

HARDWARE-IN-THE-LOOP SIMULATION FOR ESTIMATING DYNAMICS PARAMETERS OF VEHICLE

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Abstract - Information about vehicle dynamics states is indispensable for modern dynamics control system on vehicle today. For economic reasons, a technique called “virtual sensor” which bases on dynamical model of vehicle and an observation algorithm are used to estimate real states of vehicle. In this paper, a system based on Hardware-in-the-loop simulation will be used to estimate the vehicle states in real time. CarSim is a professional software for simulating the dynamics of vehicle which is used as a virtual vehicle in this paper. An observer based on Luen-berge method is developed and implemented by Arduino Mega 2560 board. Matlab/Simulink plays the role of acquisition and data transfer center. The simulation results show the good performance of observer in real time condition when the estimated values are well converged to real values given by CarSim.

Key words - Hardware-in-the-loop; the observer; dynamics; car, Arduino Mega 2560.

1. Introduction

Automatic control systems play an important role in the modern vehicle today, for example anti-br (ABS), electronic stability control system (ESC)... To operate efficiently, these controllers require the accurate information about vehicle dynamics state which come from measurement system on vehicle. However, equipping a commercial vehicle with expensive sensors leads to increasing cost for production, maintenance and as a result, reducing the competence of product. A solution to this problem is using the “software sensors” which bases on the dynamics model of object and the observer algorithms to estimate the real value of needed grandeur. This technique has been applied to many control applications, especially in vehicle control.

In Tanoury’s works [1], high gain observer and second-order sliding mode (SOSM) for estimating rolling resistance force and detecting sudden decrease of tire pressure had been developed. Second order observer for mechanical system has been presented in [2] is not only for states estimation but also for parameter identification and unknown input reconstruction. In [3], second order SMO is developed to estimate lateral force by using a bicycle model. In addition, the Kalman filter is also widely used to estimate the vehicle states and parameters [4], [5]). This filter combining with SMO observer is used to estimate side slide angle of vehicle, traction force and cornering stiffness of tires. In [6], the authors used a system of observers including Kalman filter and Luenberge observers to estimate the mass, roll and pitch angles of vehicle.

Virtual Laboratory is an advanced technology which combines real control hardware, control software and human factors in a unique system. This allows testing the interaction among the components of control system in real conditions. Hardware-in-the-loop (HIL) is in order to evaluate the performance of algorithm in real circuit board. In [7], the authors proposed a new system to implement HIL for

Advanced driver-assistance systems on the vehicle. Results show that this design has high precision and repeatable experiment conditions. HIL and LabView are combined in [8] where they are used to test the control system of Unmanned aerial vehicle. HIL is also used to test performance of powertrain control systems of electric vehicle in [9].

In this paper we propose a HIL simulation system to estimate the dynamics parameters of vehicle. Matlab/Simulink, CarSim and Arduino mega 2560 are the components of this system. The rest of paper is organized as follows: the second part presents the configuration of HIL simulation system. The third part summaries the dynamics model of vehicle CarSim and virtual vehicle with double-lane change test. The next section focus on designing Luenberge observer using pole placement method. The next part will introduce the simulation results. The last section is reserved for conclusion and perspective

2. Configuration of Hardware-in-the-loop simulation

The hardware in the loop simulation permits the integration of a specific software into a closed loop control system with a physical device in order to test the algorithm and the performance of embedded system. Figure 1 describes the configuration of our system which includes three main components. The first is CarSim for simulating the performance of vehicle and sending to Simulink the data of vehicle states. The second component is Simulink which will receive the data from Carsim and transfer to Arduino board through UDP interface. Simulink also receives data from Arduino to compare the results. The last component is Arduino board which implements the observer algorithm. Arduino Integrated Development Environment (Arduino IDE) is used for coding and programming Arduino Board through serial interface. In this research we use Arduino Mega 2560 due to its powerful calculation capacity. Realtime Matlab kernel is to run Simulink in real time mode. UDP communication protocol is chosen due to its high speed and simple configuration.

