Design of Driving Simulator for Studying Vehicle Rollover

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Abstract

Generally, vehicle dynamics is studied by the simulation and experiment test. The simulation is used in early design and development stage to reduce development cost and time. Simulation is safer for the test driver, especially when testing may result in severe motions such as rollover. Therefore, experiment is mainly used only for confirmation. In this research, Driving Simulator (DS) for testing vehicle roll motion is presented. The proposed has 2 degree-of-freedom which consists of pitch and roll that can also be used for longitudinal and lateral acceleration simulation. DS was designed based on human motion perception.ual reality motion. The DS was design to have roll and pitch axes at the driver's head position to minimize the driver's head from moving from the pitch and roll motion. The motion and force analysis are presented in this paper. These analyses were carried out both manually and with computer program. Range of motion, actuator force, and required stroke was adjusted by moving various joint positions. Finally, actual measurement is made and compared with the design values.

Keywords: Driving Simulator, Human Perception, Rollover

1. Introduction

In the design and development, driving simulator is essential for its flexibility and repeatability. Time and money can be saved by reducing the number of actual experiment required. Moreover, it is safer for the test driver, especially when testing severe motions such as rollover.

It is generally accepted that driving simulator with simulated motions; e.g., roll, pitch, and yaw (Fig. 1), give the driver more realistic feeling. In particular, driving simulators can be used to study effects of these motions on driver comfort and performance. This paper presents the design and construction of a driving simulator designed to study effects of roll and pitch motion on the driver performance. However, our initial interest was on roll over prevention study.

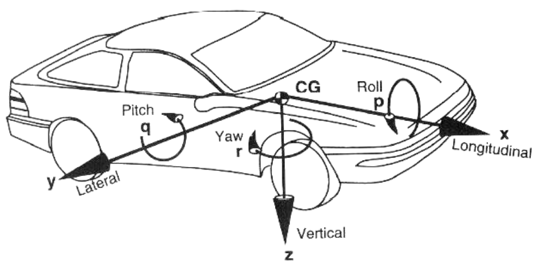

Fig. 1 The vehicle axis and motion [1]

The vehicle roll motion is the movement around x-axis which is shown in Fig. 1. It is caused by the lateral force acts at an elevated point on the vehicle such as a side wind and the inertia force acting at the center of gravity. Rollover is a serious problem that can cause severe injury on the passenger. Rollover tendency of vehicles can be represented using rollover thresholds shown in Table. 1.

Table. 1 Vehicle rollover thresholds [1]

Vehicle Type	CG Height (inches)	Tread (inches)	Rollover Threshold (g)
Sport car	18 – 20	50 – 60	1.2 – 1.7
Compact car	20 – 23	50 – 60	1.1 – 1.5
Luxury car	20 – 24	60 – 65	1.2 – 1.6
Pickup car	30 – 35	65 – 70	0.9 – 1.1
Van	30 – 40	65 – 70	0.8 – 1.1
Medium truck	45 – 55	65 – 75	0.6 – 0.8
Heavy truck	60 – 85	70 – 72	0.4 – 0.6

Before the vehicle safety design, it has to study the roll motion and its affect to driver's behavior. In the experiment study, it is very dangerous when rollover is occurred, so DS is useful for using in studying and testing because it's safety.

Driving simulator (DS) can be classified into 2 types of mechanism which is series and parallel. The parallel mechanism is better in load distribution on actuators than the series but the more complex mechanism of parallel, the harder control. Nowadays, each of DS has different mechanism and DOF because it is suitable for different objects of user such as playing games, training, experiment etc. The more number of DOF, the more virtual reality simulation and more expensive. For example, the most popular DS is Stewart platform [2] which has 6 degree-of-freedom. The simulation is good movement but the price is so expensive. Force Dynamics [3] is the 3 DOF DS that can use in marketing, training, have fun at home, or learn your next track. However, the restitution of 2 DOF movements which consist of the pitch angle simulates the acceleration and brake and the roll angle simulates the cornering is enough for the study the driver's steering behavior in vehicle roll motion.

