Modeling and Simulation of Crush Natural Gas Turbo Engine

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Abstract— **The development of Crush Natural Gas (CNG) Engine Control Unit (ECU) depends on expensive bench tests or traditional gasoline engine simulation software, which expand researching and developing period. A new approach is presented in this paper, in which a novelty CNG Turbo engine model based on Mean Value Model and Hardware In Loop (HIL) platform are included. The model acts as many roles e.g. simulation, embedded fault diagnosis and ECU test model which provide more accuracy and efficiency for development of ECU. The new HIL simulation policy is based on Matlab/Simulink, Real Time Workshop (RTW) and NI PXI board. The experiment results prove that it acquired quality Real-time response and accuracy, and economy budget.**

Index Terms— **CNG Engine Model, Mean Value Model, Trubo, Simulation, HIL**

I.INTRODUCTION

Clean energy is a trend for Automobile industry which faces more strict rules of environment protection and economy. Crush Natural Gas (CNG) engine acquired fast growing market share in southwest China, especially served for urban traffic buses. CNG engine substituted 134 million tons of coal in Sichuan province, China, 2005, with whole costs about 45% of coal. The experiment data indicate that in the same working conditions, CNG engine reduces the emission of CO, HC and SOx by 45%,67.4%,80.5%[1]. Furthermore, the refitting of CNG engine from diesel engine need CNG ECU, injectors and gas cylinders, saved more budgets for the departments that have diesel engines in service and the company which keeps on producing with traditional process and equipment.

There are huge demands for CNG Engine Control Unit (ECU) simulation tools which aim for higher power output, lower noise and emission. A few modeling and simulation tools of CNG engine could meet the research and development requirements, but surprising price and costs are also needed. Several types of CNG ECU is developed through the complicated calibration and mapping of CNG engine, which induce to high product price. Traditional simulation and analysis software for engine cannot provide fully support for CNG engine, especially for Real-time simulation.

Engine modeling is the primary target in HIL simulation. Traditional Figures and Map model relies on experiment data, which means tens of sample engine and one year test period. Mean Value Engine Models (MVEMs) was proposed by Elbert Hendricks in 1989, [2], a big step in simulation and analysis for engine control, because it provides balance between most of dynamic characters and real-time quality. MVEMs are simplified dynamic engine models which are based on differential equation rather than partial differential equation of aerodynamics, thermodynamics and chemistry. They are intended to operate as predictors of the averages rather than the cycle to cycle values of the most important engine states and variables. Therefore, traditional MVEMs have deadly disadvantages that restrict its more applications, because they could not reflect inlet valve, turbo, combustion and emission. Besides, the deficiency of freely matched hardware Input/Output (IO) interfaces restricts its application in hardware simulation. Many researchers made improvement of MVEMs[3]~[5], but most of them are based on the diesel or gasoline engine, could not be used for CNG engine, and also lack of simulation of main characteristics e.g. inlet valve, cam and thermal analysis.

Based on carefully research and analysis of MVEMs, a new CNG Turbo engine model is proposed, which is running under Matlab/Simulink environment. It provides analysis on the characters of emission control as well as crankshaft speed, cams speed and phase, air/fuel ratio (AF), spark advance angle, output torque and indicated thermal efficiency. The auxiliary sensors and actuators are simulated and capsulated in the models, such as temperature sensor, pressure sensor, injectors, spark plug control pulse. All of model IO signals are provided according to ECU standards, it could be seamlessly connected to real ECU through IO card. The software simulation code could be called by Labview RTW, downloaded into NI hardware development board when model is running. If any problem was found, it could be modified and run online. The simulation results prove that this approach provides us stability, efficiency and economy costs.

II. RELATED WORKS

Classical MVEM is divided to 3 sub-models: Fuel Flow/Evaporation Dynamics, Manifold Filling Dynamics, Crank Shaft Speed State Equation. It is composed of algebraic formula and derivative formula, which describes the air flow, gasoline flow and crank shaft speed relations. The focus is the manifold mass flow and pressure equations, and fuel evaporation dynamic, both of them are vital for Air/Fuel control and response, which is one of the most important factors influencing power output and emission in physical engine. But it didn't describe mean value of main emission wastes [6]~[10].