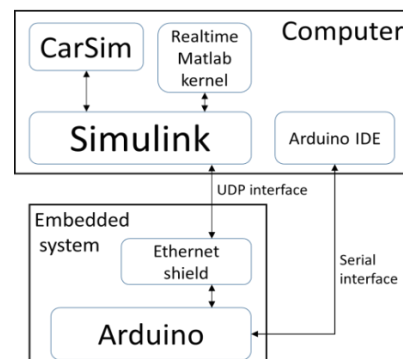


Figure 1. Configuraion of HIL simulation system

3. Dynamics model of selected vehicle

3.1. Dynamics model of vehicle

Vehicle motions are very complicated in real conditions. Therefore, to facilitate the research, in this paper, we use a flat model for a rigid bicycle vehicle having forward, lateral, yaw, and roll motions presented in Figure 2. The model of a roll-able rigid vehicle is more exact and more effective compared to that of the rigid bicycle vehicle planar model. Due to the limitation of paper length, here we present only the final model. Interested readers can refer to [10] for more details.

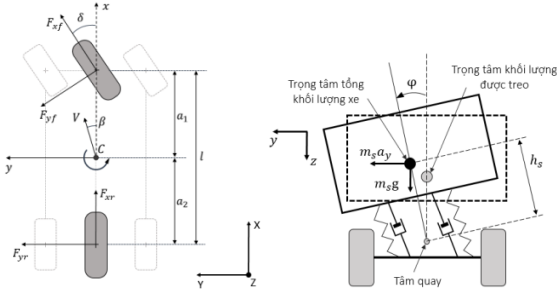


Figure 2. Rollable bicycle vehicle model

The dynamic equations of vehicle motion are given in (1) where the symbol is given in Table 1.

$$\begin{cases} \dot{v}_y = \frac{C_\beta}{m} \beta + \left(\frac{C_r}{m} - v_x \right) r + \frac{C_\phi}{m} \phi + \frac{C_p}{m} p + \frac{C_\delta}{m} \delta \\ \dot{\omega}_z = \frac{D_\beta}{I_z} \beta + \frac{D_r}{I_z} r + \frac{D_\phi}{I_z} \phi + \frac{D_p}{I_z} p + \frac{D_\delta}{I_z} \delta \\ \dot{\phi} = p = 0\beta + 0r + 0\phi + 1p + 0\delta \\ \dot{\omega}_x = \frac{E_\beta}{I_x} \beta + \frac{E_r}{I_x} r + \frac{E_\phi}{I_x} \phi + \frac{E_p}{I_x} p + \frac{E_\delta}{I_x} \delta \end{cases} \quad (1)$$

The formulas of symbols in (1) is given below:

$$C_\beta = (-C_{\alpha_f} - C_{\alpha_r})$$

$$C_r = \left(\frac{a_2 C_{\alpha_r} - a_1 C_{\alpha_f}}{v_x} \right)$$

$$C_\phi = (C_{\alpha_f} C_{\delta\phi_f} + C_{\alpha_r} C_{\delta\phi_r} - C_{\phi_f} - C_{\phi_r})$$

$$C_p = \left(\frac{C_{\alpha_f} C_{\beta_f} + C_{\alpha_r} C_{\beta_r}}{v_x} \right)$$

$$C_\delta = C_{\alpha_f}$$

$$D_\beta = -a_1 C_{\alpha_f} + a_2 C_{\alpha_r}$$

$$D_r = \left(\frac{-a_1^2 C_{\alpha_f} - a_2^2 C_{\alpha_r}}{v_x} \right)$$

$$D_\phi = \left(a_2 (C_{\phi_r} - C_{\alpha_r} C_{\delta\phi_r}) - a_1 (C_{\phi_f} - C_{\alpha_f} C_{\delta\phi_f}) \right)$$

$$D_p = \left(\frac{a_1 C_{\alpha_f} C_{\beta_f} - a_2 C_{\alpha_r} C_{\beta_r}}{v_x} \right)$$