2. Design of Driving Simulator

A DS works by replacing a real acceleration with the force we feel from gravity, shown in Fig. 2. The simulator will tilt the pitch angle to make the longitudinal acceleration and tilt the roll angle to make the lateral acceleration.

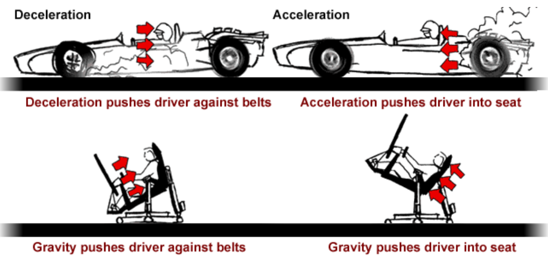

Fig. 2 Principles of simulation acceleration [4]

The virtual reality simulation depends on the correspondence between the DS movement control and the human perception of acceleration. In DS design, the human perception threshold is considered in one of the important things. The system of human perception is in the inner ears (Labyrinth) which has vestibular system which helps the body maintain its postal equilibrium. It consists of Otolith and Semicircular canal. The Otolith consists of Utricle and Saccule which response to linear acceleration or the position change of head respect to gravity. The Semicircular canal is response to rotation acceleration.

2.1 Design Requirement

From studying motion system [4], if the center of rotational is below the driver, the undesirable reverse force will occur when start the tilt motion, but if the center of rotational is over the driver, the undesirable reverse force will not occur. Therefore, the head joint of DS is selected over the driver head in order to get the better perception of acceleration.

From the driving experiment in 4 conditions [5] and studying the DS in present, the vehicle acceleration data in 2 axis, longitudinal acceleration and lateral acceleration, can conclude that the DS should tilt pitch angle (ϕ) $\pm$25 degree and roll angle (θ) $\pm$40 degree. The angle of driving module (DM) is calculated from the relation between real acceleration and the angle of DM in Eqs. (1) – (2). The a_x is the lateral acceleration and the a_y is the longitudinal acceleration.

$$\text{Pitch Angle } (\phi) = \sin^{-1}\left(\frac{a_x}{g}\right) \quad (1)$$

$$\text{Roll Angle } (\theta) = \sin^{-1}\left(\frac{a_y}{g \cdot \cos(\phi)}\right) \quad (2)$$

At the beginning, the objective of design this DS is using for considering the driver's behavior in the vehicle roll motion of frequency range 1 – 2 Hz.

In summary, the requirements for design DS are

1. DS has 2 DOF
2. The head joint over the head of driver.
3. DS has pitch angle in range of $\pm$25 degree and roll angle in range of $\pm$40 degree.
4. The frequency using in an experiment is 1 Hz.

2.2. Conceptual Design

There are 3 designs of DS which are parallel mechanism and use 2 actuators which has stroke 600 mm to control the DS. The first design, shown in Fig. 3 can simulate the pitch angle between +40 degree and -18 degree and the roll angle is $\pm$38 degree. The disadvantage of this design is the heavy weight of driving module (DM). This problem can affect the motion and load on the actuator when using in the real structure.

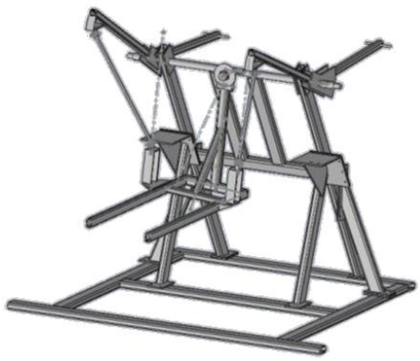

Fig. 3 Driving simulator design 1

The second design, shown in Fig. 4, can simulate the pitch angle between +25 and -45 degree and the roll angle for $\pm$40 degree. DM has light weight but there are many linkages which make uncomfortable for user to get in or out from DM.