A. *Fuel Flow/Evaporation Dynamics*

This sub model describes the model for the fuel flow dynamics in a Central Fuel Injection (CFI) or Multi Point Injection (MPI) engine. It is based on the following 3 equations:

$$\dot{m}_f = \dot{m}_{fv} + \dot{m}_{ff} \tag{1}$$

$$\ddot{m}_{ff} = \frac{1}{\tau_f}(-\dot{m}_{ff} + X\dot{m}_{fi}) \tag{2}$$

$$\dot{m}_{fv} = (1-X)\dot{m}_{fi} \tag{3}$$

According to (1), the liquid fuel is divided to 2 parts, one is $\dot{m}_{fv}$ (kg/S), another is $\dot{m}_{ff}$ (kg/S). The parameters in (2) are the time constant of fuel evaporation τ_f and the proportion of the fuel which is deposited on the intake manifold or close to the inlet valves X .Those two parameters could be described as (4) and (5), which are nonlinear functions of manifold pressure p_i (bar) and crankshaft speed n (rpm). Parameters $a_0 \sim a_9$ have to be mapped or lookup from manual of engine.

$$\tau_f(p_i,n) = a_0(a_1 n + a_2)(p_i - a_3)^2 + (a_4 n + a_5) + a_6 \tag{4}$$

$$X_f(p_i,n) = a_7 p_i - a_8 n + a_9 \tag{5}$$

B. *Manifold Filling Dynamics*

The submodel is based on following isothermal assumption: ideal gas, the same temperature, without thermal loss. According to energy conservation and ideal gas equation, (6) and (7) describe the mass flow entered into manifold is $\dot{m}_a$, $\dot{m}_{at}$ is the air quantity flow into throttle which is obtained by air flow meter in physical engine. $\dot{m}_{ap}$ is the mass of mixed air entered into the cylinder, the value difference is the air mass in the manifold. Ideal gas pressure fluctuate rate $\dot{p}$ (bar/s) in a container with volume V (m3) could be obtained by manifold pressure sensor .

$$mRT = PV \tag{6}$$

$$\dot{p} = \frac{RT}{V}(\dot{m}_{at} - \dot{m}_{ap}) \tag{7}$$

$\dot{m}_{at}$ has been shown as (8), is function of throttle open degree α (degree)and manifold pressure p , which follows the assumption the throttle and manifold section area is circle.

$$\dot{m}_{at}(\alpha, p_r) = m_{at1}\beta_1(\alpha)\beta_2(p_r) - m_{at0} \tag{8}$$

$\beta_1(\alpha)$ is obtained by fitting the experiment data, which is the function of section area of manifold, throttle shape. $\beta_2(p)$ follows (9), p_{amb} is the air pressure before throttle, normal value is 1.013MPa. $p_c = 0.4125$, is the critical air ratio. The mass flow that enters into cylinder could be calculated by engine speed and volume, that is (11).

$$\beta_2(p) = \begin{cases} \sqrt{1-(\frac{p_r - p_c}{1-p_c})} & p_r > p_c \\ 1 & p_r \le p_c \end{cases} \tag{9}$$

$$p_r = \frac{p}{p_{amb}} \tag{10}$$

$$\dot{m}_{ap} = \frac{nV_d(e_V \cdot p_i)p_m}{120\,RT_m} \tag{11}$$

V_d (m^3) is engine volume, T_m (K) is manifold temperature, the efficiency of intake charge is functions of speed n and p ,such as (12), s_i , y_i have to be mapped according to physical engine.

$$(e_V \cdot p_i) = s_i(n)p_i + y_i(n) \tag{12}$$

C. *Crank Shaft Speed State*

This section is derived from energy reservation equation, the thermal value of fuel is released after compress, combustion and work, transferred to mechanical energy of crank shaft, the increase of shaft speed equals to the difference between fuel thermal value and energy loss that includes friction, pump resistance and load. Equation (13) describes it.

$$\dot{n} = \frac{H_u}{nI}\eta_i(n,p,\theta)\dot{m}_f(t-\tau_d) - \frac{P_f(n)+P_p(n,p)+P_b(n)}{nI} \tag{13}$$

H_u is fuel thermal value, I is crankshaft inertia. Thermal efficiency rate η_i is composed of 4 parts which is shown in (14). θ (degree) is Spark Advance Angle, λ is excess air coefficient, every part can be calculated according to [6]. Friction power p_f and pump power p_p have to be mapped according to real engine.

$$\eta_i(n,p,\theta) = \eta_n(n)\eta_p(p)\eta_\theta(n,p,\theta)\eta_\lambda(\lambda) \tag{14}$$

$$\tau_d = \frac{60}{n}(1+\frac{1}{n_{cyl}}) \tag{15}$$

Parameter τ_d is the time delay from fuel injection to torque out, the mean delay could be calculated as (15).