$$D_\delta = a_1 C_{\alpha_f}$$

$$E_\beta = \frac{m_s h_s (-C_{\alpha_f} - C_{\alpha_r})}{m}$$

$$E_r = \frac{m_s h_s (a_2 C_{\alpha_r} - a_1 C_{\alpha_f})}{m v_x}$$

$$E_\phi = \left(\frac{m_s h_s (C_{\alpha_f} C_{\delta\phi_f} + C_{\alpha_r} C_{\delta\phi_r} - C_{\phi_f} - C_{\phi_r})}{m} + m_s g h_s - k \right)$$

$$E_p = \left(\frac{m_s h_s (C_{\alpha_f} C_{\beta_f} + C_{\alpha_r} C_{\beta_r})}{m v_x} - c_\phi \right)$$

$$E_\delta = \frac{m_s h_s C_{\alpha_f}}{m}$$

Table 1. List of symbol

Symbol	Definition	Unit
β	Side slip angle of vehicle	rad
δ	Steering angle	rad
δ_f	Front Steering angle	rad
δ_r	Rear Steering angle	rad
ψ	Yaw angle	rad
$\dot{\psi}$	Yaw velocity	rad/s
l	Base length of vehicle	m
a_1	Distance from front wheel to CoG	m
a_2	Distance from rear wheel to CoG	m
B	Base width of vehicle	m
m	Vehicle mass	kg
C_{α_f}	Cornering stiffness at front wheel	N/rad
C_{α_r}	Cornering stiffness at rear wheel	N/rad
$C_{\delta\phi_f}$	Front roll-steering coefficient	
$C_{\delta\phi_r}$	Rear roll-steering coefficient	
C_{β_f}	Front tire roll rate coefficient	
C_{β_r}	Rear tire roll rate coefficient sau	
C_{ϕ_f}	Front tire camber thrust coefficient	
C_{ϕ_r}	Rear tire camber thrust coefficient	
k_ϕ	Roll stiffness	Nm/rad
c_ϕ	Roll damping	Nms/rad
I_x	Moment of inertial around x axis	kg.m ²
I_z	Moment of inertial around z axis	kg.m ²
v	Vận tốc chuyển động của xe	m/s
v_x	Longitudinal velocity	m/s
v_y	Lateral velocity	m/s
a_y	Lateral acceleration	m/s ²
ω_x	roll rate	rad/s
ω_z	Yaw rate	rad/s
ϕ	Roll angle	rad
U	Steering angle	rad

Rewrite (1) in state space form we get (2)

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \quad (2)$$

where

$x = [v_y, p, \phi, r]^T$ is state vector;

$u = \delta$ is input vector;

$y = (a_y, p, r)$ is output vector with assumption that lateral acceleration, roll rate and yaw rate are measurable.

$$A = \begin{bmatrix} \frac{C_\beta C_r}{mv_x m} - \frac{C_\varphi C_p}{m} & \frac{D_\beta}{I_z} & \frac{D_r}{I_z} & \frac{D_\varphi D_p}{I_z} \\ 0 & 0 & 0 & 1 \\ \frac{E_\beta}{I_x} & \frac{E_r}{I_x} & \frac{E_\varphi E_p}{I_x} & 0 \end{bmatrix}$$
 is state matrix

$$B = \begin{bmatrix} \frac{C_\delta}{m} \\ \frac{D_\delta}{I_z} \\ 0 \\ \frac{E_p}{I_x} \end{bmatrix}$$
 is input matrix; $C = \begin{bmatrix} C_\beta C_r C_\varphi C_p \\ m & m & m & m \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$ is output

matrix and $D = \begin{bmatrix} C_\delta \\ m \\ 0 \\ 0 \end{bmatrix}$ is feedforward matrix.

It can be seen that system (2) is linear invariant time at a predefined longitudinal velocity of vehicle. It means that the model of system varies with the change of vehicle speed. Therefore, to evaluate the performance of this model, it is necessary to fix the longitudinal velocity of vehicle.