Fig. 4 Driving simulator design 2

The third design, shown in Fig. 5, can simulate the pitch angle between 0 and +10 degree and the roll angle for ± 20 degree. DM has light weight but it has problem about motion and the load on actuators.

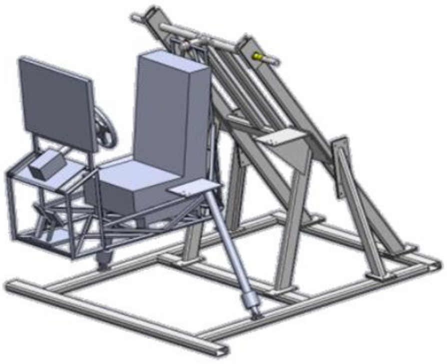

Fig. 5 Driving simulator design 3

The decision of DS design is based on the angle, weight, cost, comfort, and utilization. By using the weighted rating, it shows that the second design is the most suitable for the required conditions.

2.3 Mathematical Model

A mathematical model is used to investigated the suitable joint position and linkage length. Moreover, this model is used to determine the force on each linkage which is important to consider for the suitable actuator.

2.3.1 Center of Gravity Position

When the DS rotates, the CG position will change as shown in Fig. 6. We can explain the CG position which has reference from the head joint by using Eqs. (3) – (5).

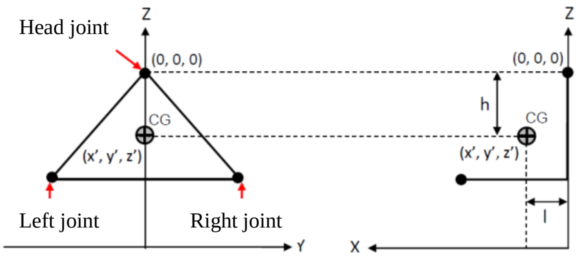

Fig. 6 The CG position before the DS rotate

$$x' = h\cos\theta\sin\phi + l\cos\phi \quad (3)$$

$$y' = -h\sin\theta \quad (4)$$

$$z' = -h\cos\theta\cos\phi + l\sin\phi \quad (5)$$

When h is the vertical displacement between CG and head joint in normal position, l is the horizontal displacement between CG and head joint in normal position, θ is the roll angle, and $\emptyset$ is the pitch angle.

2.3.2 Joint Position on Driving Module

The DM has 3 joints consist of 1 head joint, 2 DOF joint (x_1, y_1, z_1) and 2 universal joint in the side of DM, (x_{2L}, y_{2L}, z_{2L}) and (x_{2R}, y_{2R}, z_{2R}) is shown in Fig. 7. We can determine the joint position by using Eqs. (6) – (11).

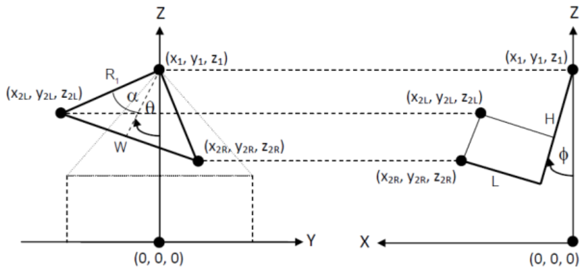

Fig. 7 The front view of joint position on DM

The left side joint is (x_{2L}, y_{2L}, z_{2L}).

$$x_{2L} = R_1\cos(\alpha+\theta)\sin\phi + L\cos\phi \quad (6)$$

$$y_{2L} = -R_1\sin(\alpha+\theta) \quad (7)$$

$$z_{2L} = z_{1L} - [R_1\cos(\alpha+\theta)\cos\phi - L\sin\phi] \quad (8)$$

The right side joint is (x_{2L}, y_{2L}, z_{2L}).

