque generation is not a direct command of demanded torque to the engine but an complex Coordinated regulation of air, fuel and Ignition timing accounting the ambient and environmental conditions. The realization of torque based control is enabled through a set of sensors that stand as backbone to provide the ground truth to the supervisory controls and for the decision and actuation. The sensors allow the ECU to estimate the driver demand torque, engine speed, load conditions, thermal state of engine and ambient air conditions. This information be used to manage the operating model of the engine such as stall, cranking and normal running conditions of the engine

The development of the engine control systems, has the increasing level of interaction between the various sub-systems, and the complexity in the calibration process have highlighted the need to overcome the challenges associated with the document-based development approach. To overcome the challenges associated with the document-based development approach the Model-Based Development (MBD) approach has been widely adopted as the most popular methodology for the development of the engine control systems.

In this article the review and the application of the Model-Based Development approach for the development of the engine controls for the torque generation of the SI engines is presented using the representative production engine.

II. Sensors and Actuators

Spark Ignition (SI) engine utilizes torque-centric control approach in which engine torque is considered as a controlled variable. It is not directly measured; rather it is estimated and controlled through the coordinated interpretation of sensor inputs and actuator behavior. In the following section the roles of major sensors and actuators in torque generation controls are described

Torque Controls Generation Sensors:

Accelerator Pedal Position (APP) sensor reflects the driver's demanded torque and it's calibrated with pedal-to-torque maps referenced to engine speed and engine conditions.

Fig.1 Images of Accelerator Pedal Position (APP), Crankshaft Position, Camshaft Position and Mass Air Flow Sensors

Crankshaft Position and Speed (CKP) sensor indicates Engine Speed in RPM and Crank Shaft Angle Reference. Engine Speed is used for idle speed control, engine over-speed protection, and with dynamic estimation of engine torque. Crank Shaft Angle Reference is used for fuel injection and spark synchronization.

Camshaft Position (CMP) sensor is used for cylinder identification, allowing for sequential fuel injection and spark control, which is necessary for synchronization.

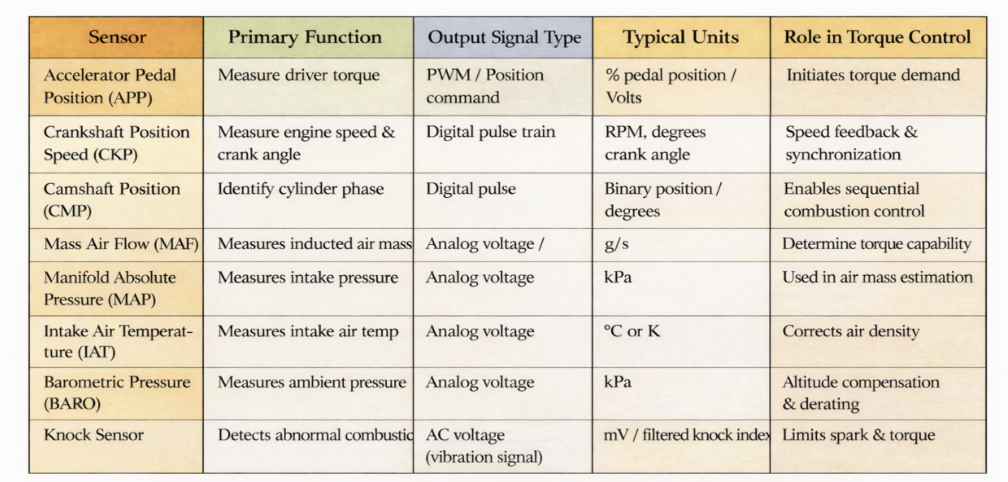
Mass Air Flow (MAF) sensor alternatively, a Manifold Absolute Pressure (MAP) sensor is used for Air mass estimation. In SI engines, torque is directly proportional to the amount of air drawn into the engine under stoichiometric conditions.

Fig.2 Images of Intake Air Temperature (IAT), Barometric Pressure (BARO), Engine Coolant Temperature (ECT) and Knock Sensors

Intake Air Temperature (IAT) and Barometric Pressure (BARO) sensors provide the environmental compensation The sensor inputs are used to correct the air density calculations, providing a consistent output of torque estimation.