3.2. Selected vehicle in CarSim

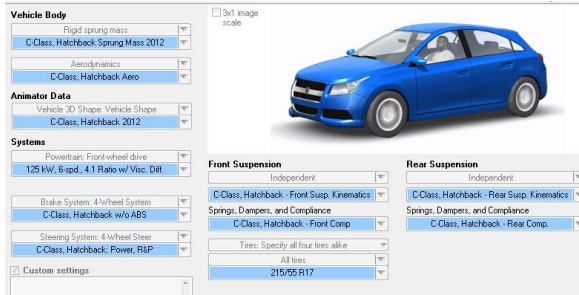


Figure 3. Type of vehicle used in this paper

CarSim is developed by Mechanical Simulation Corporation (American) from 1996. By using Multibody Dynamics modelling, this software allows recreating the behaviour of most of light vehicle on the market. One advantage of CarSim is its module structure including many sub-models of each component of car. This allows users to modify and test vehicle in many different configurations. In addition, it integrates inside many type of test including the road surface, ISO lane change test...

Table 2. Predefined parameters of research vehicle

Parameters	Value	Parameters	Value
m	1412	I_x	536.6
m_s	1270	a_1	1.015
I_z	1536.7	a_2	1.8950

Figure 3 shows the vehicle used in this paper while Table 2 presents the main parameters of this car. Due to CarSim using the different model to our model (2), the parameters of model (2) should be identified so that this model can be valid to real vehicle. This step will be done by using Simulink parameter identification tool.

Simulink parameter identification is a useful tool to determinate the parameters of model. Its principle is

simple: both reference and research model are excited by the same input signals. Then the parameters of research model will be changed by a recursive algorithm so that the outputs of research model converge to ones of reference model. In this case, the input signal is the steering angle δ during the double lane change test and the outputs are lateral acceleration and velocity, yaw and roll rate. The longitudinal velocity is fix at 65km/h. Figure 4 shows the main interface of this tool during initial configuration process. Up to now the model of vehicle is complete and next step is design observer.

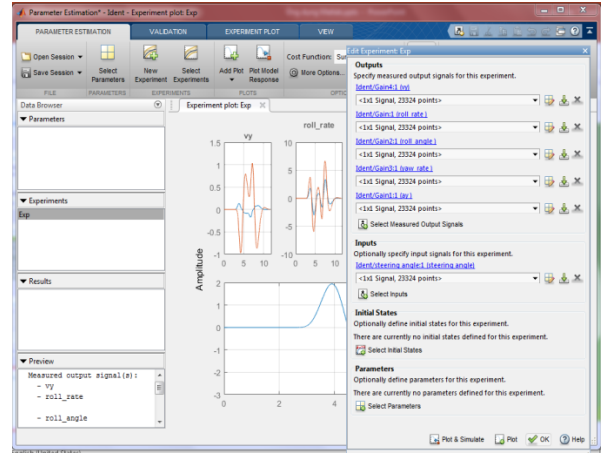


Figure 4. Interface of Simulink parameter identification

Table 3. Initial and identified values of vehicle parameters

Symbol	Initial value	Identified value
C_{af}	2 x 28648	150000
C_{ar}	2 x 26356	47222
$C_{\delta\varphi f}$	0.01	-0.063
$C_{\delta\varphi r}$	0	0.7679
$C_{\beta f}$	0.01	-1.2293
$C_{\beta r}$	0.01	1.2247
$C_{\varphi f}$	2	1.99
$C_{\varphi r}$	1	0.99
h	0.54	0.5
k	50000	94169
c	2000	17802

4. Pole placement-based observer design

The system now is a linear invariant time and therefore a linear Luenberger observer will be used. Firstly, the observability of system will be discussed. The observability matrix is built from A and C matrix as $Ob = [C, AC, A^2C, \dots, A^{n-1}C]$. It can be tested using Matlab whose rank of observability matrix in this case is 4 (full rank) and therefore the system is observable.

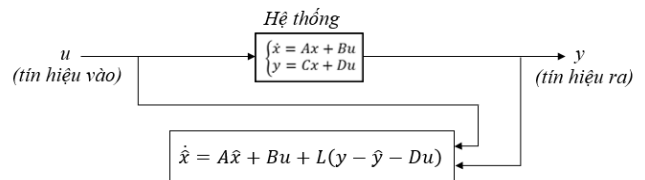


Figure 5. Structure of observer base on input and measurable output

The structure of observer is presented in (3) where the main part of system is conserved and added a correction term $L(y - \hat{y})$ which causes system convergence. Figure 5 presents the structure of observer where the input of observer is input u and output y of system.