$$x_{2R} = R_1\cos(-\alpha+\theta)\sin\phi + L\cos\phi \quad (9)$$

$$y_{2R} = R_1\sin(-\alpha+\theta) \quad (10)$$

$$z_{2R} = z_{1R} - [R_1\cos(-\alpha+\theta)\cos\phi - L\sin\phi] \quad (11)$$

When $R_1 = \sqrt{\left(\frac{W}{2}\right)^2 + (H)^2}$ and $\alpha = \arctan\left(\frac{W}{2H}\right)$

Where W is width of DM, H is height of DM, L is depth of DM, θ is the roll angle, and $\emptyset$ is the pitch angle.

2.3.3 Joint Position on Linkage

Fig. 8 shows the position on DS linkage and the position of actuator as (x_5, y_5, z_5) and (x_6, y_6, z_6). All positions can be derived by Eqs. (12) – (17).

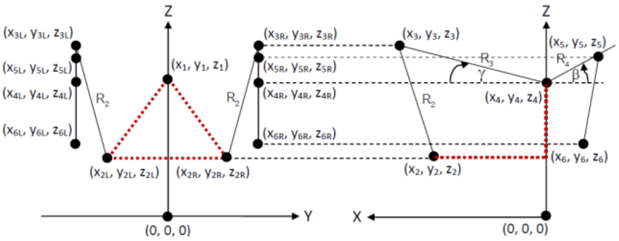

Fig. 8 Joint position on DS linkage.

$$x_{3L} = x_{4L} + R_3 \cos\gamma_L \qquad (12)$$

$$y_{3L} = y_{4L} \qquad (13)$$

$$z_{3L} = z_{4L} + R_3 \sin\gamma_L \qquad (14)$$

$$x_{5L} = x_{4L} - R_4 \cos\beta_L \qquad (15)$$

$$y_{5L} = y_{4L} \qquad (16)$$

$$z_{5L} = z_{4L} + R_4 \sin\beta_L \qquad (17)$$

When

$$R_2 = \sqrt{(x_2 - x_3)^2 + (y_2 - y_3)^2 + (z_2 - z_3)^2}$$

$$R_3 = \sqrt{(x_3 - x_4)^2 + (y_3 - y_4)^2 + (z_3 - z_4)^2}$$

$$R_4 = \sqrt{(x_4 - x_5)^2 + (z_4 - z_5)^2}$$

$$\gamma_L = -\arcsin\left(\frac{A_L}{B_L}\right) - C_L$$

$$A_L = (x_{2L} - x_{4L})^2 + (y_{2L} - y_{4L})^2 + (z_{2L} - z_{4L})^2 + (R_3{}^2 - R_2{}^2)$$

$$B_L = 2R_3\sqrt{(x_{2L} - x_{4L})^2 + (z_{2L} - z_{4L})^2}$$

$$C_L = \arctan\left(\frac{x_{2L} - x_{4L}}{z_{2L} - z_{4L}}\right)$$

Remark : Since DS is symmetry, therefore these equations can be used for both left and right side.

The actuator length can be calculated from Eqs. (18) – (19).

$$(\text{Actuator Length})_L = \sqrt{(x_{5L} - x_{6L})^2 + (z_{5L} - z_{6L})^2} \qquad (18)$$

$$(\text{Actuator Length})_R = \sqrt{(x_{5R} - x_{6R})^2 + (z_{5R} - z_{6R})^2} \qquad (19)$$

2.3.4 Calculation of Force on Actuator

The calculation is carried out by using static method with safety factor that cover dynamic load. Free body diagram of DM and supporting linkages is shown in Fig. 9.