Engine Coolant Temperature (ECT) sensor provides necessary information in terms of temperature, allowing compensation during the engine warm-up and idle cycle, and providing the necessary torque derating for engine protection.

Knock sensor is used to detect abnormal combustion in the engine. During the abnormal combustion, the spark timing is retarded, and the torque is reduced, thus capping the torque at a certain level.



Sensor	Primary Function	Output Signal Type	Typical Units	Role in Torque Control
Accelerator Pedal Position (APP)	Measure driver torque	PWM / Position command	% pedal position / Volts	Initiates torque demand
Crankshaft Position Speed (CKP)	Measure engine speed & crank angle	Digital pulse train	RPM, degrees crank angle	Speed feedback & synchronization
Camshaft Position (CMP)	Identify cylinder phase	Digital pulse	Binary position / degrees	Enables sequential combustion control
Mass Air Flow (MAF)	Measures inducted air mass	Analog voltage /	g/s	Determine torque capability
Manifold Absolute Pressure (MAP)	Measures intake pressure	Analog voltage	kPa	Used in air mass estimation
Intake Air Temperat-ture (IAT)	Measures intake air temp	Analog voltage	°C or K	Corrects air density
Barometric Pressure (BARO)	Measures ambient pressure	Analog voltage	kPa	Altitude compensation & derating
Knock Sensor	Detects abnormal combustic	AC voltage (vibration signal)	mV / filtered knock index	Limits spark & torque

Fig.3 Sensors used for Torque Generation in SI Engines

Torque Controls Generation Actuators:

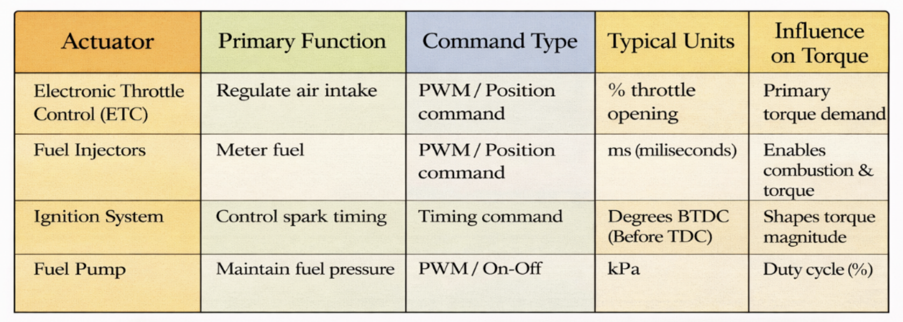
Electronic Throttle Control (ETC) Actuator is the primary torque actuator in SI engines. The throttle, through the amount of inducted air, determines the upper bound of the available torque.

Fuel injectors are used to inject fuel in proportion to the mass of inducted air, thereby maintaining the desired air-fuel ratio. Though the amount of fuel does not provide a means to increase the amount of torque beyond the air mass bound in a stoichiometric mixture, it is used to provide stability in the mixture and thereby allow accurate torque control.

Fig.4 Images of Actuators in SI Engine - Electronic Throttle Control, Fuel Injectors, Fuel Pump and Ignition Coil (Actuators)

Ignition system is used to control the spark timing, which has a direct effect on the amount of torque. An advance in spark timing is used to increase the amount of torque, up to the Maximum Brake Torque (MBT) bound, and retard the spark timing to reduce the amount of torque.

Fuel pump is used to ensure the required fuel pressure and delivery capacity. Though the fuel pump does not, in itself, provide a means to increase the amount of torque, it ensures the required amount of fuel is commanded.



Actuator	Primary Function	Command Type	Typical Units	Influence on Torque
Electronic Throttle Control (ETC)	Regulate air intake	PWM / Position command	% throttle opening	Primary torque demand
Fuel Injectors	Meter fuel	PWM / Position command	ms (miliseconds)	Enables combustion & torque
Ignition System	Control spark timing	Timing command	Degrees BTDC (Before TDC)	Shapes torque magnitude
Fuel Pump	Maintain fuel pressure	PWM / On-Off	kPa	Duty cycle (%)

Fig.5 Actuators used for Torque Generation in SI Engines

In a torque-centric SI engine control system, sensors supply the necessary state information, supervisory control calculates a feasible torque command, and actuators implement this torque command via air, fuel, and spark regulation. The accuracy of torque generation depends on the precision of sensors, supervisory control, and actuators.

