PRACTICAL TRAINING ON ENGINE MANAGEMENT SYSTEMS AT ROBERT BOSCH ENGINEERING AND BUSINESS SOLUTIONS LTD., INDIA

Practical Training/Internship Report

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By

CHETHAN R REDDY

(11MC04F)

UNDER THE GUIDANCE OF

DR. SHRIKANTHA S RAO

ASSOCIATE PROFESSOR

DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA

SURATHKAL, MANGALORE -575025

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CHAPTER 1

STEPPER MOTOR MODEL FOR IDLE AIR CONTROL ACTUATOR

What is idle control actuator and why is it needed?

An idle air control actuator or idle air control valve (IAC actuator/valve) is a device commonly used in fuel-injected vehicles to control the engine's idling RPM. The IAC actuator is basically an electrically controlled valve, which gets its input from the vehicle's ECU (Electronic Control Unit). The valve is fitted such that it bypasses the actual throttle valve. The actuator usually consists of a solenoid that controls a plunger/valve which variably restricts air flow through the device's body. Electric current through the solenoid determines how much (or less) the plunger constricts air-flow which means that the amount by which the valve opens can be controlled by an electric current. Thus, the ECU can control the amount of air that bypasses the throttle when the throttle is fully closed, thereby controlling the Engine's idle RPM. In Tata Nano (which is the reason to build a Stepper Motor interface), a Stepper Motor is used to actuate the IAC valve, instead of Solenoid actuated valve. The input pulse given to the Stepper Motor, from the ECU, controls the valve opening and hence the mass flow rate.

1.1 MODELLING A STEPPER MOTOR

A SONCEBOZ LINEAR ACTUATOR 7230 (4-pole variable reluctance Stepper motor) was considered, as reference, for modeling the Stepper Motor in MATLAB/Simulink environment.

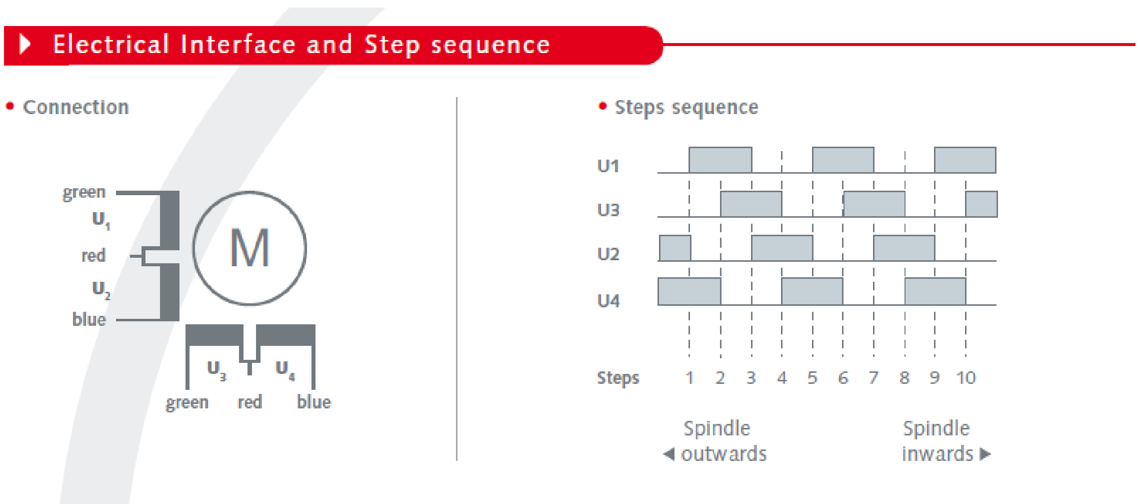
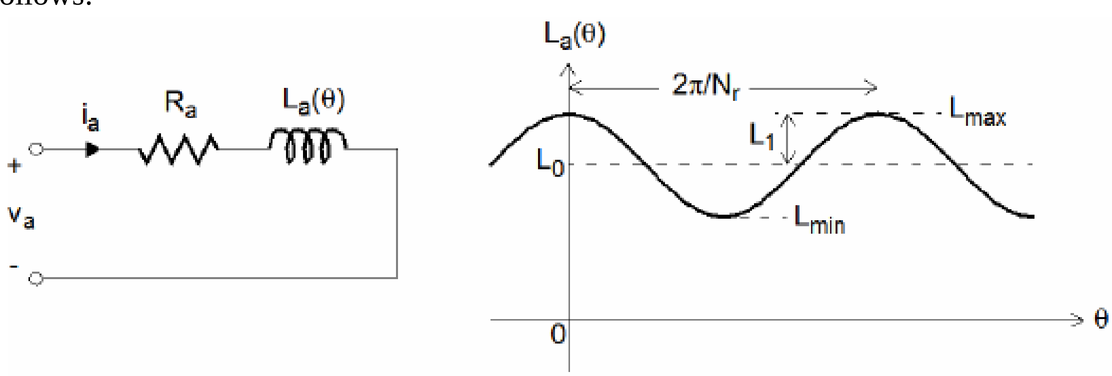


Fig 1: Electrical Interface and step sequence of SONCEBOZ LINEAR ACTUATOR 7230

The basic physics of a variable reluctance Stepper Motor can be summarized as follows:



(a) (b)

Fig 2: VR stepper motor model.
(a) Equivalent circuit for one phase, (b) Winding inductance variation.