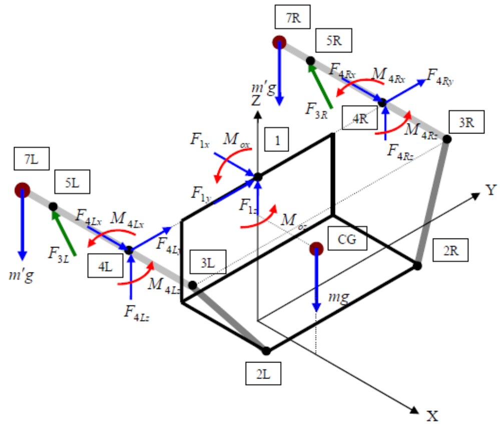

Fig. 9 Free body diagram of driving module (DM) and supporting linkages.

The force on R_2 linkage and moment on head joint can be determined by using Eqs. (20) – (22) when R_2 is the linkage between the joint 2L and 3L or 2R and 3R and head joint is the loint 1 in Fig. 9.

$$F_{2L} = \frac{E\left[N + M_o \sin\phi + \frac{JI}{E}\right]}{KE - GJ} \qquad (20)$$

$$F_{2R} = \frac{-(I + GF_{2L})}{E} \qquad (21)$$

$$M_o = \frac{S - RQ}{R\sin\phi + \cos\phi} \qquad (22)$$

When

$$E = -x_{2R}\left|\hat{z}_{23R}\right| + z_{2R}\left|\hat{x}_{23R}\right| - z_1\left|\hat{x}_{23R}\right|$$

$$G = -x_{2L}\left|\hat{z}_{23L}\right| + z_{2L}\left|\hat{x}_{23L}\right| - z_1\left|\hat{x}_{23L}\right|$$

$$I = mg(x'_{CG})$$

$$J = y_{2R}\left|\hat{z}_{23R}\right| - z_{2R}\left|\hat{y}_{23R}\right| + z_1\left|\hat{y}_{23R}\right|$$

$$K = y_{2L}\left|\hat{z}_{23L}\right| - z_{2L}\left|\hat{y}_{23L}\right| + z_1\left|\hat{y}_{23L}\right|$$

$$N = mg(y'_{CG})$$

$$O = x_{2R}\left|\hat{y}_{23R}\right| - y_{2R}\left|\hat{x}_{23R}\right|$$

$$P = x_{2L}\left|\hat{y}_{23L}\right| - y_{2L}\left|\hat{x}_{23L}\right|$$

$$Q = N + \frac{IJ}{E}$$

$$R = \frac{PE - OG}{KE - JG}$$

$$S = \frac{OI}{E}$$

The force on actuator can be calculated by using Eqs. (23) – (24).

$$F_{3L} = \frac{m'g(x_{7L}-x_{4L})+F_{2L}|\hat{z}_{23L}|(x_{3L}-x_{4L})-F_{2L}|\hat{x}_{23L}|(z_{3L}-z_{4L})}{|\hat{z}_{65L}|(x_{4L}-x_{5L})-|\hat{x}_{65L}|(z_{4L}-z_{5L})} \quad (23)$$

$$F_{3R} = \frac{m'g(x_{7R}-x_{4R})+F_{2R}|\hat{z}_{23R}|(x_{3R}-x_{4R})-F_{2R}|\hat{x}_{23R}|(z_{3R}-z_{4R})}{|\hat{z}_{65R}|(x_{4R}-x_{5R})-|\hat{x}_{65R}|(z_{4R}-z_{5R})} \quad (24)$$

2.4 Design Analysis

In design step, we have to choose the specification of the DS device such as actuator, therefore the objective of design analysis is to consider the suitable actuator stroke and motor size for using in DS.

From calculation of the actuator stroke, we found that the length of R_2 linkage has the most influence on the actuator stroke. From this reason, graph between the stroke of actuator and the pitch angle when vary the length of R_2 linkage is plotted as shown in Fig. 10 to consider the stroke of actuator.