III. Overview Torque Generation in SI Engine

Torque generation in a spark-ignition (SI) engine occurs through a coordinated interaction between driver demand inputs, supervisory control logic, actuator execution. The control architecture illustrated in the system diagram defines a structured pathway from sensor inputs to mechanical torque delivery at the crankshaft.

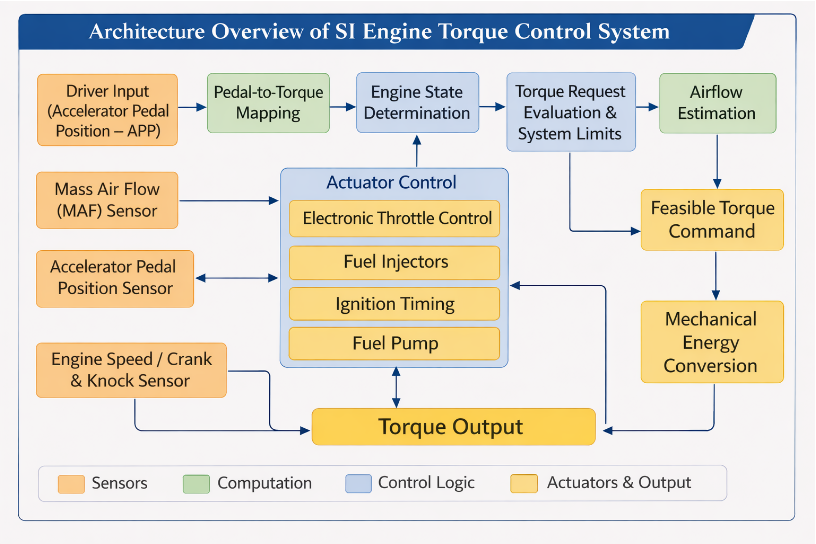


Fig.6 Architecture overview of SI Engine Torque Generation

Driver Demand Interpretation

The first step in the torque production is the Accelerator Pedal Position (APP) sensor, representing the driver's request. The APP is converted into the desired torque request through calibrated pedal-to-torque maps, depending on the engine speed.

Engine State Determination and Mode Control

The state of the engine is determined using feedback signals from the Crankshaft Position and Speed (CKP) sensor, and the engine is categorized as being in either a stall, crank, or run mode of operation.

Torque Request Processing and Limitation

The torque is processed and evaluated under normal run mode operation, and the engine operation is restricted by certain constraints, such as speed limits, thermal restrictions, and shutdown managers, which define the minimum and maximum governor limits for the engine operation. The airflow is estimated using the MAF sensor or by calculating the air per cylinder, and the resulting torque is sent for implementation.

Actuator Command Generation

The actuators control the amount of energy released during combustion. The final torque command is executed through the coordination of the actuators:

- Electronic Throttle Control actuator is responsible for the amount of air induced into the Engine.
- Fuel injectors control the amount of fuel injected into the combustion chamber to maintain the desired air/fuel ratio.
- Ignition timing is used to control the amount of torque generated during combustion.
- Fuel pump control actuator is used to ensure the desired amount of fuel is pumped into the combustion chamber.

Combustion and Mechanical Energy Conversion

The compressed air/fuel mixture is ignited at the top dead center in the combustion chamber. The ignition process results in the combustion of the fuel, leading to the release of thermal energy into the combustion chamber. The thermal energy released results in an increase in temperature in the combustion chamber, leading to the application of force to the piston via the connecting rod, thus rotating the crankshaft.

Closed-Loop Feedback Regulation

The closed-loop regulation is achieved through the feedback from the engine speed and knock sensors, thus ensuring that the torque generated is within the desired limits while at the same time satisfying the constraints of stability and safety.

