Development of a Mechatronic Control System for a Mechanical Fuel Injection System of a Four Cylinder Automotive Diesel Engine

Mostafa Abdulrahman Kortam
Faculty of Engineering, Mechatronics
Engineering Department, Ainshams
University, Cairo, Egypt

Prof. Faried Abdulaziz Tolba
Faculty of Engineering, Mechatronics
Engineering Department, Ainshams
University, Cairo, Egypt

Dr. Adham Mohamed Abdelkader
Hassen
Faculty of Engineering, Automotive
Engineering Department, Ainshams
University, Cairo, Egypt

Abstract:-The aim of this paper is developing a mechatronic control system to replace mechanical fuel injection system of a four-cylinder automotive diesel engine, to study what are the important electronics fuel injection parameters which have the highest effect on the engine performance. All the paperwork performed on Isuzu engine 4HF1 which is 4 cylinder diesel engine working with fully mechanical fuel injection system. To develop mechatronics fuel system, must install crank sensor which measure the engine speed in RPM and specify the piston position, cam sensor which specifies the injection order, common rail fuel injection system which includes electronic injectors, high pressure pump and common rail, ECU which control all the system inputs and outputs, and injectors driver controller which responsible for delivering the required high voltage for the injectors with high speed switching. ECU software will be developed from scratch to develop injection quantity, injection time and injection order output signals to be compatible with the common rail fuel system. Mathworks tools (Matlab-Simulink-Stateflow) will be used for developing ECU software application layer which divided into many models as crankshaft speed model, crankshaft sensor piston position, cam sensor injection order model, pedal speed model, injectors model,torque model and final model which collect all the previous models. Embedded coder toolbox will be used for generating C code which will be integrated with the microcontroller layer and uploaded to the selected ECU.

Keywords:-Diesel Engine, Internal Combustion Engine, Engine Management System, Diesel Engine Software, Engine Modeling And Simulation, Engine Embedded System.

I. INTRODUCTION

The Internal combustion engine is one of the fastest growing industry in the world since it is the heart of a lot of applications as automotive industries, heavy equipment, power generation and a lot of other applications, so there is a big need to enhance the performance for internal combustion engine continuously.

Engines manufacturer expenses a lot of money on research and development trying to figure out a lot of new enhancements of many parameters as, decreasing fuel consumption, sounds, vibration, emissions and increasing power and torque.

Mechatronics now plays an important role in these enhancements, so most of the internal combustion engines now contains a lot electronics and controllers so in this paper a mechatronic control system will be developed to replace mechanical fuel injection system of a four-cylinder automotive diesel engine, to study what are the important electronics fuel injection parameters which have the highest effect on the engine performance.

II. CAM SENSOR AND RELUCTOR WHEEL INSTALLATION

Due to overhead cam tight area which not allow installing anyreluctor wheel, small separate tooths machined and stuck on the camshaft gear, three and the fourth is wider than others to be the marked tooth, tooth thickness .5 cm, tooth width .9 cm and the wider tooth width 2.7 cm, since the space between the camshaft gear and the rocker arm end is .41 cm so there is no enough space for the tooth to rotate freely without hitting the rocker arm.So, for free rotating the rocker arm grinded 1.5mm

Fig 1. Rocker Arm Before and After Grinding

A. Tooths Installation

To install the first tooth, crankshaft rotated until piston one at TDC in combustion position 3rd stroke then the first tooth fixed which is the wider stuck it on the cam gear directly under the cam sensor surface area, the second tooth installed after first tooth by 90 degrees,after other 90 degrees the third and finally the fourth tooth so, when the cam sensor detecting the wider tooth this means that the piston 1 in the position of fuel injection.

Fig 2. Cam Sensor Tooths Installation

B. Cam Sensor Installation

The overhead engine cover drilled with diameter 1.33 cm to fit the sensor

Fig 3. Cam Sensor Installation

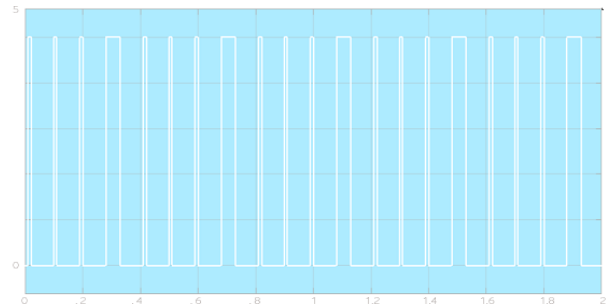*C. Testing the Cam Sensor and Tooths Signal*

Fig 4. Cam Sensor Signal Detected by Oscilloscope

III. CRANK SENSOR AND RELUCTOR WHEEL INSTALLATION

There is a special hole already exists at theflywheel housing with diameter 1.75 cm fitted for the crank sensor, a special reluctor ringmachined to be fitted over the flywheel anddirectly under the hole with diameter 42and 59 tooths.