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + L(y - \hat{y}) \\ y = C\hat{x} + Du \end{cases} \quad (3)$$

It can be seen that the error dynamics of observer and model as (4).

$$\begin{aligned} \dot{x} - \dot{\hat{x}} &= A(x - \hat{x}) - L(Cx - C\hat{x}) \\ &= (A - LC)(x - \hat{x}) \end{aligned} \quad (4)$$

The problem now is to choose value of L to stabilize system (4). This can be done easily by using pole placement method where the pole of error dynamics system can be chosen arbitrarily. In most cases, the recommended values of observer poles are 5 times the poles of original system so that the estimated values can converge rapidly to real ones. Using Matlab, matrix L is determined as in (5). The final structure of system is presented in Figure 6.

$$L = \begin{bmatrix} 1.3137 & -18.2159 & -63.1412 \\ -0.1084 & 28.4993 & 3.2035 \\ 0.5995 & -3.8569 & -11.3383 \\ -1.9779 & 3.5376 & 58.5043 \end{bmatrix} \quad (5)$$

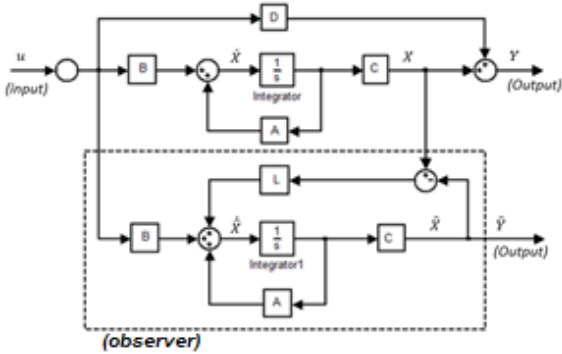


Figure 6. Structure of Luenberger state observer

5. Hardware in the loop simulation results

In this research, the lateral acceleration, yaw rate and roll rate are assumed measurable. Therefore, it remains lateral velocity and roll angle needs to be estimated. The first results are presented in Figure 7 and Figure 8 with longitudinal velocity of 30km/h. The initial values of observer are set to 0. It can be seen that lateral velocity is very well estimated while roll angle is also well estimated with only small error at the end of experiment.

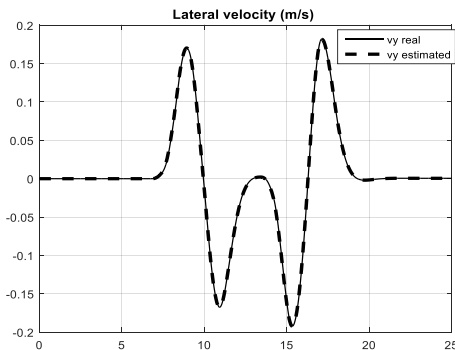


Figure 7. Estimation of lateral velocity at 30km/h

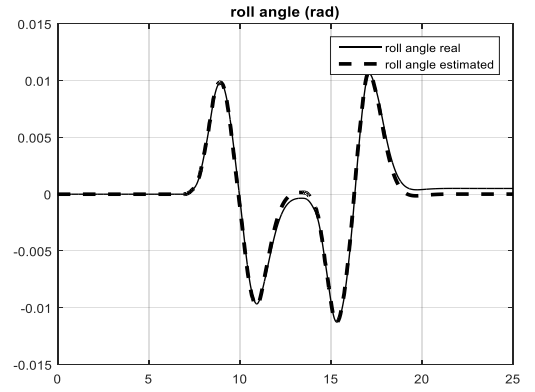


Figure 8. Estimation of roll angle at 30 km/h

The similar results are obtained at longitudinal velocity 45km/h which are shown in Figure 9 and Figure 10. In Figure 9 the velocity in lateral direction is well estimated. There are only some small errors of estimation of roll angle at about time instant 9s. This can be explained that at that time, vehicle is recovering to the straight path from curvature path and therefore the response of roll angle may be more complex than linear invariant model and it causes that error.