III. THE PROPOSED THEORY

In this section, we propose a novel CNG Turbo engine model and a few techniques in HIL. First, the model theory is introduced; second, the model is constructed with Matlab/Simulink; thirdly, the HIL simulation process and methods are presented.

CNG engine is obviously different from diesel or gasoline engine for the reasons below: 1. CNG fuel influence the manifold pressure because it is gas rather than liquid fuel; 2. CNG would not deposit in the manifold. 3. CNG fuel is more sensitive to temperature than gasoline and diesel, so the engine characters are different. Except for above reasons, the CNG engine power loss problem should be resolved, the suggested solution[7~9] is turbo charging, for higher manifold pressure, higher intake efficiency. Furthermore, for better emission, Exhaust Gas Recirculation (EGR) should be simulated. Our model consists of five sub-models: CNG Injection, Manifold, Crank Speed, Turbo Charging, Emission.

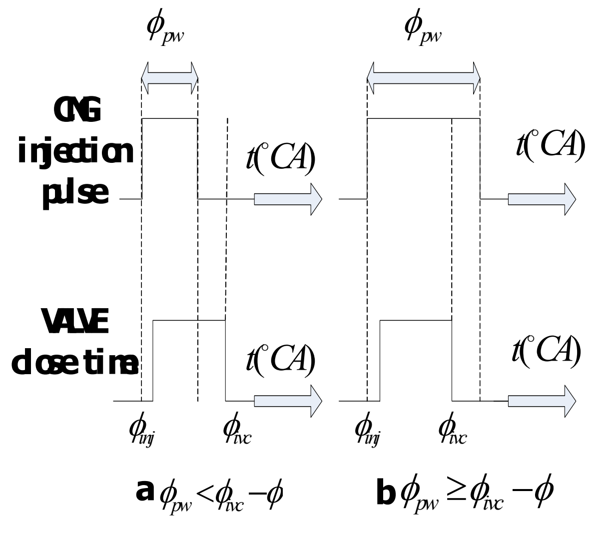

Figure 1. CNG injection and valve close time phases

A .CNG Injection Submodel

The dynamic structure of CNG engine is simpler than fuel engine which has no 'fuel deposit' effect. Most CNG engine adopt Sequence CNG Injection algorithm, injectors are located near intake valves. Normally, all of the CNG are inhaled cylinders, but there are other possible condition, that is, injector is still spraying when the intake valve have been closed. So the gas flow would be pumped into cylinder when next intake cycle as shown in Fig 1.

ϕ_{inj}（°CA）is the beginning time of injection, ϕ_{ivc}（°CA）is the close time of intake valve, which are converted to Crankshaft Angel (CA degree). The delay of CNG injection is one of the most important influences to engine. The first delay time is from the ECU calculation finished pint to injector beginning point. The delay could be calculated by (16).

$$\tau_a = \begin{cases} \pi/(2\omega_e) & n_{cyl}=4 \\ \tau_a = \pi/(3\omega_e) & n_{cyl}=6 \end{cases} \tag{16}$$

ω_e is the mean speed of crankshaft. The ϕ_{inj} is defined as the beginning related to Top Dead Center (TDC), another time delay occurs. τ_b from ϕ_{inj} to ϕ_{ivc} ,the average delay is shown as (17).

$$\tau_b = (\phi_{inj} - \phi_{ivc})/\omega_e \tag{17}$$

$$\tau_1 = \tau_a + \tau_b \tag{18}$$

$$\tau_2 = 4\pi/\omega_e \tag{19}$$

The delay of CNG entered into cylinder could be calculated as (20).

$$m_f = \begin{cases} m_{fi}(t-\tau_1) & if\ \phi_{pw} < \phi_{ivc} - \phi_{inj} \\ X_c m_{fi}(t-\tau_1) + (1-X_c)m_{fi}[t-(\tau_1+\tau_2)] & else \end{cases} \tag{20}$$

$X_c = \dfrac{\phi_{ivc} - \phi_{inj}}{\phi_{pw}}$. m_f is the mass flow of CNG pumped into cylinder, $m_{fi}(t-\tau_1)$ is the CNG quantity entered into valves after τ_1 delay. ϕ_{pw} is injection pulse width based on CA.

