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Flat Ride Over the Gravel Road

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Abstract— **One of the main objectives for vehicle designers is to achieve flat, safe ride in any environmental conditions. When a vehicle is moving along the road it is exposed to vibrations in multiple axes and directions. Vehicle behavior is extensively investigated in reference to road imperfections that could be expressed as single step disruptions, like remote bumps on the road. A simulation model, previously designed, was already used to investigate vehicle behavior, when riding over the step inputs. This model is further upgraded and now can perform simulations of the scenarios when vehicle is subjected to continuous imperfections on the road, like long runs of the gravel road in the country areas. Vehicle behavior is analyzed for few, common, speed levels in such scenarios. We can achieve lover amplitudes of pitch vibrations driving with the certain speed, but far the best outcome is obtained when active suspension is applied.**

I. Introduction

Modeling of any engineering system could be conducted using physical networks approach, presented and comprehensively explained earlier [1, 2]. Physical networks approach, in vehicle modeling, is already used in the research of vehicle performances, i.e. vibrations, while driving over the single step imperfection on the road [3, 4]. Sustainable flat ride suspension design is also presented for those scenarios [5]. Vehicle designers mainly follow widely accepted approach which results in obtaining natural frequencies of the front suspensions being 80% of that of the rear suspensions. Empirically was established that this results in the better flat ride and comfort for the passengers. In this report, a model is presented that can be used to investigate vehicle behavior when riding over the series of step, sinusoidal or any other type of inputs. From the control point of view, when investigating system's behavior, we analyze system responses for the sinusoidal, step and delta inputs. We are trying to control vibrations around *pitch* axes, as shown in Fig.1. Vibrations along *roll*, or *yaw* axis could be investigated using similar modeling approach as one presented here. Since step inputs have already been extensively used in vehicles' performances investigations, [3, 5], we are now concentrated on cases when sinusoidal inputs are applied.

II. Modeling a Vehicle on the Road

One of the most popular approaches in vehicle modeling is the application of a simplified bicycle model, as shown in Fig. 2. Similar models are used in vibration studies, [3-5], as well as in path planning [6]. For vibration studies, vehicle is shown as a beam of mass m equally distributed along the vehicle's length, l, which is a sum of front and rear parts, $l=a_f+a_r$. Moment of inertia is labeled as I, while mass center, C, is the center of rotation with angular speed w and angle Θ.

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Figure 1. A moving vehicle is exposed to vibrations along all three axes

Wheels and suspensions are together represented as springs. We are investigating vibrations around pitch axis which are expressed through the changes in car chassis upward velocities, front v_f center v_c and rear v_r, as well as associated three displacements: z_f, z_c, z_r.

Forces acting on the vehicle come from the ground, through the two springs when riding over the bumps. Magnitudes of those forces are defined by the Hooke's law $F=kA$, where k represents the spring constant, while A is the height, or amplitude of the road imperfection. Forces are labeled as F_f and F_r referring to front and the rear of the vehicle. Forces acting on the opposite sides of the body cause rotation around the center C, shown by angle Θ and the angular speed w. Moment of inertia and the total mass define radius of gyration. Equation (1) express effects of vertical and rotational actions of the two ground based forces, F_f and F_r,

$$\begin{bmatrix} 1 & 1 \\ -a_f & a_r \end{bmatrix} \begin{bmatrix} F_f \\ F_r \end{bmatrix} = \begin{bmatrix} m\frac{dv_c}{dt} \\ I\frac{dw}{dt} \end{bmatrix} = \begin{bmatrix} m\frac{dv_c}{dt} \\ mR^2\frac{dw}{dt} \end{bmatrix} \tag{1}$$

where R is the radius of rotation.