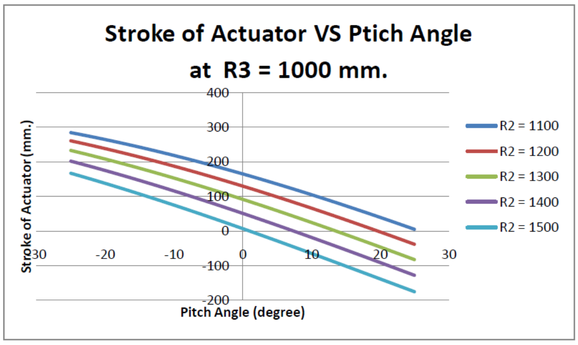

Fig. 10 The graph between stroke of actuator and pitch angle

R_2 is the linkage between the joint 2L and 3L or 2R and 3R, shown in Fig. 9. R_3 is the linkage between the joint 3L and 4L or 3R and 4R, shown in Fig. 9. From the graph in Fig. 10, the total actuator length stroke when using any R_2 length is within 500 mm.

From calculation of force on the actuator, we can plot the relation between force and roll angle in the roll motion of DS shown in Fig. 11. The force is varied by the roll angle of DM between -40 and 40 degree. From graph, the maximum force is about 2500 N in static approach.

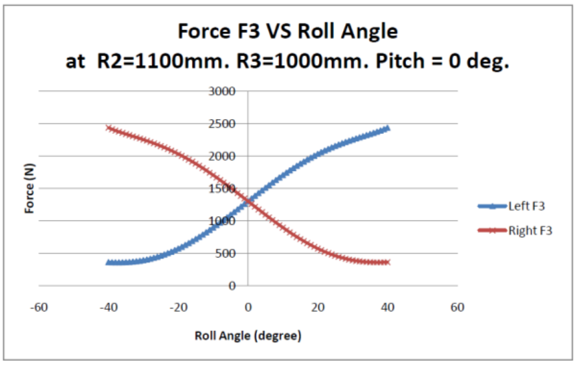

Fig. 11 The graph show the force on actuator

From the actuator stroke and force analysis, the actuator which is suitable for this DS is Servomech actuator that has 600 mm stroke length. It can use with the maximum static load 6000 N (push), 4000 N (pull) and the maximum dynamics load 4000 N.

3. Simulation Model

The DS movement can be investigated by using simulation on MATLAB SimMechanics shown in Fig. 12. In addition, the force of actuator as well as the pitch and roll angle of DM can be determined in a different motion. The simulation model was produced based on the position of joint, the length of linkage, and the stroke of actuator which are determine from mathematical model. Types of joint used in the model are shown in Fig.13.

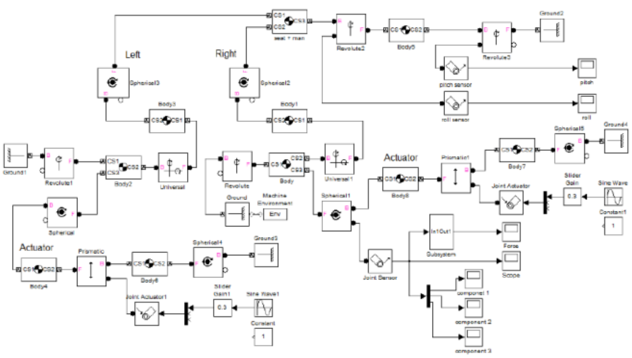

Fig. 12 Program MATLAB SimMechanics

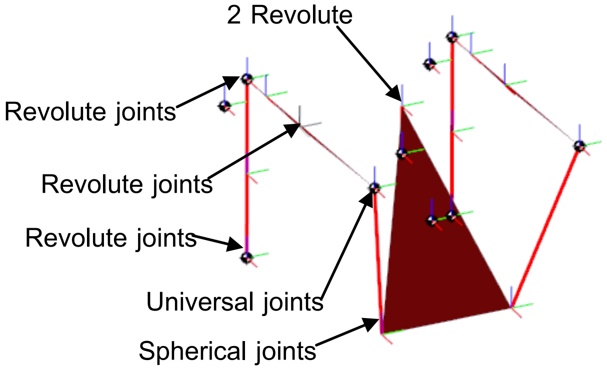

Fig. 12 The simulation model of DS

In simulation for testing general roll motion of the vehicle, one actuator was fixed and another one was varied by the 1 Hz sine wave input which has a stroke limited to 5 cm. From this simulation, it can show that the mechanism movement has the same motion as our expectation.