B.Manifold Submodel

Most of MVEMs are based on (7) [8~10] that foll0ws the isothermal assumption. But now we think it a adiabatic assumption rahter than isothermal, because there is huge difference between the temprature of air passed thottle, CNG and EGR, that is, there are engery and thermodynamic during mixing process in manifold. According to The First Law of Thermodynamics, the manifold is seclected as open and adiabatic system, to get the manifold dyanamic of CNG engine.

Equation (21) displays us the Energy balance of open thermodynamic system, E_{CV} is the air internal energy, δQ is the thermal energy in the whole system, $\delta m_{in}, \delta m_{out}$ is the air mass flow of flow in and out of the system respectively, δW_{net} is the net power out of system. h is the Enthalpy of gas in manifold. c, g, z are gas internal kinetic, gravity and potential parameters.

$$\begin{aligned}\delta Q = dE_{CV} + \delta W_{net} + (h + c^2/2 + gz)_{out}\delta m_{out} \\ -(h + c^2/2 + gz)_{in}\delta m_{in}\end{aligned} \quad (21)$$

$$dE_{CV} = h_{out}\delta m_{out} - h_{in}\delta m_{in} \quad (22)$$

$$\begin{aligned}(\dot{m}_a + \dot{m}_{CNG} - \dot{m}_{ap} + m_0)u' - m_o u \\ = h_{out}\delta m_{out} - h_{in}\delta m_{in}\end{aligned} \quad (23)$$

$$\begin{aligned}(\dot{m}_a + \dot{m}_{CNG} - \dot{m}_{ap} + m_0)C_v T_m - m_0 C_v T_0 \\ = C_p T_a \dot{m}_a + C_p T_{CNG}\dot{m}_{CNG} - C_p T_m \dot{m}_{ap}\end{aligned} \quad (24)$$

Equation (22) could be simplified from (21), if it follows the adiabatic assumption, in which the internal energy of gas in and out the system equal to the Enthalpy. Then the equation became (23), of which left side is the change rate of gas internal energy. $\dot{m}_a, \dot{m}_{CNG}, \dot{m}_{ap}, m_0$ is the mass flow rate of gas ,CNG, mixed air into cylinder and original gas in manifold. $u = C_v T$, $h = C_p T$. C_v, C_p are the heat capacity ratio with constant volume and pressure. Then (24) is the integrate equation. T (K) is the gas absolute temperature. $T_a, T_{CNG}, T_m, T_{EGR}$ are the gas temperature of air, CNG, mixed air, EGR, which was regarded same one in (7). $(\dot{m}_a + \dot{m}_{CNG} - \dot{m}_{ap} + m_0)$ is the mass quantity in manifold, then (25) is the mixed gas following the ideal gas equation (6) of the manifold thermal dynamics. If the EGR switch is on, it is (26).

$$\dot{p} = \frac{KR}{V}(T_a \dot{m}_a + T_{CNG}\dot{m}_{CNG} - T_m \dot{m}_{ap}) \quad (25)$$

$$\dot{p} = \frac{KR}{V}(\dot{m}_{at}T_a + \dot{m}_{CNG}T_{CNG} + \dot{m}_{EGR}T_{EGR} - \dot{m}_{ap}T_m) \quad (26)$$

If we transform the (24) to (27), $K = C_p / C_v$,the original gas mass m_0 follows ideal gas as (6).

$$\begin{aligned}m_0(T_m - T_0) = \dot{m}_a(KT_a - T_m) \\ + \dot{m}_{CNG}(KT_{CNG} - T_m) - \dot{m}_{ap}(K-1)T_m\end{aligned} \quad (27)$$

$$\begin{aligned}\dot{T}_m = \frac{RT_m}{P_m V}[\dot{m}_{at}(kT_a - T_m) + \dot{m}_{CNG}(kT_{CNG} - T_m) \\ + \dot{m}_{EGR}(kT_{EGR} - T_m) - \dot{m}_{ap}(k-1)T_m]\end{aligned} \quad (28)$$

The left is the change rate of gas temperature in manifold, if the EGR flow is considered, then the temperature equation is (28). (26) and (28) is the thermodynamic equation of CNG engine manifold.