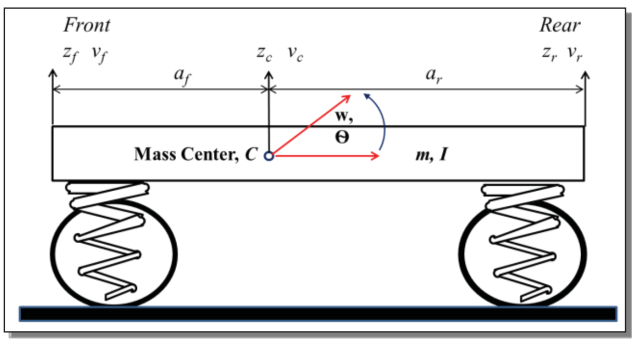

Figure 2. Bicycle model of the vehicle

Mass of the vehicle can be split into masses that correspond to the front, m_f, the rear part of the body, m_r, and a mutual mass, m_m, between them. Mutual mass is introduced to express influences of the forces acting on one part of the vehicle to the other. As shown previously [3], they can be calculated using expressions given in (2).

$$\begin{bmatrix} m_f \\ m_r \\ m_m \end{bmatrix} = \frac{m}{l^2} \begin{bmatrix} a_r^2 + R^2 \\ a_f^2 + R^2 \\ a_f a_r - R^2 \end{bmatrix} \tag{2}$$

Now, looking at (2), we can decuple the systems when mutual mass is equal to zero as show in (3)

$$m_m = 0 \quad => \quad R^2 = a_f a_r \tag{3}$$

When we apply this constraint, system is decoupled and following that, front and the back of the vehicle act independently. It is much easier to analyze the behavior of the system. With our modeling, we do not need to apply any restrictions, while at the same time we can analyze system behavior more comprehensively. Following the introduction of nonzero mutual mass, we can perform system modeling using vector equation as shown in (4).

$$\begin{bmatrix} m_f & m_m \\ m_m & m_r \end{bmatrix} = \begin{bmatrix} \frac{dv_f}{dt} \\ \frac{dv_r}{dt} \end{bmatrix} = \begin{bmatrix} F_f \\ F_r \end{bmatrix} \tag{4}$$

Derived system equations are enough to perform modeling using some of the modeling and simulation environments, like MATLAB/Simulink, or LabVIEW.

III. Model Conversion To Electrical System

Few more steps are conducted in order to simplify final solution. Physical systems approach is applied and whole mechanical system model is converted to an electrical. Electromechanical analogies, thoroughly defined in [1, 2], were used for the final modeling. In the new system mechanical force corresponds to electrical current, while velocity relates to voltage. Both force and the current are *through* type of the physical variables, which mean that they go through the network elements and can be measured and monitored that way. Voltage and the velocity are *across* type of the physical variables, and accordingly they are measured across the network elements.

Network elements in an electrical system have properties like resistivity, or conductivity as opposite, inductivity and capacity. Elements from mechanical system that correspond those are:

- mass to capacity, $m \sim C$
- spring stiffness to inductivity, $k \sim 1/L$
- damping constant to conductivity, $B \sim G = 1/R$.

When MKS system is used then numerical values for the network elements and variables are the same across the various physical networks which simplify all conversions. Forces acting on the wheels are represented as electrical current sources, while three mass components are given as capacitors.

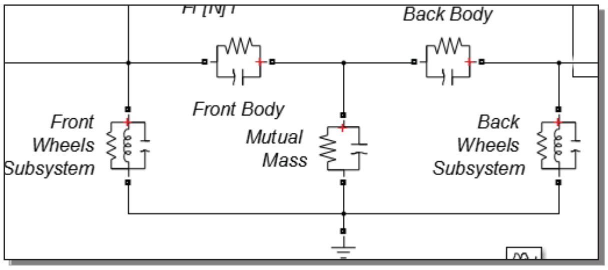

Figure 3. Bicycle model converted into Simulink electrical model

The core of the vehicle model is shown in Fig. 3. We can see front, rear and mutual masses, represented as capacitors. We can also see modeling of front and the rear wheels where friction and the masses are added for the more accurate model representation.

IV. Forces Modeling

Our vehicle is riding over the gravel road as shown in the Fig. 4. It has a repeating harmonic pattern with the amplitude of $A=0.05m$. Forces, acting on the front and the rear of the vehicle body, could be simulated by sinusoidal wave functions, as shown in (5), with the frequency f defined by the speed of the vehicle v and the wavelength λ of the pattern. In the environment that we have observed measured wavelength was $\lambda = 0.25m$.

$$F_f = k_f * A * sin(2\pi ft+\varphi_1) \qquad F_r = k_r * A * sin(2\pi ft+\varphi_2) \tag{5}$$

where φ is the phase shift. More important than the phase is the phase difference (6):

$$\Delta\varphi = \varphi_2 - \varphi_1 \tag{6}$$

The length of our vehicle is $4m$, while the distance between front and rear wheels is $D = 3.625 = 3.5 + 0.125$. Half of the wavelength leads to phase shift of $\Delta\varphi = \pi$.