A. Reluctor wheel Installation over the Flywheel
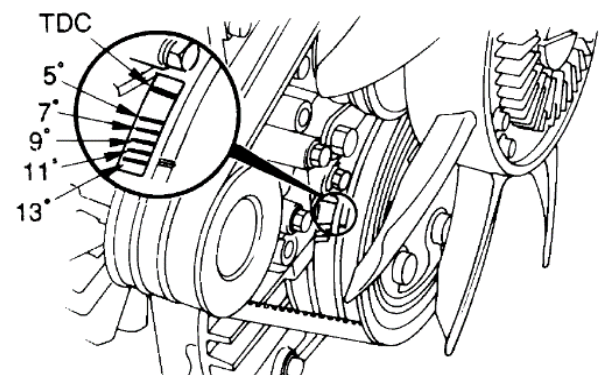
Since the isuzu 4HF1 manufacturer mark crankshaft pully with marks which specify piston position in degrees before

TDC, so for reluctor wheel installation, crankshaft rotated until reach the 12 degrees mark then the reluctor wheel installed with consideration the missing tooth will be under the sensor surface area directly, this means, when detecting marked tooth the piston will be before the TDC by 12 degrees

Fig 5. The Missing Tooth

B. Crank Sensor Installation

There is a manufacturer made hole with 1.75 cm diameter at the gearbox casing which can fit the crank sensor and will be directly over the reluctor ring

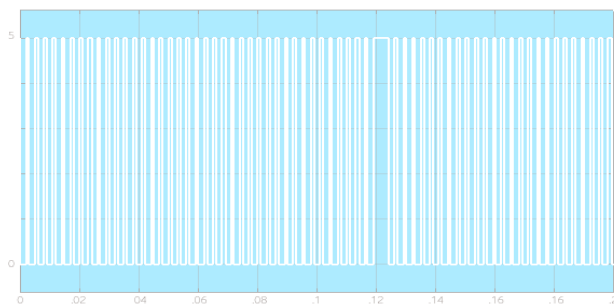Fig 6. Crank Sensor Installation

C. Testing crank Sensor by Oscilloscope

Fig 7. Crank Sensor Signal Detected By Oscilloscope

IV. INSTALLING THE ELECTRICAL INJECTORS SELECTED INJECTOR

Siemense common rail electronic injector with part number 9636819380 The main reason for selecting this injector, it has same geometry of the Isuzu injector and same diameter, so there is no need to make any modification on the engine cylinder head, but there are other differences as follows:

- There is a small difference in dimension at the middle of the injector but it solved by made a little grinding at the middle of the injector body.
- The injector body does not have the compression seal as in the Isuzu injector so it grinded for seal installation.

Fig 8. Injector after Grinding and Making Seal Groove

- The Siemens injector comes with ignored nozzle hole angle data so it replaced with Denso nozzle (ND-DLLA 154P717)which hassame Isuzu injector nozzle specs 5x.215x154 and same nozzle diameter, but there is a difference in nozzle length.

Fig 9. Siemens Common Rail Injector

length problem solved by made a special ring seat, installed under the injector seat and since the Siemens injector nozzle length 22.5 mm and Isuzu injector nozzle 21.3mm the ring thickness is the difference = 1.2mm

and machined to has the same geometry asoriginal injector nozzle seats as photos:

Fig 10. Machining of the Seat Ring Upper Face to Fit with the Old Seat

- The Isuzu injector tighten socket could not be used with the common rail injector due to the geometry of the electronic solenoid and this problem solved by made a special new one

Fig 11. Injector Tighten Socket

Fig 12. After Installing the Injectors

V. COMMON RAIL PUMP AND RAILINSTALLATION

It is a high-pressure pump (1600 bar), only responsible for injecting a high pressure fuel in the common rail , so it does not control anything or have any effect on engine injection timing which allow to replace it is external gear with any one suitable with the engine, but the main problem is the pump geometry and dimensions, since the area which the Isuzu inline pump is installed is not big enough, this problem solved by removing the power steering pump and using it is place for the common rail pump.

The rail installed upper the pump since there a fixation area available already by Isuzu manufacturer made

Fig 13. Installing Common Rail with Inlet and Return Pipes

VI. ENGINE CONTROLLERS

A. ECU

Engine manufacturers usually use expensive high quality processor to guarantee high processing speed and zero errors since it working with hard real time software, according to the project low-cost,Raspberry pi with the following specs will be a suitable choice:Raspberry Pi 3 Model B a quad-core 64-bit ARM-Cortex A53 clocked at a 1.2GHz.

B. Injectors Driver Controller

This controller responsible for transferring the signal from the ECU to the injectors in high-speed switching with write voltage.