C.Crank Speed Submodel

There is no change on CNG engine crankshaft and other mechanical parts, so it still follows (13). The difference is the CNG injection delay (20) is added.

D.Turbo Charging Submodel

The Turbo Charging aims for waste emission recycling, which could rotate turbo and compressor and increase the pressure of manifold, to acquire higher charging efficiency and power output without increase of cylinder volume. Gas temperature will increase after compressed, therefore cooler is needed. The turbo can be described as (29)~(31)[3]

$$T_c = T_{a0}\{1 + \frac{1}{\eta_C}[\pi_C^{(\frac{K-1}{K})} - 1]\} \quad (29)$$

$$\phi_q = \frac{1}{\eta_C} . \frac{k}{k-1} \cdot \frac{30}{\pi \cdot n_c} \cdot \dot{q}_{mc} RT_1[\pi_c^{(\frac{K-1}{K})} - 1]\} \quad (30)$$

$$P_2 = P_1 \cdot \pi_c \quad (31)$$

π_c is the compress ratio, η_c the rotation efficiency of turbo fan, they are nonlinear functions of gas flow mass rate $\dot{q}_{mc}$ and fan speed of turbo. n_c is rotate speed of compressor. Equation (30) is the compressor and turbo mechanical and energy balance equation. Exhaust gas drive turbo which rotate compressor through torque transfer. π_c, η_c is derived from characteristic curve provided by manufacture. In order to be easily used in simulation model, it is fitted as Fig. 2, encapsulated as sub-models, can be dynamically mapped with interpolation.

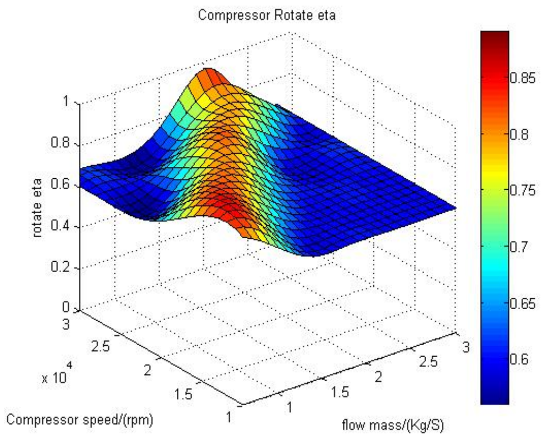

Figure 2. The fitted compressor rotate efficiency curve.

Two parameters of cooler are our focus, the air temperature and pressure after cooling. In this paper, we adopt curve fitting from the datasheet. The average exhaust gas temperature is calculated by the way presented in [11]~[13].

E.Emission Submodel

Much more complicated equation is involved when calculate the emissions, which slows simulation speed and stability. After analysis, Spark Advance Angle and A/F are the key factors influencing emission. So we fitting a three dimension map, according to experiment data, the quantity of three pollution elements NOx, CO, HC is indexed with λ and θ.

F.Auxiliary Units

Traditional MVEMs deal with IO signals by physical values, but now we want to use this model as embedded in model in real-time target hardware. If the IO interfaces are realized by hardware, it need more special circuit boards or sensors that increase the whole platform complexity, costs and reduce the stability and development efficiency. So an integrity solution is proposed, that is, we simulated common signal sources, sensors, which transform the physical values of input, output to electrical signals, both analog and discrete. All of them are built in sub-models according to ECU interface standards, making it easily to cooperate with real-time hardware seamlessly.[14]

Real crank speed is frequency controlled pulse, so the physical speed (rpm) should be transfer by Pulse Width Modulation (PWM) square. Most simulation algorithms use time as a benchmark to calculate other value. It is difficult realize PWM pulse except by using S-function which adds more simulation time cost. A PWM pulse source is introduced below to simulate speed sensor. A isosceles triangle pulse in constructed firstly, and its peak is 1, so bottom angel is β, it follows (32), T is the pulse period.