In this model, R_a and $L_a(\theta)$ represent respectively the resistance and the inductance of phase A winding. The winding inductance varies as a function of the rotor position and can be approximated as a sinusoidal function:

$$L_a(\theta) = L_0 + L_1 \cos(N_r \theta)$$

Where L_0 is the average inductance, L_1 is the maximum inductance variation and N_r is the rotor teeth number. Note that at the reference position ($\theta = 0$), the rotor tooth is fully aligned with A-axis pole so that the A-phase winding inductance is then maximum.

The total electromagnetic torque produced by the motor is the sum of the torques produced by the motor phases:

$$T_e = \sum_{x=1}^{m} 0.5 i_x^2 \frac{dL_x}{d\theta}$$

Where m is the phase number, i_x is the winding current in phase x and L_x is the inductance function of phase x winding.

The mechanical section is represented by the movement equation:

$$T_e = J \frac{d\omega}{dt} + B\omega + T_L$$

Where J is the total inertia (motor + load), B is the total friction coefficient (motor + load), T_L is the load torque and ω is the motor rotation speed.

1.2 SIMULINK MODEL BUILT

- Stepper Motor

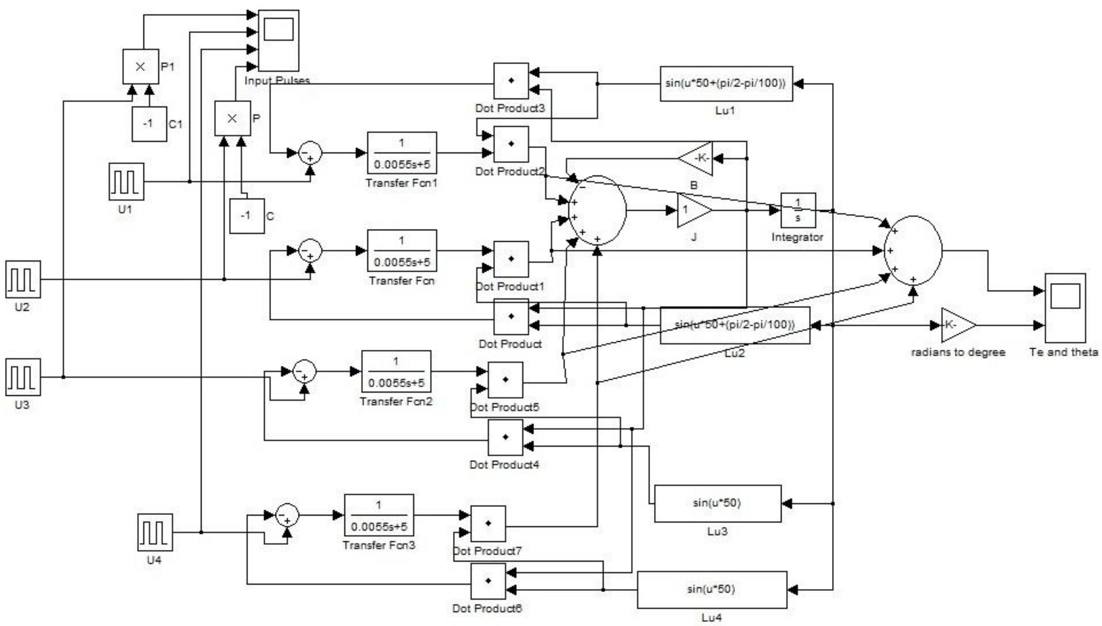


Fig 3: Stepper Motor build on Simulink environment

As we can see in the model built on Simulink environment,

→ U1, U2, U3, U4 represents the 4 poles of the Stepper Motor
→ The denominator of the 4 transfer functions are of the form [1/Ls+R]
→ The poles U1 and U2 are offset by [pi/2-pi/100] i.e. pi/2-half step size
→ The factor 50 in the sine terms is determined by = 360/ (no. of poles*step angle)
→ Therefore, the step angle is 360/ (4*50) = 1.8^0

- Flow model

IAC valve is modeled similar to throttle flow (isentropic compressible flow equation). Here the mass flow rate is given by

$$\dot{m}^i = A_{eff} f(p_u, p_d, T_u, T_d)$$

A_{eff} = Effective area of the orifice, considering the coefficient of discharge

$$f(p_u, p_d, T_u, T_d) = \begin{cases} \frac{p_u}{\sqrt{RT_u}} \Psi_0\left(\frac{p_d}{p_u}\right) \; if \; p_u \geq p_d \\ \frac{p_d}{\sqrt{RT_d}} \Psi_0\left(\frac{p_u}{p_d}\right) \; if \; p_d > p_u \end{cases}$$

with

$$\Psi_0(x) = \begin{cases} \gamma^{\frac{1}{2}} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \; if \; x \leq r_c \\ x^{\gamma} \sqrt{\frac{2\gamma}{\gamma-1}\left(1 - x^{\frac{\gamma-1}{\gamma}}\right)} \; if \; x > r_c \end{cases}$$

Considering sonic and sub-sonic flow regimes,

Where $r_c = (2/\gamma+1) \wedge (\gamma/(\gamma-1))$ is the critical pressure ratio and, p_u, T_u and p_d, T_d are the upstream and downstream pressures and temperatures, respectively.