Injectors driver controller circuit includes:
1-DC-DC Boost Converter 8-32V to 45-390V
since the common rail injectors is a piezoelectric type with 100v
2- TIP31C transistor used for high speed switching with high dc voltage due to injector high voltage at 100v dc

VII. INSTALLING AND CALIBRATING POTENTIOMETER (SPEED PEDAL)

The potentiometer will work as speed pedal sensor to increase the engine speed

Incremental point	Volt
0	4.989
1	4.713
2	4.174
3	3.705
4	3.153
5	2.650
6	1.995
7	1.355
8	.783
9	.403
10	.014

Table 1: Potentiometer Calibrating Data :

VIII. ECU SOFTWARE

Typical powertrain control strategies contain several hundred thousand lines of C code and thousands of associated parameters and calibration variables requiring thousands of man-hours to calibrate, although the ongoing efforts in self-calibrating approaches and tools may substantially reduce this time-consuming task. Mathworks tools play important role in design the embedded system algorithms for Automotive industry. Using Mathworks products, Simulink, Stateflow and Embedded coder allow generating C code which can be ported to the microcontroller.

The AUTOSAR architecture distinguishes on the highest abstraction level between three software layers: Application,Runtime Environment and Basic Software which run on a Microcontroller.

Mathworks tool (Matlab, Simulink,Statesflow and Embedded Coder) will be used to develop the application layer as follows:
1-Crank sensor speed model
2-Crank sensor piston position model
3-Cam sensor injection order model
4-Pedal speed sensor model
5-Injectors model
6-Torque model
7-Final model
Before starting software developing there is an important note must be taken into consideration through software developing, changing the injection frequency will decrease or increase the

engine rpm but changing the fuel injection quantity will decrease or increase the engine load.

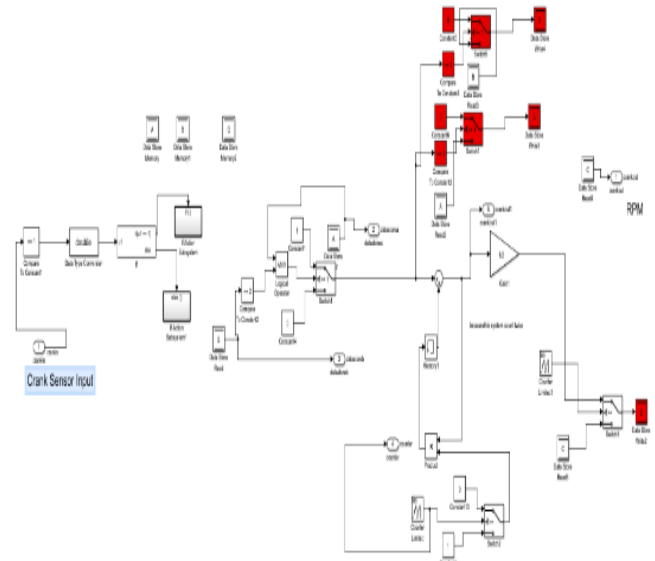### A. Crank Shaft Sensor Speed Model

Fig 14. Crank Sensor Speed Model

This model measure the engine speed (RPM), it will count every high pulse detected by the crank sensor and since the reluctor wheel is 59 tooths, when sensor detects 59 high signal, this will be one rpm, Simulink model blocks:

- 1-Model starting with comparing block to compare the pulse high or low.
- 2-The results of comparing will be input to if condition block, if it 1 means signal is high and will store 1 in data store A, if 0 means signal is 0 and will store 2 in the data store B.
- 3-Comparing data store B with 2, if correct then the output will be 1 and if false the output will be 0.
- 4-Comparing the result of comparing data store B and data store A with AND logic block, if the result is 1 this means the pulse is high.
- 5-The output of AND logic block will be input to switch block, if the input is one then the output will be 1 going to the counting cycle which will start to count 1, this means the first detection of a high signal, in same time the data store block A and B will be reset to be zero value.
- 6-In case the output of the switch block is 0 then there is no any added value to counter,

In same time the values of data store block A and b will be same values, for example when model started and if block

detect one then the data store A block will be 1 and no any add to store B, if data store B still contains zero due to reset with 0, the output of AND 1 0 will be 0,means no detection for high pulse and the values of data stores blocks will be same, this because the signal may be high but also it is may give 1 at start of high or middle or end or through any point on the