$$tg\beta = 4/T\,, f = tg\beta/4 \tag{32}$$

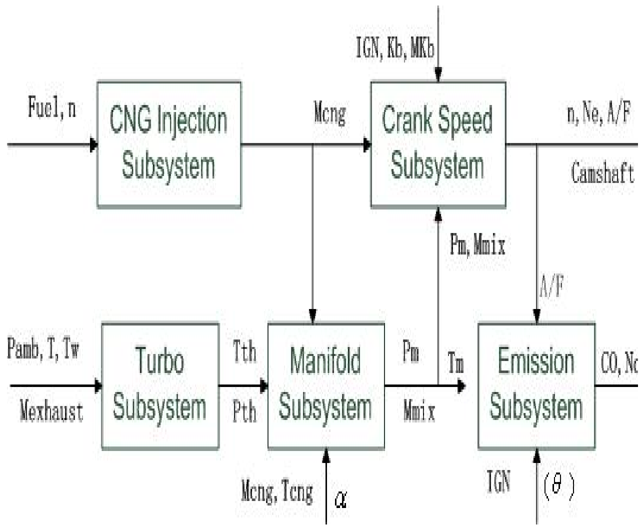

Figure 3. Simulation Model logic frame

If we need a pulse frequency $f = f_a$, the amplify output y_d is (34), that can be realized with a integral circuit.

$$y_d = \int_0^{T/4} tg\beta dt = \int_0^{T/4} 4 f_a dt \tag{33}$$

Cam position and phase signals are very important to ECU, but traditional model do not deal with intake and combustion. A pulse signal is simulated which strictly followed phase relation, 14th and 58th pulse phase as CA.

Manifold temperature and pressure sensor are simulated as (34). P (kpa) is pressure, V_{ref} (V) is reference voltage. Temperature model is made in a lookup table.

$$V_{out} = V_{ref}\left(0.01059 \times P - 0.10941\right) \tag{34}$$

TABLE I.

MODEL IO PORTS DEFINITION

Input	Description	Output	Description
Fuel	CNG injection pulse	Mcng	CNG amount (kg/s)
IGN	Spark signal	n	Crank speed (rpm)
α	Throttle Open degree	Pm	Manifold Pressure(bar)
T	Temperature of air(K)	Ne	Output Torque (N.m)
kB	Load ratio	A/F	Air/Fuel ration
Mkb	Load (kw)	Camshaft	Cam signal
Tcng	CNG temprature	Tm	ManifoldTemp
Tw	Temp of water	EMISSION	Nox,CO2,NO

IV. THE PROPOSED TECHNOLOGY

A.CNG Injection Submodel

Simulation engine is a reconstructed Toyota 8-A, Line 4 cylinders, MPI,4 strokes, power 63KW, in which injectors and turbo is added. Simulation logic frame refers to Fig.3. The definition of model IO ports are listed in Table .I..

B. Simulation Hardware Platform

CNG engine HIL simulation platform is cooperated on Host computer and Real-time target based on TCP/IP. Host computer is working with Matlab/Simulink platform, real-time target is PXI-8196 made by NI. Data collection Card is PXI-7831R made by NI. Host computer provide environment for software modeling and simulation, on the other side, real-time target act as data collecting, run simulation model, input/output simulation result and communication. Simulation Interface Toolkits (SIT) integrates Simulink/Labview with IO, which could built fast model code based on Simulink Model. This approach provides us more advantages such as easier ECU control policy constrcution and test, fast ECU interface time sequence matching, hardware development, and support complicated ECU function test. In this way, ECU could be developed and tested easily on the platform with few bench tests, saved us most costs and time.

Platform Work Flow refers to Fig.4.The Matlab/Simulink model is called by Labview RTW, then SIT start the SIT Server on the Real-time Target, download Model DLL and Driver VI, and running the model. When the parameters change, SIT Server will be notified in time and receive the new value, and execute new code to refresh the model parameters and IO values.