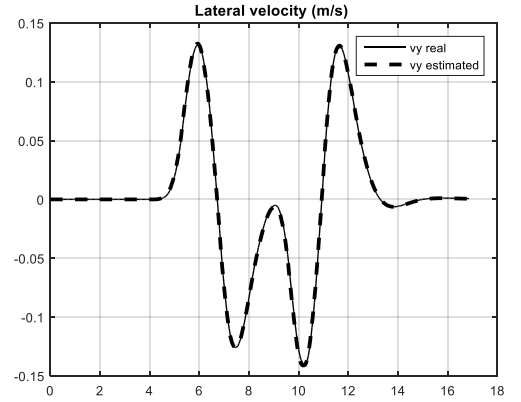


Figure 9. Estimation of lateral velocity at 45km/h

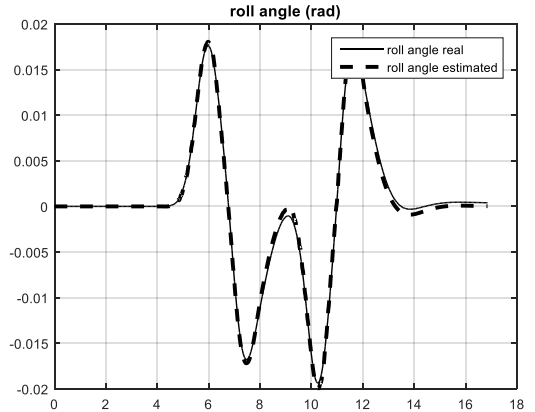


Figure 10. Estimation of roll angle at 45km/h

However, when longitudinal velocity increases, the estimation results have different behaviours. Figure 11 shows the estimation of lateral velocity of vehicle during double lane change test at 65km/h.

Figure 11 shows the estimation which is good but there are some moments when the errors become more important than the case of 35km/h and 45km/h. This can be explained that at this velocity, the dynamics of vehicle have a

change in the sign of side slip angle during the second cornering of double lane change test and that creates the abnormal behaviours. However, there is no influence on estimation of roll angle as shown in Figure 12 where the results are still very good.