IV. Framework and Application of Model Based Design (MBD) for the Torque Generation in SI Engines

Model-Based Design Framework

Torque controls strategy is employed with Model-Based Design framework, in which the system requirements were achieved by applying the system architecture using the model-based design tools, primarily the Simulink models

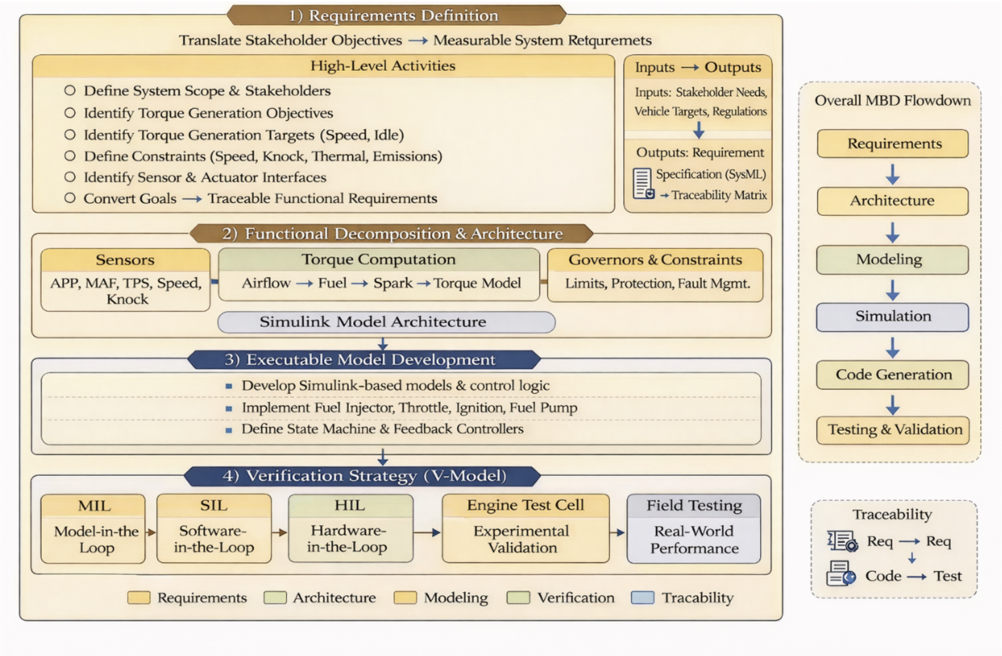


Fig.7 Overview of MBD Framework for SI Engine Torque Controls

Requirements Definition

The system-level torque specifications were defined and traced to the system functional requirements, which are quantifiable and verifiable. The system functional requirements are as follows:

- Accurate relationship between the pedal and the torque, considering the engine speed
- Stable minimum speed regulation (Idle Governor)
- Maximum speed regulation (Overspeed Governor)
- Robust system operation in the stall, crank, and run states
- Safe system operation in the presence of knock and thermal constraints
- Smooth system transient response in the presence of tip-in and tip-out

Functional Decomposition & Architecture

The architecture of the torque control system was designed in the following layered fashion:

- Sensor Abstraction Layer: Processing of APP, CKP, CMP, MAF, IAT, and ECT sensor inputs.
- Supervisory Torque Computation Layer: Processing of pedal demand and computation of torque request.
- Governor and Constraint Layer: Enforcement of minimum and maximum speed limits.
- Mixture and Airflow Control Layer: Computation of air-per-cylinder and fuel-per-stroke values.
- Actuator Control Layer: Computation of throttle duty cycle, injector pulse width, and spark timing values.