pulse width, so this value will not be detected as high until detection of zero occur, in this case the data store B will be 2 and AND logic block will give 1 and the signal will be detected as high
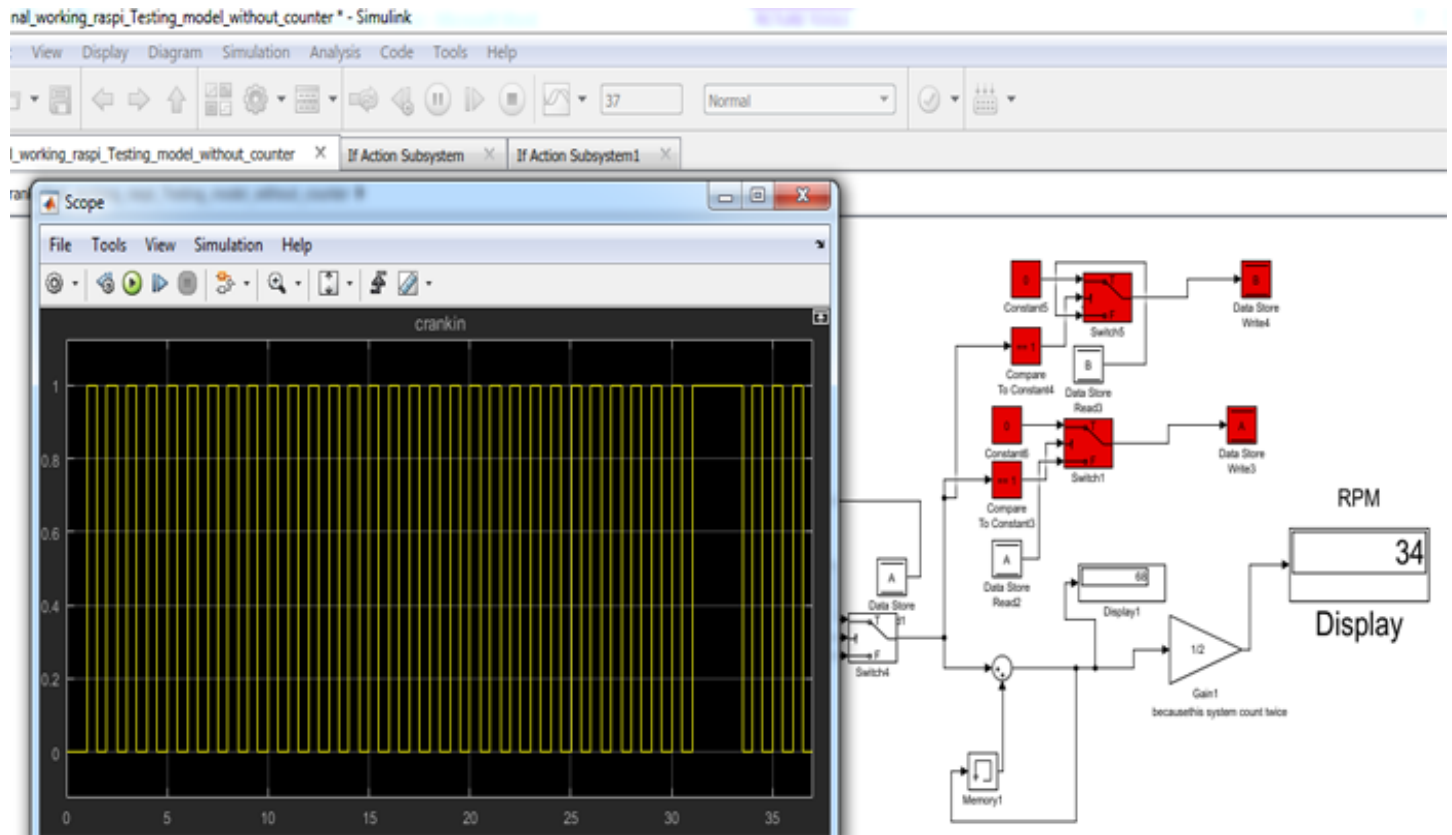

Fig 15. Crank Model Testing with Simulated Crank Sensor Signal

B. Crank Sensor Piston Position Model and Cam Injection Order Model

This model will compare every tooth width with the next one until detecting the wider one, the model has five subsystems blocks(first tooth subsystem block-next tooth-model resetting-comparing-independent subsystem block)
Starting with crank speed model, after detecting the high pulse the output of the AND logic block will be input to the K data store block and the independent subsystem Block which contains the following blocks :

1-F data store connected to increment stored integer block with initial value 0
2-J data store connected to decrement stored integer block with initial value 4

3-Enable block, every time this subsystem receiving 1 it will decrease the data store J and increase the data store F block by 1
Modelresetting subsystem:

It used to reset F and Jdata store blocks
1-The data store F block starting initially with 0then increased to 1 then 2 and reset to 0 valuewhen it reaches 2
2- The J block will starting initially with 4 then decreased to 3 then 2 then1 and reset to 4 when it is value reaches 0

The first tooth subsystem:
It is enabled subsystem contain counter which start counting when enable block receiving 1 from the main input signal, the result of this counter will be input to switch block and will be added to the C data storeblock in case the value of data store F is 1, if not equal 1 it will keep the same previous value of data store C as it is.

When model running, at the beginning the data store block F initial value is 0,once high signal detected, the block will be increased by 1 so it is value will be 1 then the counter will store the counting value in the C data store block,once another detection of high the data store F will be increased by one to be 2, so the C block value will be the same previous value and the Block F will be reset to be zero value, after another detection will be increased by one to be 1.