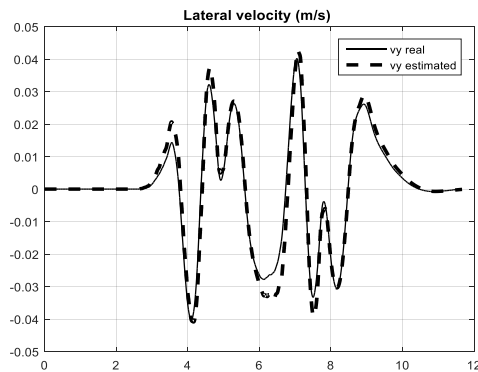


Figure 11. Estimation of lateral velocity at 65km/h

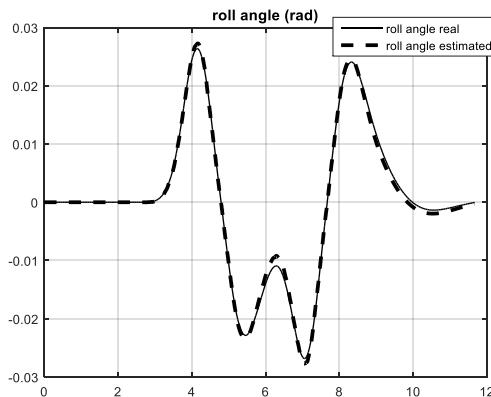


Figure 12. Estimation of roll angle at 65km/h

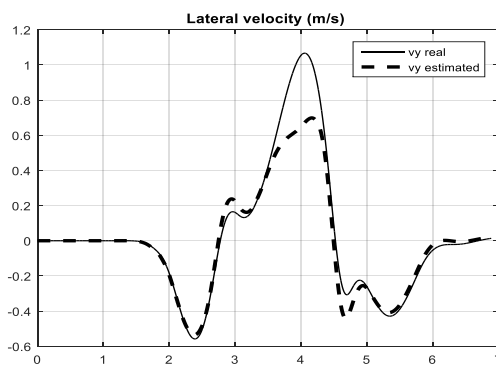


Figure 13. Estimation of lateral velocity at 110km/h

Increasing longitudinal velocity to 110km/h, the estimation results of lateral velocity in Figure 13 clearly shows the errors in comparison with the lower longitudinal velocity cases. This phenomenon happens not only to lateral velocity but also in roll angle in Figure 14. These errors can be explained by the modelling errors of our linear invariant time model. This model is created by identifying the parameters of vehicle at 65km/h. But in case the velocity is near two times of this point, the precision of this model is reduced significantly. Another important factor is that when

manoeuvring double lane change at 110km/h the lateral acceleration is excessive $0.4g$, the threshold of linear model and therefore the linear model is not valid in this case.

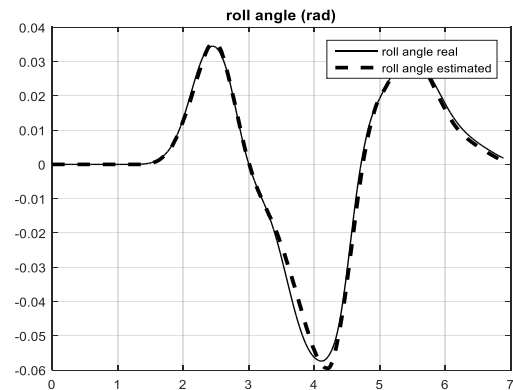


Figure 14. Estimation of roll angle at 110km/h

6. Conclusion

This paper presents a HIL simulation system using Arduino Mega 2560 and Ethernet shield to implement an observer algorithm. The experiment results show that the Arduino Mega 2560 can well execute the Luenberger observer with 4 double type variables. The dynamics states of vehicle are well estimated in realtime. The precision of results depends on the precision of vehicle model. The nearer operation point (linearization point) the higher precision.

REFERENCE

- [1] Charbel El Tannoury and al., "Synthesis and Application of Nonlinear Observers for the Estimation of Tire Effective Radius and Rolling Resistance of an Automotive Vehicle", *IEEE Transactions on control systems technology*, 2013.
- [2] J. Davila, L. Fridman and A. Poznyak, "Observation and Identification of Mechanical Systems via Second Order Sliding Modes", in *International Workshop on Variable Structure Systems*, Alghero, Italy, 2006.
- [3] J. Davila, L. Fridman and A. Levant, "Second-Order Sliding-Mode Observer for Mechanical Systems", *IEEE transactions on automatic control*, vol. 50, pp. 1785-1789, 2005.
- [4] H. B. Pacejka, Tyre and Vehicle Dynamics, *ELSEVIER*, 2006.
- [5] S. Kuntanapreeda, "Estimation of Longitudinal Tire Force Using Nonlinearity Observer", *Open Journal of Applied Sciences*, vol. 3, pp. 41-46, 2013.
- [6] B. Wang, "State observer for diagnosis of dynamic behavior of vehicle in its environment", *Universite de Technologie de Compiegne*, Compiegne, 2013.
- [7] Tafner, M. Reichhartinger and M. Horn, "Estimation of Tire Parameters via Second-Order Sliding Mode Observers with Unknown Inputs", in *13th IEEE Workshop on Variable Structure Systems*, Nantes, France., 2014.
- [8] S. C. O. A. L. B. M Feingesicht, "Hil validation of an embedded system acting as a nonlinear Takagi-Sugeno state observer on an Arduino board", in *6th European Embedded Design in Education and Research*, Milan, 2014.
- [9] The Tyre Rolling resistance and fuel savings, *Société de Technologie Michelin*, 2003.
- [10] U. Sandberg, "Rolling Resistance – Basic Information and State-of-the-Art on Measurement methods", *Swedish National Road and Transport Research Institute*, 2011.