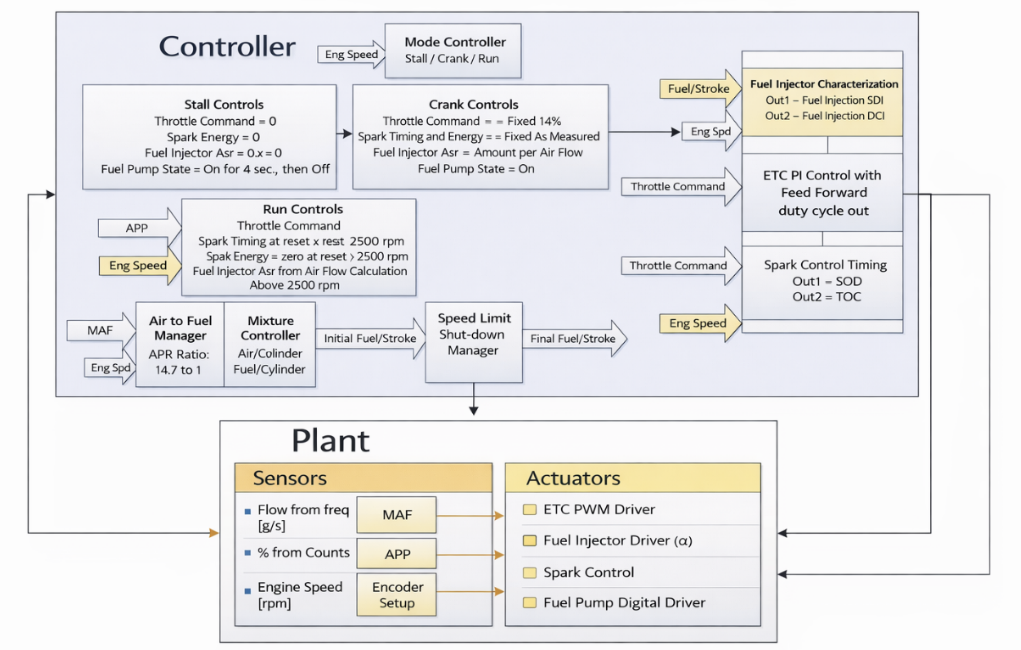


Fig.8 Functional Decomposition & Architecture overview of SI Engine Torque Controls

Executable Model Development

The torque control logic was implemented in the Simulink environment using the following blocks:

- Pedal-to-torque lookup tables driven by engine speed
- Minimum and maximum governor logic driven by engine speed
- Airflow estimation blocks using MAF sensor values
- Stoichiometric mixture control (λ = 1)
- Spark energy and timing control blocks
- Shutdown and protection managers

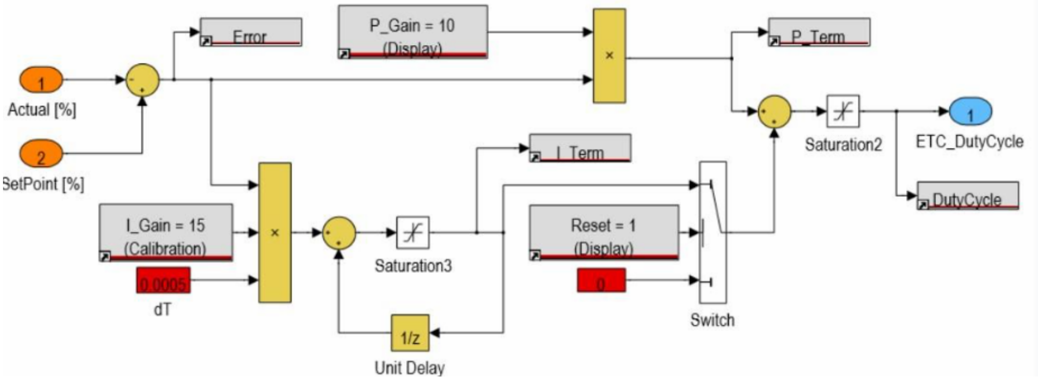


Fig.9 Simulink Model of Throttle Controls

The APP sensor driver demand was converted to a corresponding torque request. Engine speed, derived from the CKP sensor, indexed the torque request against capability maps to ensure the torque request did not exceed physically realizable limits.

The control logic implemented within Simulink is based on a PI controller for the throttle control. The error between the actual throttle position and the setpoint position is computed. A proportional gain is used for the P-term, and the error is integrated using an I-gain with a unit delay and saturation. Finally, the result is limited using saturation to produce the ETC duty cycle.

