Dynamic performances analysis of a real vehicle driving

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Abstract. Vehicle dynamic is the effects of movement of a vehicle generated from the acceleration, braking, ride and handling activities. The dynamic behaviours are determined by the forces from tire, gravity and aerodynamic which acting on the vehicle. This paper emphasizes the analysis of vehicle dynamic performance of a real vehicle. Real driving experiment on the vehicle is conducted to determine the effect of vehicle based on roll, pitch, and yaw, longitudinal, lateral and vertical acceleration. The experiment is done using the accelerometer to record the reading of the vehicle dynamic performance when the vehicle is driven on the road. The experiment starts with weighing a car model to get the center of gravity (COG) to place the accelerometer sensor for data acquisition (DAQ). The COG of the vehicle is determined by using the weight of the vehicle. A rural route is set to launch the experiment and the road conditions are determined for the test. The dynamic performance of the vehicle are depends on the road conditions and driving maneuver. The stability of a vehicle can be controlled by the dynamic performance analysis.

1. Introduction
Vehicle riding comfort is important on automobile industries which have impact on the drivers of the vehicle, the safety on road and the efficient of the transportation. A running vehicle causes vibration and affecting the riding performance of a vehicle. The vibration from the vehicle causes the noise and reduces the riding comfort of the vehicle. Suspension system is needed to control the vibration influence by the road irregularity and the speeds of the vehicle [1, 2]. The vehicle vibration also generated by the running engine, the forces of actuators and the resonant frequency of the body [3]. Modeling of vehicle dynamics performance is important to absorb the unneeded vibration from the vehicle to increase the dynamic performance as well as the drivers comfort. The critical part of the dynamics is the suspension system including the tires of the vehicle because of the road irregularity so the vibration is absorbs by the system [4].

The suspension system is designed by considering the human effect because human weight can change the riding comfort of a vehicle. The acceleration on the vehicle dynamics performance is different when
the vehicle has passengers. This causes the suspension plays the important role to control the riding performance of the vehicle [5]. There are several researchers has done improvement to the vehicle dynamic performance of a vehicle such as K. Dongshin that introduces the electronic stability program (ESP) system for vehicle when in emergency situation and A. Sohel introduces the predictive control algorithm for yaw stability management of a vehicle [6].

The analysis of the vehicle dynamic performances is also important for the vibration study for the energy regenerative suspension system (EReSS). The EReSS is applicable on the suspension system that uses the vertical vibration of the vehicle [7]. Vehicle parameters are important for variety of purposes such as the center of gravity (COG) of the vehicle. The COG of a vehicle is rarely provided by the automobile manufacturers. The estimation process needs some knowledge of the COG to have a correct bias for gyroscope measurement [8]. The COG location is important considering the passenger and load distribution. The location is difficult to be estimated because the COG positions changes when the weight on the vehicle changes. Vehicles that have higher COG are more tends to rollover accidents [9]. The COG of vehicle is important to be calculated for producing vehicle in automobile industries for the safety of the user and the public traffic [10].

2. Methodology

2.1. Experimental set up

The experiment done is for determining the longitudinal, lateral, and vertical accelerations, roll, pitch and yaw effect on the vehicle while driving on irregular road surface. Firstly, the route for the experiment is determined to ease the experiment process. Figure 1 illustrates the route that is used for the experiment. It is a combination of urban and highway roads with several corners, roundabouts bumpers and turns. The length is 9.6 km.