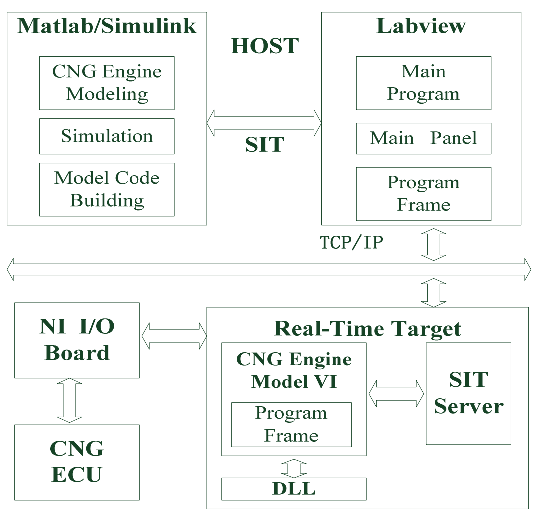

Figure. 4. Hardware Simulation Flow

V. EXPERIMENT

First step, we verified the software simulation, as work condition is crank speed 2500 rpm, throttle open degree from 30degree to 40 then 20, the simulation curves are shown as Fig. 5. It indicates that the simulation data is close to engine test bench data, with average error about 5%,. Manifold pressure curves changes ahead the bench test data, but the average result error still less 5%. That proves the MVEMs are applied for control model rather than full dynamics model, because the biggest error usually occurs at suddenly change of throttle or manifold

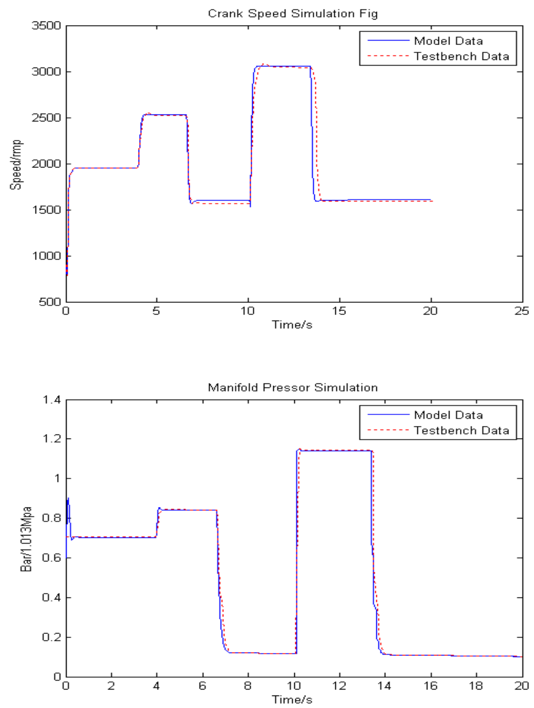

Figure 5. Simulation Result and Bench Test Data

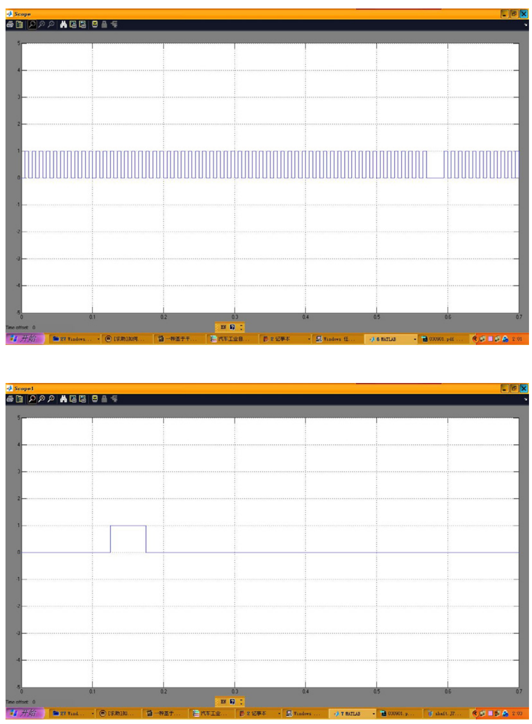

Figure 6. Crank and Cam Speed Pulse Wave

pressure.

As shown in Fig.6, the physical value of crank speed and cam speed is transformed to PWM pulse, of which duty is 0.5, amplification is 1, and the most important character frequency is changing with the crank speed. According to the ECU time sequence requirements, the crank speed generates 58 pulses in one cycle, and the cam pulse phase is located in the 14th~19th pulse of crank pulse.

VI. CONCLUSION

Traditional MVEMs are based on the assumption of isothermal process of manifold gas flow in which cam and crankshaft phase are not described. We proposed a new approach that follows adiabatic assumption, presented new equations of manifold dynamics and CNG injection delay. Furthermore, we present a new CNG Turbo engine model based on improved MVEMs and the HIL platform, of which IO are keep up with the real circuit signals. The platform could reduce CNG ECU development cost and period. The simulation results of both software and HIL prove that the model has good accuracy ,stability and time response.

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