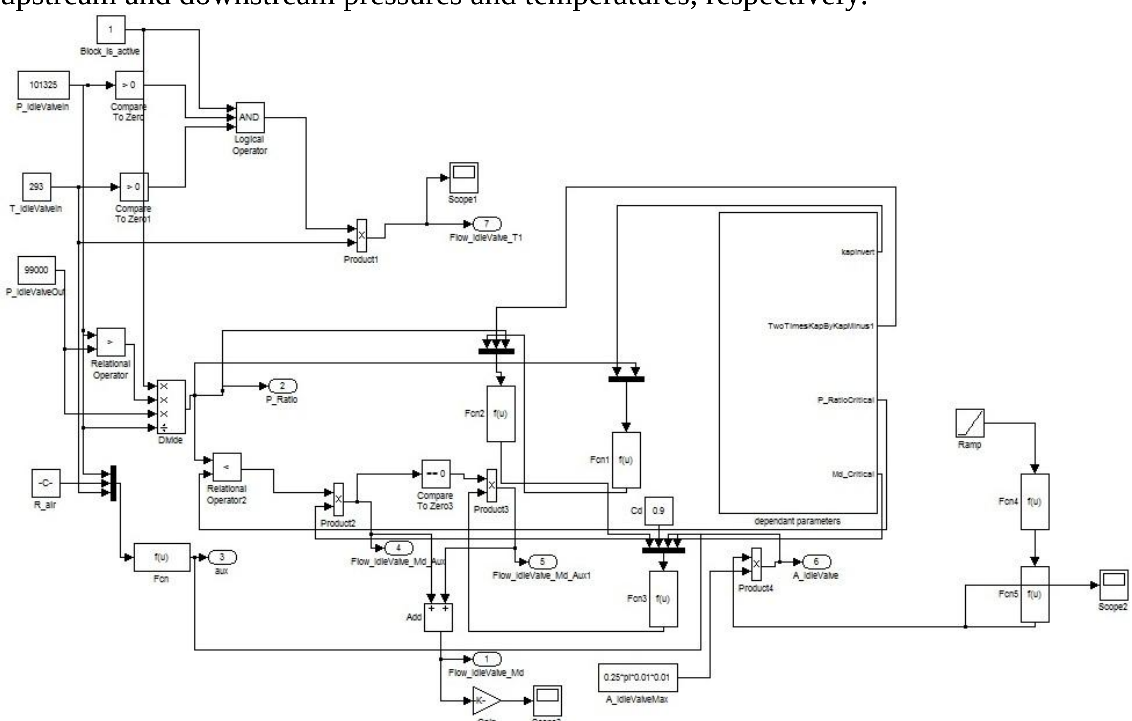


Fig 4: Flow model built on Simulink environment

- Interface of the two models

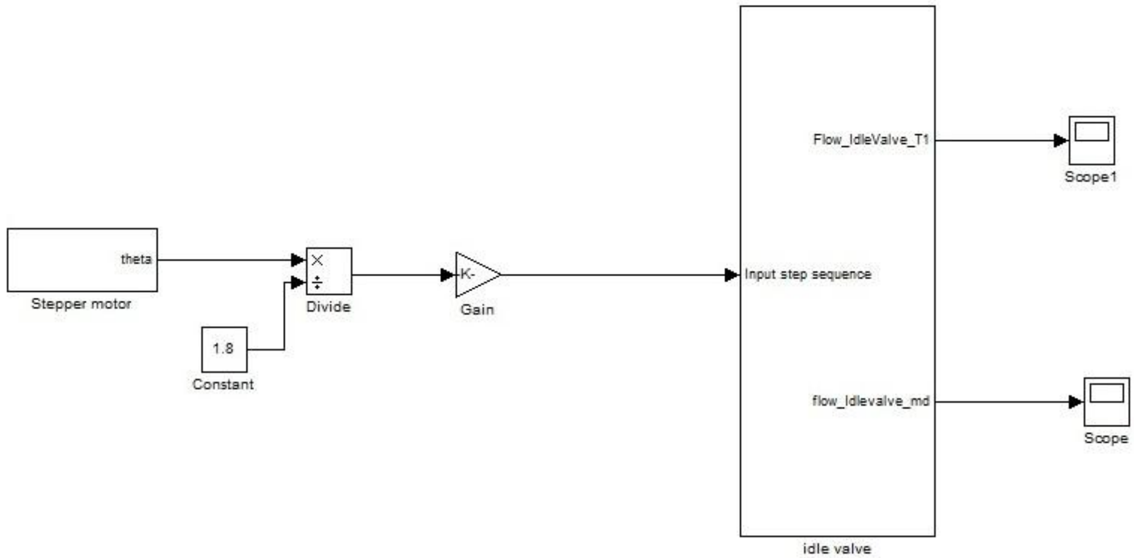


Fig 5: Interface of the two models (output of Stepper Motor model fed as input to Flow model)

Here,
→ 1.8 (Step angle) is divide from Stepper Motor output to count the number of steps
→ The gain K represents that each step corresponds to 0.0254 mm (in accordance with SONCEBOZ LINEAR ACTUATOR 7230)

1.3 SIMULATION

Assumptions –

- → Pipe diameter – 10mm
- → Ambient pressure and temperature is 101325 pa and 293 k respectively.
- → The manifold pressure is assumed to be 96000 pa