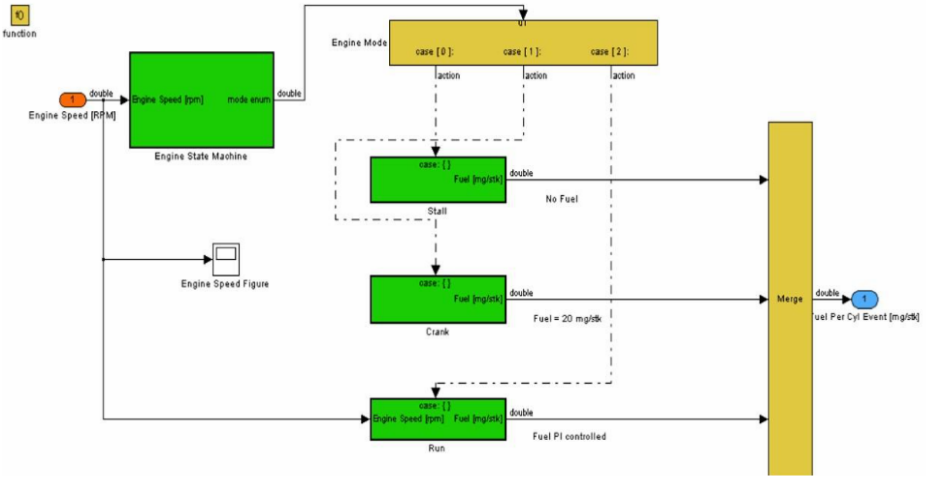


Fig.10 Simulink Model of Engine States

The governor logic is implemented through Simulink for the development of a model-based control framework, wherein the controller controls engine operation through Min/Max limiting stages and an Operating stage.

The minimum limits will set the minimum limits for the throttle, fuel injected, and spark timing so that they can be high enough to allow for combustion when idling or when low engine speed is maintained.

The maximum limits will set the limits for the throttle, fuel injected, and spark timing so that they can be kept low enough so that engine overspeed, fuel consumption, or engine damage does not occur. These limits will be implemented as saturation blocks in the control implemented through Simulink.
The Operating stage governor regulates the closed-loop control of the engine's speed using a PID controller. The inputs from the sensors, such as the engine's speed, airflow (MAF), and throttle position, are continuously compared to the desired setpoint. The PID controller then computes the error value from the difference between the desired setpoint and the current engine's speed. The air/fuel mixture manager computes the amount of required fuel for each cylinder depending on the airflow rate and the desired air/fuel ratio. The fuel injector characterization block computes the injector's on-time, while the spark control block computes the spark timing events. The actuator drivers then send the required actions to the electronic throttle, fuel injectors, fuel pump, and ignition system

Verification Strategy

- Model-in-the-Loop (MIL): Verified torque tracking, governor functionality, and transient response.
- Software-in-the-Loop (SIL): Verified the equivalence of the model and auto-coded C code.
- Hardware-in-the-Loop (HIL): Run the compiled controller code on the ECU hardware with a real-time engine plant simulator.
- Engine Test Cell Validation: Validated torque realization, idle stability, and constraint satisfaction with physical operating conditions.

V. Results

Idle Stability and Minimum Governor Performance

The results achieved in the implementation of the closed-loop simulation and the test cell validation results evidenced the verified idle stability in different load conditions. The overshoot behavior is possible with a dynamic ramp generator function which establishes a smooth transition to desired set point. The controls functions are verified on MIL/SIL/HIL/Engine Test Cell

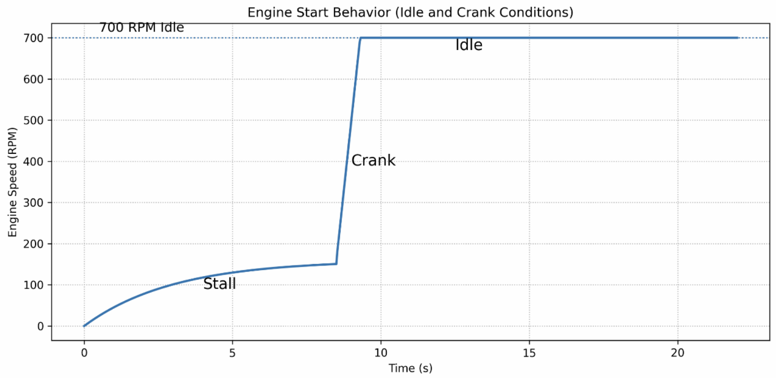


Fig.11 MIL Simulation results of Torque controls identifying the Engine Stall / Crank / Idle States

The profile from simulation testing shows three states - stall, crank, and idle. During stall, engine speed slowly increases as the starter begins rotating the crankshaft. In the crank phase, speed rapidly rises as fuel and spark initiate combustion. Finally, the engine stabilizes at approximately 700 RPM during idle under closed-loop speed control.