At the end when value of F block reach 0 the value of C will beadded to X output block

The next tooth subsystem :
It is enabled subsystem contain counter which start counting when enable block receiving 1 from the main input signal, the result of this counter will be input to switch block and will be added to the D data store in case the value of data store J is 1, if not equal 1 it will keep the same previous value of data store D as it is.

When model running at the beginning the data store block J initial value is 4 and once detection of high signal the block value will be decreased by one to be 3, the counter will not store the counting value and the value of D data store will be the same which initially zero, and once another detection of the block by otherhigh signal the data store Jwill be decreased by one to be 2so the D block value will be the same previous value and after another detection will bedecreased by one to be 1,the counter value will be stored in D data store block,another high detection will decrease the J value by 1 to be 0,which will reset the J blockvalue to be 4 as initial value.
At the end whenvalue of J block reach 4 the value of D will be added to Y output block then will compare the value of X with the Value of Y as follows:
1-If same counting value, this means that the pulse width is the same which will give 0
2-if different values this means that the pulse width is different and this is the marked wider tooth and will give 1 value
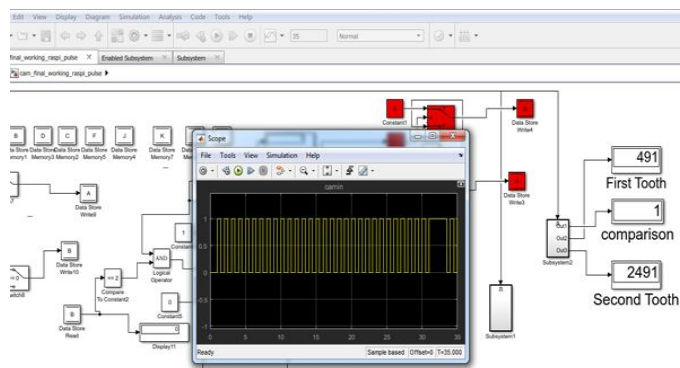

Fig 16. Crank Model Tested With Simulated Crank Sensor Signal

a). Crank Sensor Model Injection Time

The crank model will start injection before TDC by 9 degrees and since the crank sensor reluctor wheel installed to consider when detecting the marked tooth, the piston will be before TDC by 12 degrees so the model developed to count one pulse and half after detecting the marked tooth for cylinder 1 injection time, for next cylinder injection time the model will count after detecting the marked tooth by 181.5pulses.

b). Cam Senor Model Injection Order

The cam model injection order 1 3 4 2.
The cam sensor reluctor wheel has four tooths, after detecting the marked tooth will inject cylinder 1 and when detecting the next pulse will inject cylinder 3, next will be cylinder 4 then cylinder 2

C. Models Generated C Code

using embedded coder toolbox, C code will be generated and manually integrated with the ECU input and output pins.
Part of crank sensor model generated C code:
* Model version : 1.26
crank_final_working_raspi_code_generation.c
* Code generated for Simulink model 'crank_final_working_raspi_code_generation'
* Simulink Coder version: 8.12 (R2017a)
* Target selection: ert.tlc
#include"crank_final_working_raspi_code_generation.h"
#include"crank_final_working_raspi_code_generation_private.h"
#include<wiringPi.h>
/* Exported block signals */
intcrankout;   /*
/* Block states (auto storage) */
DW_crank_final_working_raspi__T
crank_final_working_raspi_co_DW;
/* Real-time model */
RT_MODEL_crank_final_working__Tcrank_final_working_raspi_co_M_;
RT_MODEL_crank_final_working__T
*constcrank_final_working_raspi_co_M =
&crank_final_working_raspi_co_M_;
/* Model step function for TID0 */
void crank_final_working_raspi_code_generation_step0(void)
/* Sample time: [0.001s, 0.0s] */
{
        while
        {
                wiringPisetup();
                pinMode(23,INPUT);
crankin-digitalRead(23);

```
      printf("crankout=%d\n",crankout);
        int32_T rtb_Switch4;
real_T rtb_Sum1;
  uint16_T rtb_FixPtSum1;
uint16_T rtb_FixPtSwitch;
datastorea = A;
datastoreb = B;
rtb_Switch4 = ((A != 0.0) && (B == 2.0));
  rtb_Sum1 = (real_T)rtb_Switch4 +

crank_final_working_raspi_co_DW.Memory1_PreviousInput;
```

D. Speed Pedal Model

This model used for determining the driver's wish so it works as input for the driver wish map to calculate the fuel injection quantity.