Simulation was carried out by giving pulses to the Stepper Motor model
Simulation was carried out for 10 seconds

→ Simulation results

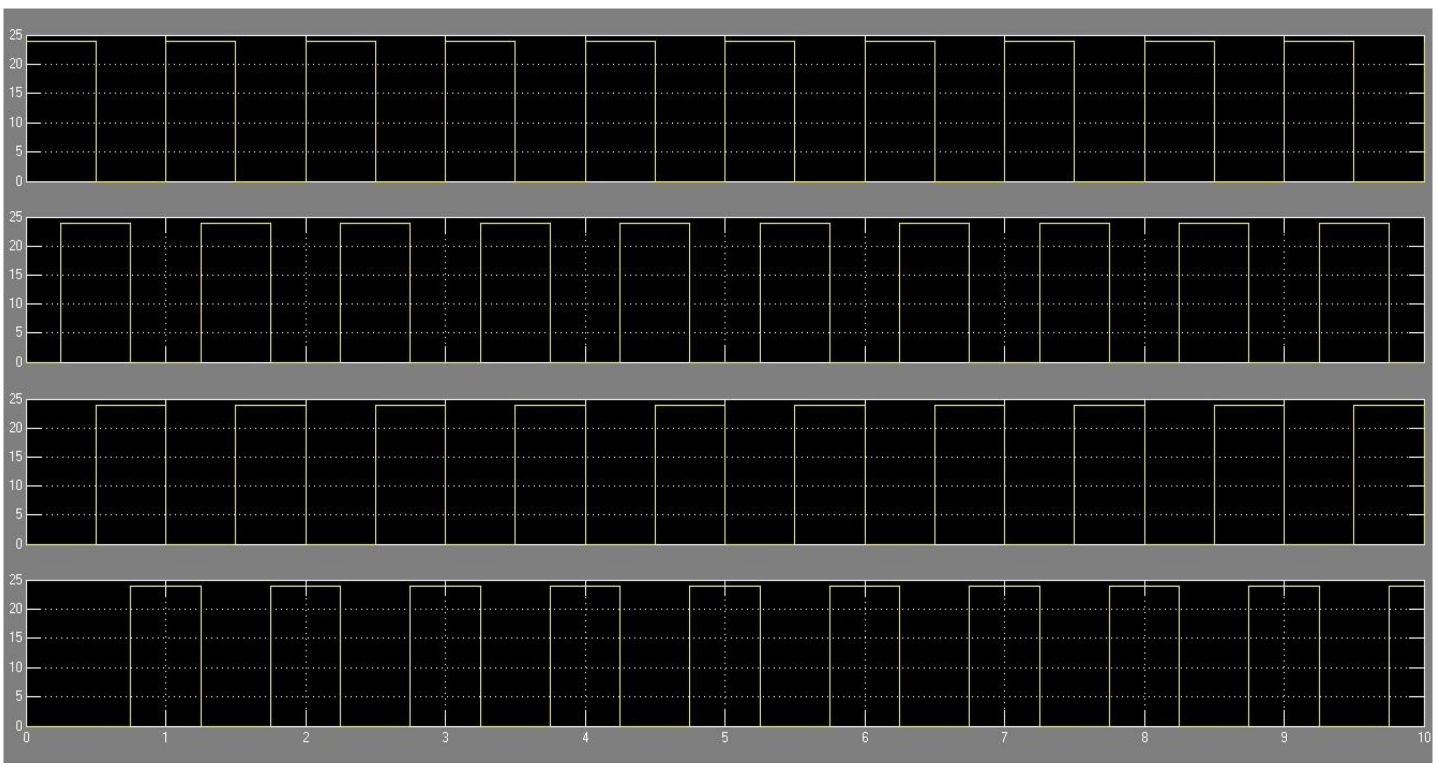


Fig 6: Input pulses in volts vs. time in seconds

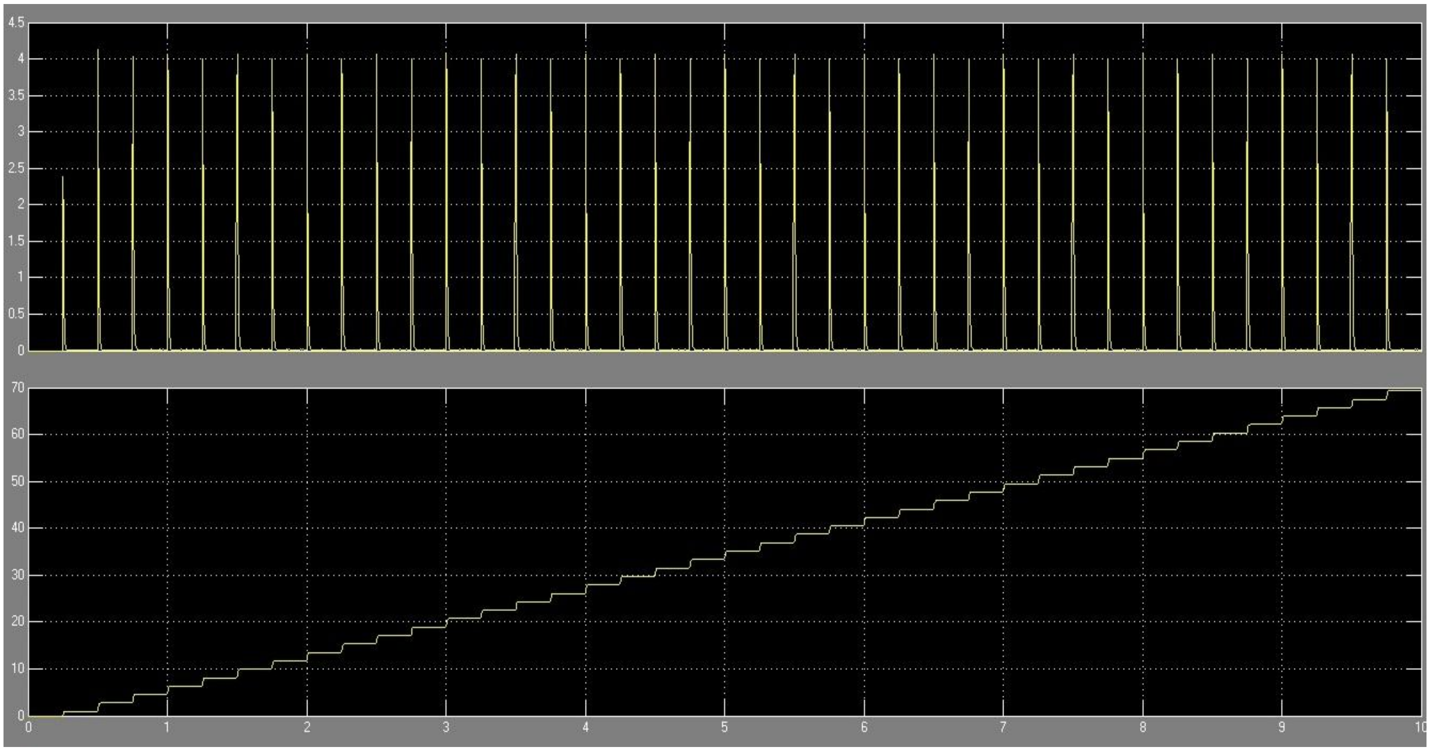


Fig 7: Output of Stepper motor – step angle (below – in degrees) and induced torque (above – in Nm) vs. time in seconds