Overspeed Protection Efficiency

The maximum governor logic performed satisfactorily in limiting the engine speed during the rapid acceleration condition. The constraint enforcement process occurred smoothly without any interruptions in the engine torque. MIL simulations provided the basis for PI / PID controller logic verification and tuning, thus reducing the controls modification efforts on HIL and Engine test cell

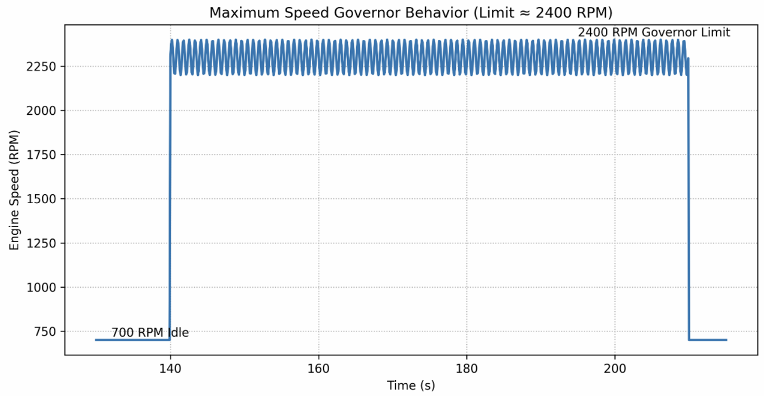


Fig.12 MIL Simulation results of Torque controls identifying the Maximum Speed limits

The maximum speed governor limits engine speed to a calibrated threshold (≈2400 RPM) by regulating fuel and air input, preventing further acceleration and protecting the engine from overspeed conditions.

Verification Efficiency

The MIL-based validation results verified the occurrence of transient oscillations, which were addressed before the verification on Engine Test Cell. The tuning of controls on MIL/HIL proved to be effective during the transient torque request conditions. MBD approach assisted in achieving the integration process in an efficient manner.

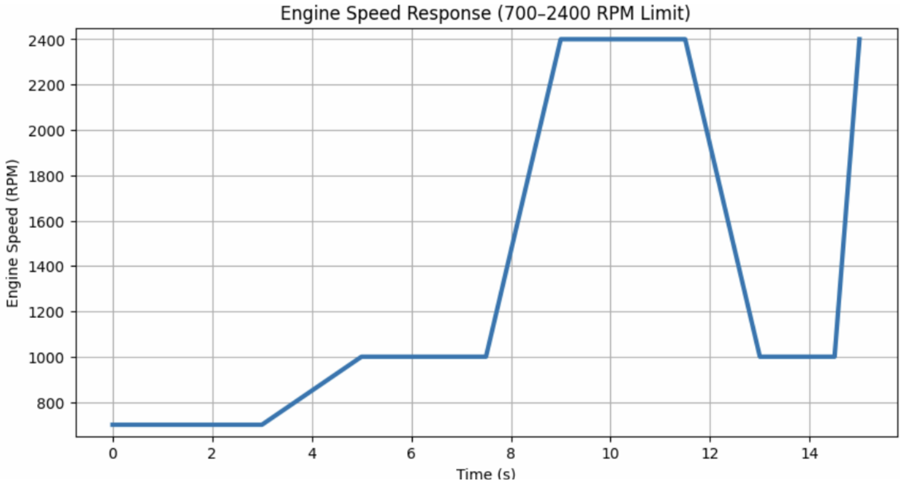


Fig.13 MIL Simulation results of Torque controls during the Run State

Torque requested is incremented with step until engine speed reaches 1000 RPM, this verified the engine entering from idle to Run state. The torque requests are further increased until the speed approaches the maximum limit, the governor restricts further acceleration and stabilizes the engine near 2400 RPM, preventing overspeed while maintaining steady operation.

VI. Conclusion

Structured Model-Based Design (MBD) strategy for torque generation control in SI engines and demonstrated the applicability by developing a supervisory torque control architecture. The proposed architecture includes governor logic, airflow-based torque estimation, and actuator control strategy.

MBD approach enabled:

- Clear traceability from requirements to implementation
- Early validation of torque controls
- Reduced late-stage integration risk

The torque-generation exercise confirmed that a torque-centric supervisory architecture implemented through MBD provides a scalable and robust solution for modern SI engine control systems.

VII.Future Scope

Future developments shall update to plant model with the use of a physics-based engine model that can replace the fixed gain controllers with an adaptive or gain scheduled design. The controls model shall be enhanced with functionalities such as closed loop lambda control with cold start enrichment, power enrichment control schemes, and catalyst light off modeling in order to consider the emission requirements. Furthermore adding the thermal warm up torque behavior and cold start idle behavior can improve the production readiness of the controls model.

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