Figure 1. The route use for the experiment.
Next, the car model for the experiment is selected. The specifications of the vehicle are shown in table 1.

| Criteria       | Specifications                      |
|----------------|-------------------------------------|
| Model Code     | 4G13                                |
| Transmission   | F5M21                               |
| Fuel system    | MPI                                 |
| Max.power      | $55\text{ kW}(74\text{ hp})@6000\text{ rpm}$ |
| Max.torque     | $108\text{ Nm}@3000\text{ rpm}$    |
| Bore & Stroke  | 71x82                               |
| Displacement   | 1299cc                              |
| Max.speed      | $164\text{ km/h}$                  |
| Overall length | 4360mm                              |
| Overall width  | 1680mm                              |
| Overall height | 1385mm                              |
| Wheelbase      | 2500mm                              |
| Kerb weight    | 980 kg                              |

After that, the vehicle will be weight to find the center of gravity (COG). The DAQ used for the experiment is Lego Mindstorms EV3 as shown in figure 2 (a). Figure 2 (b) shows the car is being weighted using load sensor. The weighting process starts with adding extra load on the load sensor so that the car is in inclined position which is 5 cm and the data is recorded. Then, the car is weighted on normal condition.

![Figure 2](image)

**Figure 2.** Experimental set up (a) Lego Mindstorms EV3; (b) car being weighted.

### 2.1. Experimental procedure

The experiment process is done according to the road set for the experiment. The data is recorded by the DAQ Lego Mindstorm EV3 data logger. Figure 3 shows the Lego Mindstorms EV3 is put on the COG of the car. The equipment is ensured to be fixed on the COG only to avoid any error on recording the data acquisition. While driving, the road condition and the velocity of the car every 30 s is recorded. The road
used is according to the route that has been set up. All the data required for the experiment is recorded by the Lego Mindstorms EV3 equipment as all sensors needed for the reading is attached on it. The road condition for the experiment is identified to know the effect of the reading of the dynamic performance of the car. The time of the experiment is recorded.

![Lego Mindstorms EV3](image)

Figure 3. Lego Mindstorms EV3 put on the center of gravity (COG). Top box shows the gyro meters and bottom box shows the accelerometer.

3. Result and discussions
The center of gravity (COG) is obtained from calculation and used as the place to put the Lego Mindstorms EV3. The calculation starts from the car in normal condition as shown in figure 4. The car is at horizontal condition with no slope with the force distribution acting on the vehicle. The force is solved using equation (1) which is moment law of equilibrium.

\[ \sum M = Fd \]  

where

- \( F \) is the force in N,
- \( d \) is the distance in m.

![Car Diagram](image)

Figure 4. Force acting on car in normal condition.

The calculation to find \( L_1 \):

- Wheelbase, \( L_1 + L_2 = 2.5m \)
- Mass of vehicle, \( m = 923.49kg \), \( W = mg = (923.49kg)(9.81m/s^2) = 9059.44N \)
- Rear wheel mass, \( N_r = 339.27kg = (339.27kg)(9.81m/s^2) = 3328.24N \)
The calculation to find \( L_2 \) :
\[
L_2 = 2.5m - 0.918m = 1.582m
\]
The calculation of the COG position continues by using the car weight on inclined position which have slope when weighing the car. Figure 5 shows the car on inclined position.

![Figure 5. Force acting on car in inclined position.](image)

The calculation to find \( h \) :
\[
N_f (L_1 + L_2) + W L_1 = 0
\]
\[
L_1 = 0.918m
\]
The calculation to find \( L_2 \) :
\[
L_2 = 2.5m - 0.918m = 1.582m
\]
The calculation of the COG position continues by using the car weight on inclined position which have slope when weighing the car. Figure 5 shows the car on inclined position.

The calculation to find \( h \) :
\[
N_f \cos \theta + N_f \cos \theta - W \cos \theta = 0
\]
\[
\sin \theta = H / Wb
\]
\[
\theta = \sin^{-1} \frac{0.05}{2.5} = 1.15^\circ
\]
\[
N_f \cos \theta (L_1 + L_2) + W \sin \theta (h_1) - W \cos \theta (L_2) = 0
\]
\[
h = 0.34m
\]