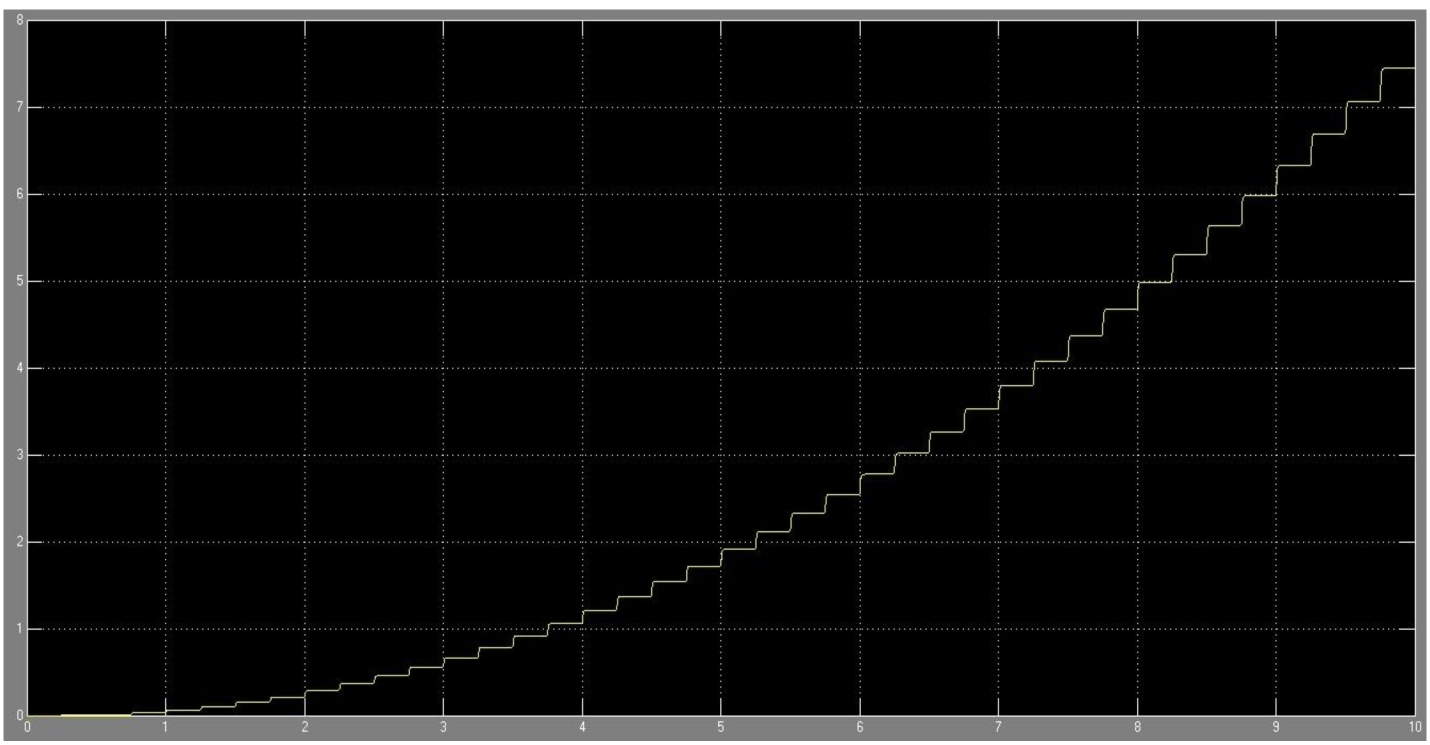


Fig 8: Flowrate from valve in kg/hr (cd of 0.9) vs. time in seconds

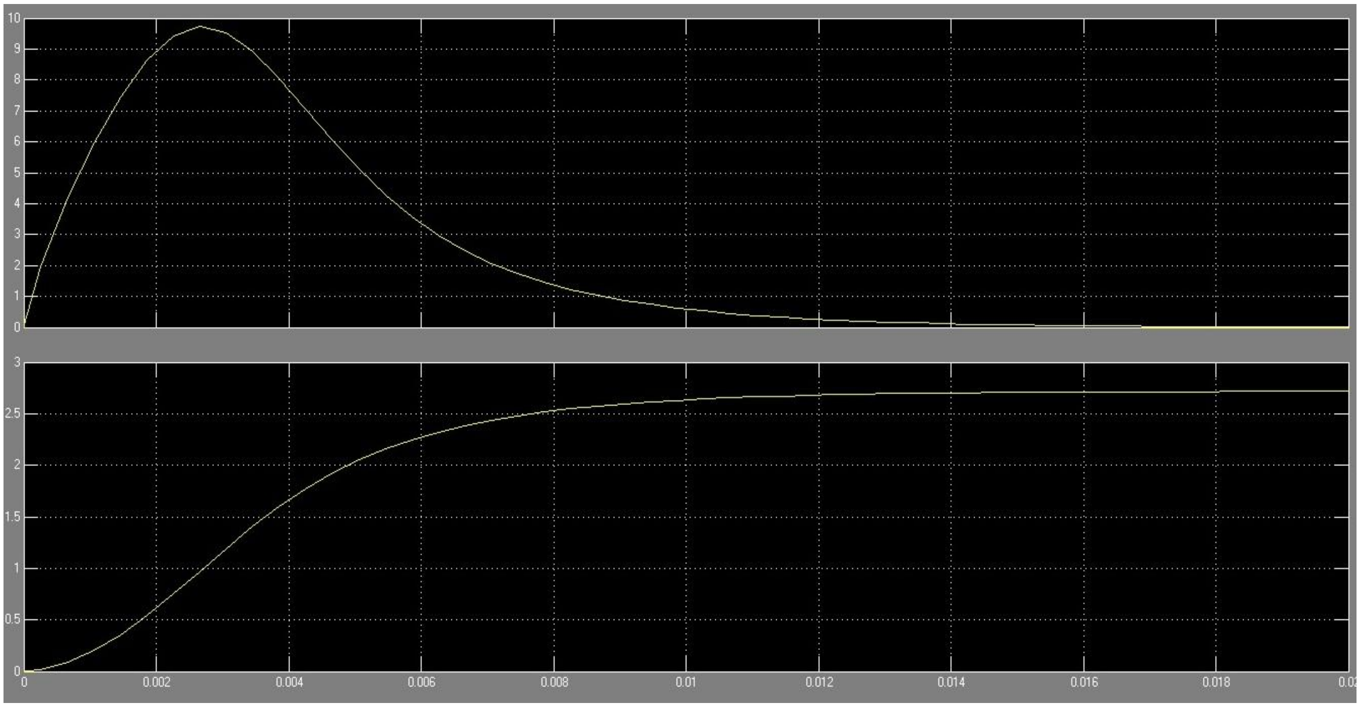


Fig 9: Torque in Nm (above) and step angle (below – from reference, in degrees) when all poles are given ON pulses vs. time in seconds

→ As we can see the rotor gives a holding torque of about 9.5 Nm against the load when all the pulses are ON

CHAPTER 2

MODEL COMPARISON

Model Comparison was done for vehicle Engine Management Systems (Air intake system, Fuel system, Combustion system, Exhaust system) between RBEI Models – VEMoX (Vehicle Engine model for X – Gasoline, Diesel, Hybrid) and a commercially available vehicle simulation tool – AVLBOOST. Appropriate models required for Tata Nano (the system being simulated) Vehicle was considered. This model comparison was carried out mainly to understand the different approaches considered in both cases and find the most accurate one while keeping in mind its response in real time.

2.1 AIR SYSTEM

For Air system, the components considered are

1. Throttle valve
2. Air filter
3. Intake manifold
4. Air flow meter
5. Idle Air control valve

Inference

- Throttle valve in VEMoX library is modeled as two components, the Throttle valve and the Throttle mass flow.
- In AVL BOOST, the Throttle valve component is available.
- In both cases, the Throttle valve is modeled as an isentropic compressible flow given by

$$\dot{m} = \alpha \cdot A_{geo} \cdot p_{o1} \cdot \sqrt{\frac{2}{R_o \cdot T_{o1}}} \cdot \psi$$

Where,

$\dot{m}$	mass flow rate
α	flow coefficient
A_{geo}	geometrical flow area
p_{o1}	upstream stagnation pressure
T_{o1}	upstream stagnation temperature
R_o	gas constant