The model consisting of one lookup table contain potentiometer calibration data:

Incremental point	volte
10	4.989
9	4.713
8	4.174
7	3.705
6	3.153
5	2.650
4	1.995
3	1.355
2	.783
1	.403
0	.014

Table 2: Potentiometer Calibration Data

E. Torque Model

In diesel engine the mass of air is constant but the mass flow rate is variable at variable speed, so at constant speed, the only variable in air to fuel ratio is the mass of fuel which will control the engine load by increasing or decreasing the fuel quantity.

This model is used for calculating the engine required fuel injected quantity trough two lookup tables:
1-The first lookup table is driver wish map which used for calculating the fuel injection
quantity according to two inputs RPM and
Pedal sensor value and will be created using the following equations:

$$P = \frac{\eta_f \eta_v N V_d Q_{HV} \rho_{a,i}(F/A)}{2}$$

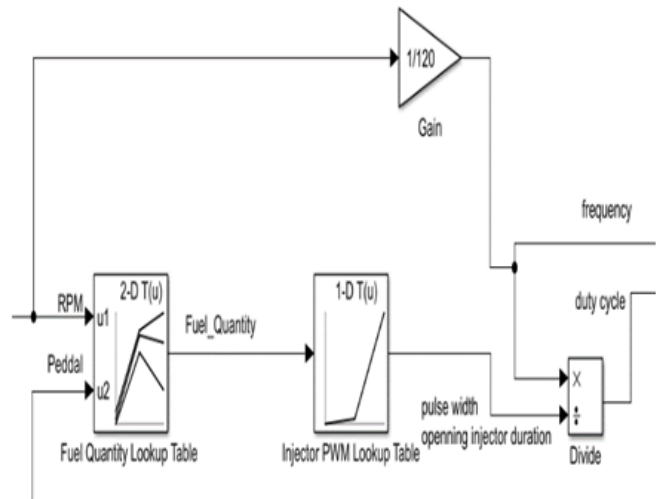$$T = \frac{\eta_f \eta_v V_d Q_{HV} \rho_{a,i}(F/A)}{4\pi}$$

Fig 17. Torque Model

Practical fuel injection volume for 4HF1 zexel pump and zexelinjector at different rpm:

RPM	Period (sec)	volume
520	116 sec	10 ml
1380	52 sec	13 ml

Table 3: Calculate Practically The Injector Injection Quantity At 520rpm And 1380 Rpm.

From this table we can calculate practically the injector injection quantity at 520rpm and 1380 rpm at no load in mg/stroke:
At 520rpm with no load and 116 sec, the injection quantity for one injector is 10ml
Diesel fuel density =840kg/m3
Convert the 10 ml to mg =10x840=8400mg
the fuel injected per second for one injector =8400/116=72.413 mg/sec and to convert it to mg/stroke, number of injector strokes in one secmust be calculated as follows:engine rotations per sec =520/60=8.6, since the engineis four stroke engine so each injector will stroke once every four strokes which every two crank rotation, so for 8.6 rotationsper sec the injector will stroke 8.6/2=4.3 strokes, it mean the injector will inject 4.33times, sothe injection quantity for one injector at 520 rpm = 72.4/4.3=16.72 mg/strokeAt 1380 rpm with no load and 52 sec the fuel

injection for one injector is 13ml, convert ml to mg 13ml =13x840=10920mg

The fuel injected per second 10920/52=210mg/sec

Engine rotations per sec=1380/60=23

So for 23 rotations per sec the injector will stroke 23/2=11.5 strokes then the injection quantity at 1380 rpm = 210/11.5=18.26 mg/stroke

ped al rp m	0 %	10	20	30	40	50	60	70	80
20 0	91. 87	---- ----	---- ----	----- -----	----- ----	----- -----	----- -----	----- -----	
55 0	16. 72	---- ----	---- ----	----- -----	----- -----	----- -----	----- ----	----- -----	---- -----
96 5		17. 49	23. 17	28. 85	34. 63	40. 21	45. 89	52. 42	57 .2 6
13 80	----- -----	---- ----	18. 26	28. 31	38. 32	48. 36	58. 40	68. 4	78 .4 7
17 95	----- -----	---- ----	---- ----	18. 68	30. 88	43. 09	55. 29	67. 41	78 .8 8
22 10	----- -----	---- ----	---- ----	----- -----	20. 75	35. 11	48. 78	63. 83	78 .1 9

Table 4: Calculation of other wish Driver Map Points :

Driver wish MAP

For Isuzu diesel engine, Volumetric efficiency is .8 ,Fuel conversion efficiency assumed .3 ,Heating value =44800000 j/kg.k ,Cylindersvolume =4334cc=.004334 m3 and from engine performance curves at 1380rpm,power=40.617KW and torque =280.5NM

Calculation for fuel injection quantity at 1380 rpm with 80 % pedal pressed

280.5=.3x.8x448000x.004334x(f/a)/12.56

F/A=.0756

each cylinder volume =4334/4=1038 cc =1038mg and in mg/stroke = 1038mg/stroke

F/A)=.0756 =Mfuel/Mair

Mfuel=1038x.0756=78.47 mg/stroke.