From the calculation, the COG is located at \( L_1 = 1.582 \text{ m} \) from the front wheel and \( h_1 = 0.34 \text{ m} \) from the horizontal. The Lego Mindstorm EV3 is then put on the COG for the test. Figure 6 shows the data for roll of the vehicle. The roll is the movement or rotational motion on the x-axis. At 39.34 s, the value of the roll moment is 3 \(^\circ\)/s where the vehicle is cornering at the roundabout. When the vehicle is stop in a traffic light at 134.4 s, the value of the moment is -2 \(^\circ\)/s. The roll moment is high when the vehicle is moving through a bumper with reading 6 \(^\circ\)/s. It is get that the roll moment will affect when the vehicle is at cornering phase.
Figure 6. Roll moment of the vehicle.

Figure 7 shows the pitch moment of the vehicle that acting at y-axis. The value of pitch is high when the vehicle is passing through the bumper at 48.14 s with 32 °/s. The pitch is 28 °/s at 124.3 s as the vehicle stop at the traffic light and passing through a bumper again with the value of 38 °/s. The pitch of the vehicle is affected when the car is passing through the bumper.

Figure 7. Pitch moment of the vehicle.

Figure 8 illustrates the data for yaw of the vehicle. The yaw moment is the moment acting on the z-axis. The yaw of the vehicle is 32 °/s at 40.34 s when the vehicle is turn in a roundabout and at 68.92 s the value of the yaw is 27 °/s where the vehicle was turn to a right junction. At 122.1 s the vehicle stopped at the traffic light and give out the yaw value of 8 °/s. The higher the yaw value, the vehicle will overseer.
Figure 9 shows the longitudinal acceleration of the vehicle which is acting on the x-axis ($A_x$). The longitudinal acceleration is affected by various conditions of the road surface and including the acceleration, braking and aerodynamics of the vehicle. The acceleration is $1.029 \text{ m/s}^2$ when the vehicle is taken a corner at 172 s and $1.372 \text{ m/s}^2$ when the vehicle is passing through a bumper at 283.7 s.

Figure 10 shows the lateral acceleration on the vehicle acting on the y-axis ($A_y$). At 57.16 s, the reading is $2.646 \text{ m/s}^2$ which the vehicle is taking a junction to the right. When the vehicle taking a junction to the left at 93.9 s, the acceleration is $2.156 \text{ m/s}^2$ and the acceleration is smaller when the vehicle stops at a traffic light at 125.4 s with reading of $0.098 \text{ m/s}^2$. The vehicle is passing through a bumper and the reading of the lateral motion is higher with $4.165 \text{ m/s}^2$ at 257.3 s.
Figure 10. Lateral acceleration of the vehicle ($A_y$).

Figure 11 shows the vertical acceleration of the vehicle that acts on the $z$-axis ($A_z$). The acceleration of the vehicle is 12.1 m/s$^2$ at 23.86 s when the vehicle is moving on a straight road with irregular road surfaces that causes bumping and the vertical vibration is higher. The vehicle is moving and stops at a traffic light at 114.3 s with the acceleration of 10.93 m/s$^2$. The value is also high because when braking, the vertical motion is affected. At 334.2 s, the vehicle is on a straight road which accelerates after taking a corner that made the vertical acceleration higher with 14.26 m/s$^2$.

Figure 11. Vertical acceleration of the vehicle ($A_z$).

Figure 12 shows the vehicle speed during the experiment. The speed of the vehicle is inconsistent with disturbance such as road bumps and corners. The vehicle is at highest speed when on a straight road.
In this research, the dynamic performance of the vehicle is analyzed with the effect of the various road conditions. The center of gravity (COG) of the car is important to determine the dynamic performance as all the forces and moments are acting at the COG. The stability of the vehicle depends on the road conditions and driving maneuvers. Other than that, this performance will help the manufacturer to investigate the safety and comfort of the vehicle itself. Besides, it helps in controlling the stability of the vehicle while driving on different road inputs. The results are also potential to be benefited for energy harvesting from vibration.

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