The pressure function ψ depends on the gas properties and on the pressure ratio

$$\psi = \sqrt{\frac{\kappa}{\kappa - 1} \cdot \left[\left(\frac{p_2}{p_{o1}} \right)^{\frac{2}{k}} - \left(\frac{p_2}{p_{o1}} \right)^{\frac{\kappa+1}{k}} \right]}$$

Where,

p_2 downstream static pressure

κ ratio of specific heats

- In VEMoX library, Throttle valve model gives as its output the free cross section (A_{geo}) are by taking the Throttle angle as input. While the Throttle mass flow takes this area information to give mass flow through the Throttle valve.
- In VEMoX library, the Idle Air control valve is modeled based on the same Isentropic compressible flow equation. It takes the Idle Air control Actuator control signal (driven by the ECU) as input to calculate the free cross section area (A_{geo}).
- In AVL BOOST, Rotary valve can be compared to the Idle Air control valve of VEMoX library. It is also modeled by isentropic compressible flow equation but the percentage opening of the valve (to calculate A_{geo}) w.r.t. crank angle has to be user defined.
- Air filter in VEMoX is modeled as a constant pressure drop model, where the outlet pressure is inlet pressure minus the pressure drop.
- In AVL BOOST, Air filter is available as Air cleaner model. Air cleaner can be modeled as either a fixed pressure drop model or by defining friction coefficients. By defining friction coefficients, the pressure drop of the air cleaner is calculated using the specified values for laminar and turbulent friction coefficients and the specified hydraulic diameter of the pipe.
- In VEMoX library, Intake manifold is modeled as a summation of all mass flows, Pressures and Temperatures (from Throttle, from EGR (Exhaust Gas Recirculation), back flow from Cylinder).
- In AVL BOOST, the Intake manifold can be modeled using the Pipe element and Plenum element.
- The Plenum is modeled based on the Steady flow Energy equation (SFEE) as

$$\frac{d(m_{Pl} \cdot u)}{d\alpha} = -p_{Pl} \cdot \frac{dV}{d\alpha} - \sum \frac{dQ_w}{d\alpha} + \sum \frac{dm_i}{d\alpha} \cdot h_i - \sum \frac{dm_e}{d\alpha} \cdot h_e + \frac{dQ_{reac}}{d\alpha}$$

Where,

m_{Pl}	mass in the plenum
u	specific internal energy
p_{Pl}	pressure in the plenum
V	plenum volume
Q_w	wall heat loss
α	crank angle
dm_i	mass element flowing into the plenum
dm_e	mass element flowing out of the plenum
h_i	enthalpy of the in-flowing mass
h_e	enthalpy of the mass leaving the plenum
Q_{reac}	enthalpy source due to chemical reactions

- The Pipe model in AVL BOOST, considers the Reynolds number of the flow, hence computing whether the flow if laminar or turbulent. This information gives the pressure drop and is used in Euler Energy equation.
- The critical Reynolds number taken in AVL BOOST in 2300. That is, less than 2300 is considered laminar and between 2300 and 5000 is transition zone where in both laminar and turbulent flow regime is seen and above 5000 is considered turbulent.
- The Pipe model in AVL BOOST also considers the Heat transfer by modeling various empirical Equations to calculate the Nusselt number.
- In VEMoX library, Air flow meter is a mass flow measuring device model. In AVL BOOST, measuring points serve the same purpose.

2.2 FUEL SYSTEM

For Fuel system, the components considered are

- Fuel Tank
- Fuel Pump
- Fuel Vaporization
- Fuel Consumption

Inference

- All these models are not available directly in AVL BOOST. They can be built using individual element like Plenum, Pipe, Compressor, Turbine and specifying the Air Fuel Ratio (AFR)
- The Fuel Tank and Fuel pump models in VEMoX library are modeled as a fluid level control. If the Fuel tank is empty or half empty a control signal to the pump (from the ECU) is given to fill the pump.
- The outputs of Fuel pump and Fuel tank are the Fuel pressure, mass flow rate and Fuel level in tank respectively.
- Fuel Vaporization model is a 2D map – Engine speed, load on Engine against Fuel Vaporization at a specified ambient Temperature and Pressure
- Fuel consumption is modeled by considering fuel burned (which is obtained by intake port mass flow) and speed of the Engine.

2.3 COMBUSTION SYSTEM

For Combustion system, the components considered are

- Fuel Injector
- Port mass flow
- Combustion, Engine Torque
- Engine coolant, Engine oil system

Inference

- In VEMoX library, Fuel Injector is modeled as Intake port Fuel injector system. As the name suggests this model calculates the mass flow of the Fuel depending on the Intake port opening and the cam profile.
- In AVL BOOST, Injector element is modeled as an Isentropic Compressible flow as discussed in section 2.1. AVL BOOST also allows choosing between continuous injection and intermittent injection.
- Both the VEMoX and AVL BOOST models does not consider wall wetting.
- Engine coolant and Engine oil system models are not available directly in AVL BOOST. Both these models in VEMoX library are map based – wherein the heat transfer to Engine coolant or Engine oil is mapped against Engine speed and Load on the Engine.
- In VEMoX library, Intake port flow is modeled as Cylinder fill. This model is summation of mass flows (Air and Fuel) considering the cam profile (hence the change in area of Intake port).
- In AVL BOOST, Intake port flow, Engine Combustion and Engine Torque is modeled as Cylinder.
- The calculation of the thermodynamic state of the cylinder is based on the first law of thermodynamics.