Since 1380 rpm engine speed cannot achieved by pressing on the pedal less than 20% to 80% ,Soat 1380 rpm the calculations will be only for 20 30 40 50 60 70 80 %

From practical test at 1380 rpm with 20%pedal pressed with no load: F/A=18.26/1038=.01759,so the torque T=.3x.8x44800000x.004334x.01759/12.56=65.26 N.M

For the other points, Torque step =280.5-65.26=215.24 NM, 215.24/6=35.87

Pedal % @1380	Power @1380 KW	Torque @1380 NM
0	----------	-----
10	--------------	-------
20	9.42	65.26
30	14.62	101.13
40	19.80	137
50	24.98	172.87
60	30.17	208.74
70	35.35	244.61
80	40.54	280.5

Table 5: Calculation Power and Torque

At 30% pedal and at 1380rpm the power= 14.62 KW and torque=101.13 NM so for fuel quantity:101.13=.3x.8x44800000x.004334x(F/A)/12.56

Mfuel=0.027x1038=28.31 mg/stroke

At 1380 rpm and with 40% pedal pressed, the torque is 137,F/A=137/3710.124=.036

Mfuel =036x1038=38.32 mg/stroke,and same calculation for other points.

2-Second look up table is to convert the injection quantity to pulse width.

Injection quantity (mg)	Injector pulse width (msec)
10	.2
35	.7
60	1.2
80	1.6
105	2.1

Table 6: Common Rail Injectror Testing Results:

F. Injectors Model

This model for switching the 4 injectors with specific injection order and specific pulse width modulation signal

The model contains :

1-PWM subsystem block which generates variable frequency variable duty cycle pulse width modulation signal according to the input data of duty cycle and engine frequency.

2-Flowstate chart

The Stateflow chart used for specify the injector fuel injection order and injection time according toit is inputs which arethe cam sensor signal, the crank sensor signal and the PWM signal(fuel injection quantity).
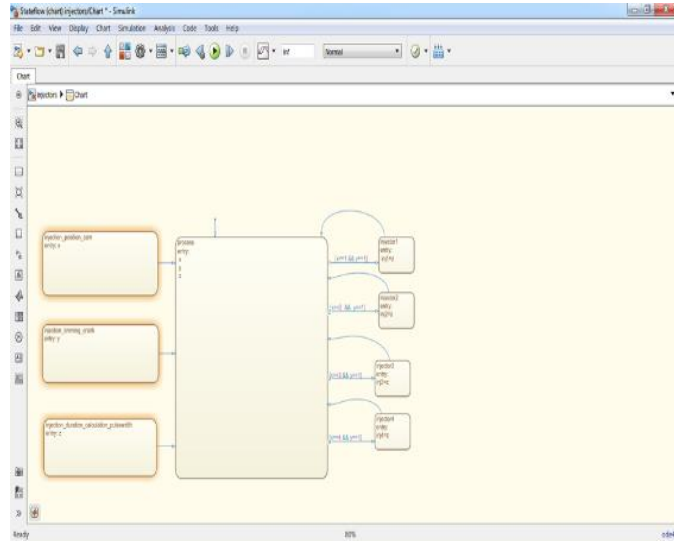
Fig 18. Injectors Flow State Chart

G. Final Model

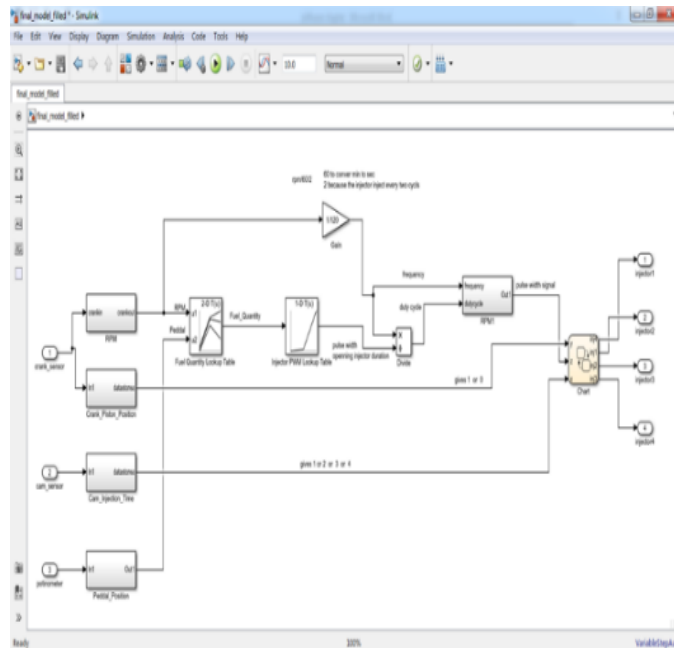This model is the final model which collecting all the previous models.