From the simulation result, the maximum force is about 600 N and the maximum velocity is 0.1π m/s. Thus, the power is 188.50 W. From this data, we choose the DC servomotor size 200 W for drive linear actuators.

4. Experiment and Result

The DS was fabricated after we designed and verified it by using simulation technique. In the experiment, we use the real DS structure, shown in Fig. 14, to test for the work space then compare with simulation result. During the test, DC servomotor which connects to the linear actuator is controlled to vary the stroke of each actuator.

Fig. 14 The DS structure

In experiment and simulation, one side of actuator is set to constant stroke and another actuator is varied stroke at every 10 cm to measure the pitch and roll angle, then we can plot the work space graph, shown in Fig. 14 which show the work space of DS comparing between the simulation and the experiment result.

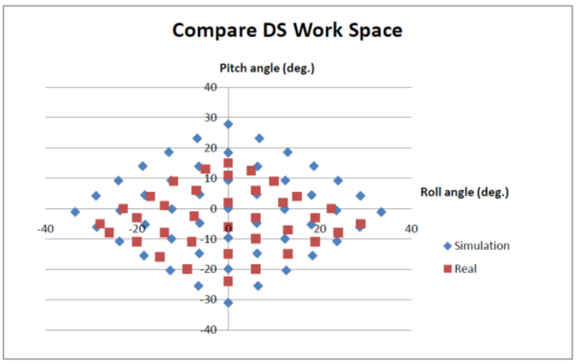

Fig. 14 The DS work space graph

We found that the experiment result isn't the same as the simulation result because the movement of DM crashes with the main structure which isn't considered in the simulation. Another reason is the linkage length has some errors due to non uniform accuracy in fabrication. The working space from experiment is smaller than working space from simulation. The difference of maximum possible value for pitch and roll angle is about 20% and 25% less than simulation results respectively. For the preliminary study, this error is acceptable because this work space can use to study the general vehicle roll motion. The next step of work, this error will be reduced by modifying some part of DS structure.

5. Conclusion

This paper presents the design and construction of a driving simulation (DS) designed to study effects of roll and pitch motion on the driver performance, especially, in rollover condition. The analysis of motion and force in actuator was done by simulation to select appropriate actuator. Working space of DS was investigated both by simulation and real experiment. From comparison between these results, the difference of maximum possible value for pitch and roll angle is about 20% and 25% less than simulation results respectively but it is acceptable for using this DS in general roll motion testing. In the next step the force on actuator will be experimentally confirmed before install the real actuator into the system. Then we will use DS to study the general roll motion before develop DS to perform rollover study.

6. References

[1] Thomas D. Gillespie, *Fundamentals of Vehicle Dynamics*, ISBN: 1-56091-199-9, Society of Automotive Engineers, Inc.

[2] Salcudean, S.E.; Drexel, P.A.; Ben-Dov, D.; Taylor, A.J.; and Lawrence, P.D. A Six Degree-of-Freedom, Hydraulic, One Person Motion Simulator, paper presented in *IEEE International conference (3 May 1994): 2437-2443*.

[3] David, W. *Force Dynamics motion simulator[Online]*, URL:http://www.force-dynamics.com, access on 2010,July 25

[4] Simuline Inc. *Motion simulator platform [Online].* 2009, URL:http://www.simuline.com, access on 2010, July 25

[5] Nuksit Noomwongs, Rachatin Chanchareon, Supavut Chantranuwathana, and Witaya Wannasuphoprasit. Development of Novel Evaluation Systems for Vehicle Dynamics, Driving, and Components, *Research report 2006*