$$\frac{d(m_c \cdot u)}{d\alpha} = -p_c \cdot \frac{dV}{d\alpha} + \frac{dQ_F}{d\alpha} - \sum \frac{dQ_w}{d\alpha} - h_{BB} \cdot \frac{dm_{BB}}{d\alpha} + \sum \frac{dm_i}{d\alpha} \cdot h_i - \sum \frac{dm_e}{d\alpha} \cdot h - q_{ev} \cdot f \cdot \frac{dm_{ev}}{dt}$$

- The variation of the mass in the cylinder can be calculated from the sum of the in-flowing and out-flowing masses

$$\frac{dm_c}{d\alpha} = \sum \frac{dm_i}{d\alpha} - \sum \frac{dm_e}{d\alpha} - \frac{dm_{BB}}{d\alpha} + \frac{dm_{ev}}{dt}$$

where:

$\frac{d(m_c \cdot u)}{d\alpha}$	change of the internal energy in the cylinder
$-p_c \cdot \frac{dV}{d\alpha}$	piston work
$\frac{dQ_F}{d\alpha}$	fuel heat input
$\sum \frac{dQ_w}{d\alpha}$	wall heat losses
$h_{BB} \cdot \frac{dm_{BB}}{d\alpha}$	enthalpy flow due to blow-by
m_c	mass in the cylinder
u	specific internal energy
p_c	cylinder pressure
V	cylinder volume
Q_F	fuel energy
Q_w	wall heat loss
α	crank angle
h_{BB}	enthalpy of blow-by
$\frac{dm_{BB}}{d\alpha}$	blow-by mass flow
dm_i	mass element flowing into the cylinder
dm_e	mass element flowing out of the cylinder
h_i	enthalpy of the in-flowing mass
h_e	enthalpy of the mass leaving the cylinder
q_{ev}	evaporation heat of the fuel
f	fraction of evaporation heat from the cylinder charge
m_{ev}	evaporating fuel

- Port Mass flow is modeled as an Isentropic Compressible flow equation as discussed in 2.1. Here $\alpha * A_{geo}$ is

$$A_{eff} = \mu\sigma \cdot \frac{d_{vi}^{\ 2} \cdot \pi}{4}$$

$\mu\sigma$	flow coefficient of the port
d_{vi}	inner valve seat diameter (reference diameter)

- Engine Combustion is modeled in cylinder element of AVL BOOST by the popular Wiebe function.
- Heat transfer to the cylinder walls during combustion is also modeled in AVL BOOST as

$$Q_{wi} = A_i \cdot \alpha_w \cdot (T_c - T_{wi})$$

Q_{wi}	wall heat flow (cylinder head, piston, liner)
A_i	surface area (cylinder head, piston, liner)
α_w	heat transfer coefficient
T_c	gas temperature in the cylinder
T_{wi}	wall temperature (cylinder head, piston, liner)

- In the case of the liner wall temperature, the axial temperature variation between the piston TDC and BDC position is taken into account

$$T_L = T_{L,TDC} \cdot \frac{1 - e^{-c \cdot x}}{x \cdot c}$$

$$c = \ln\left(\frac{T_{L,TDC}}{T_{L,BDC}}\right)$$

T_L	liner temperature
$T_{L,TDC}$	liner temperature at TDC position
$T_{L,BDC}$	liner temperature at BDC position
x	relative stroke (actual piston position related to full stroke)

- For the calculation of the heat transfer coefficient, AVL BOOST provides the following heat transfer models:

  • Woschni 1978
  • Woschni 1990
  • Hohenberg
  • Lorenz (for engines with divided combustion chamber only)
  • AVL 2000 Model
- All these above Heat Transfer models are empirical

2.4 EXHAUST SYSTEM

For Exhaust system, the components considered are

- Catalyst
- Exhaust pipe
- Lambda Sensor

Inference

- In VEMoX library, Catalyst model considers the fraction of burnt and unburnt gases in the exhaust and maps the same against Engine speed and load on the Engine and gives an output the fraction of emissions.
- In AVL BOOST, Catalyst can have an option of chemical reactions activated or not. It is modeled as an Isentropic Compressible flow equation as discussed in 2.1.
- If chemical reactions are activated, Chemical reactions are modeled taking into account the chemical reactions' activation temperature (Temperature at which chemical reactions start) and the Kinetics of chemical reactions.
- In VEMoX library, Exhaust pipe is modeled as taking the fraction of emissions as input and giving the Lambda value as the output (Lambda value is a fraction of gases burnt to form oxides)
- In AVL BOOST Exhaust pipe is modeled as a aftertreatment pipe similar to the Catalyst.
- In AVL BOOST, the aftertreatment pipe gives the Lambda value as one of its output.
- In VEMoX library, Lambda sensor characteristics are modeled. It takes the lambda value as input and gives the value given by the sensor as the output considering the delay time to give that value.

CHAPTER 3

CONCLUSION

A Stepper Motor interface as the Idle Air control Actuator was not available in VEMoX library and hence was built. Its accuracy and real time response was checked. A detailed model comparison was done and the best models were chosen to build the Tata Nano system. It was observed that, the VEMoX models required a lot of inputs, was mostly map based, was not highly accurate. On the other hand, the AVL BOOST was highly accurate in reproducing the actual system but didn't give the response in real time.

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