Fig 19. Final Simulink Model

H. ECU C Code

The Generated C Code from every model will integrate togeather manually then will integrate with the microcontroller layer which define all the controller hardware input and out

pins, these pins will integrate with the input and output of the application layer.

At the end, this C code will compile and uploaded to the controller for starting the engine.

IX. CONCLUSION

The engine started but not efficiently since there is a hunting and when trying to increase the rpm, the engine shut off, from this problem we can specify the important electronics fuel injection parameters which have the highest effect on the engine performance since this problem causes be as follows:1- At engine speed 420 rpm ,the engine must inject at least three times per second and it is clear from the below oscilloscope reading that there is a lag in the injection pulses ,this may be caused be the following:
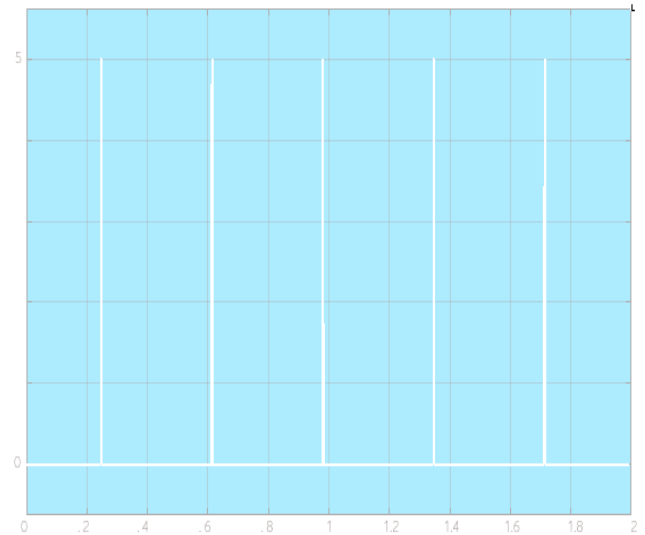

Fig 20. Oscilloscope Reading that There Is A Lag in the Injection Pulses

- The oscilloscope reading for injectors signal at 420 rpm

  ➢ Lag in the processor speed since the Raspberry pi is initially loaded with the Linux operating system.
  ➢ Transistor quality, which is not fast as required.
  ➢ Transformer quality which causes a lag in the converting volt.
  ➢ Wiring and connectors quality may cause lags in the systemalso, wiring length since shorted the wires improved the engine starting.
  ➢ Due to the size of the tooths, the tooths material and the way of installing, the cam sensor tooth's signal have a
  ➢ problem.From the piezoelectric injector testing results and the engine software, injector injection

timing is too small since the working range is .2 to 2.6 millisecond (600) microseconds which need a very efficient system to work with as CAN network.

- Any lag in the processor speed will causes increase or decrease in the response of the injector opening and closing which will cause wrong injection quantity.
- The high-pressure fuel injection system increase the fuel pressure and speed which may be causes spreading the fuel into waves which hitting the cylinder walls and causes reflections and interferences which makes incomplete combustion.
- The injection quantity values in driver wish map (torque model/injection quantity lookup table) may be inaccurate and also the injector pulse width in the second lookup table may be not accurate hence the injector may inject more or less fuel than the required.
- The software may be need improvement to increase the speed of processing.
- The injection timing for the mechanical system before the TDC by 12 degrees but for the mechatronics system this not starting the engine and started at 9 degrees before TDC, so with variable speed this value should be variable.

REFERENCES

[1]. John B.Lheywood, internal combustion enginefundamentals,1988.
[2]. Richard Stone, Introduction to Internal Combustion Engines,1999.
[3]. Klaus Mollenhauer, Helmut Tschoeke, Handbook of Diesel Engines,2010.
[4]. industrial information technology series, Series Editor RichardZurawski, Automotive Embedded Systems Handbook Edited by Nicolas Navet and Françoise Simonot-Lion,2009.
[5]. D.H.C. Taylor, The analysis of fuel spray penetration and distribution in a medium speed diesel engine using optical techniques, Loughborough University Institutional Repository, A Doctoral Thesis. Submitted in partial fulfillment of the requirements for the award of Doctor of Philosophy of Loughborough University,1967.
[6]. JörgSchäuffele, Thomas Zurawka, Translated by Roger Carey, automotivesoftware engineering principles processes methods and tools,2005.
[7]. Konrad Reif, Automotive Mechatronics ReifEd, Automotive Networking · Driving Stability Systems ·Electronics,2015.
[8]. Kevin Hoag BrianDondlinger, Vehicular Engine Design, Second Edition,2006,2016.
[9]. Allan W. M. Bonnick, MPhil CEng MIMechE MIRTE, Automotive Computer Controlled Systems.Diagnostic tools and techniques,2001.
[10]. Autosar, layered software architecture version 3.4 part of realease 4.1