From the expression (7) we could calculate frequency:

$$v = f * \lambda \tag{7}$$

In our simulation we will analyze vehicle behavior when driving over the gravel road with the most commonly applied and prescribed, i.e. regulated speeds of around

$$v = (5, 10, 20\ (m/sec))$$

They correspond to

$$v = (18, 36, 72\ (km/h))$$

and the frequencies of

$$f = (20, 40, 80\ (Hz))$$

Figure 4. Gravel road that could be seen as repeated sinusoidal input

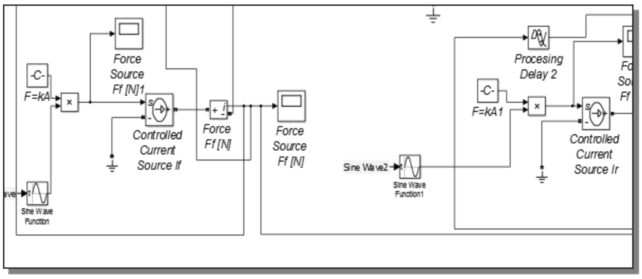

Figure 5. Submodel of the sinusoidal inputs

Other parameters needed to perform simulations are as following:

- Vehicle mass is $m = 1500\ (kg)$
- Front spring stiffness is $k_f = 10000\ (N/m)$
- Rear spring stiffness is $k_r = 15000\ (N/m)$
- It is assumed that $a_f = a_r = 2\ (m)$
- Finally, other necessary parameters are calculated using equations (1) - (4).

V. Simulation Results

Simulations were conducted for the large number of vehicle's speeds. Results for just three scenarios are presented here, as already proposed. Simulation model created in MATLAB R2015B Simulink incorporates vehicle model design, as well as input design, as already presented. It also incorporates a large number of monitoring points through the scopes, so that any of the system's variable could easily be traced. That includes vertical acceleration, speed and displacement, as well as forces, in various parts of the vehicle, like front, center, or rear, as shown in Fig. 2. Since the instant power is the product of force and velocity, given

$$p(t) = v(t) * F(t)$$

we could easily calculate power and energy introduced into the system. That is vibration energy coming from the road imperfections. From the car occupants' point of view, the most important is to have minimum vibrations' magnitudes in the passengers' seats. Fowling that, we have presented vibrations in the vertical directions, at the center of mass location, i.e. z_c as shown in Fig.1. Fig. 6 shows the case when the vehicle speed is *5 m/s*, Fig. 7 presents vibrations when the speed is *10 m/s* and Fig. 8 displays scenario for *20 m/s*.

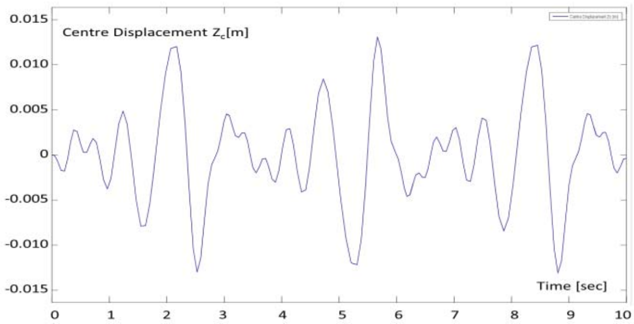

Figure 6. Vibrations Z_c for the speed of *5 m/s*

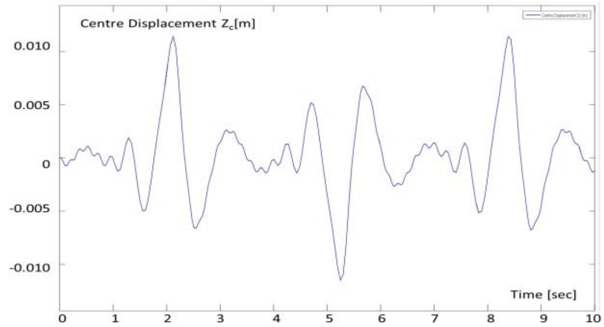

Figure 7. Vibrations Z_c for the speed of *10 m/s*

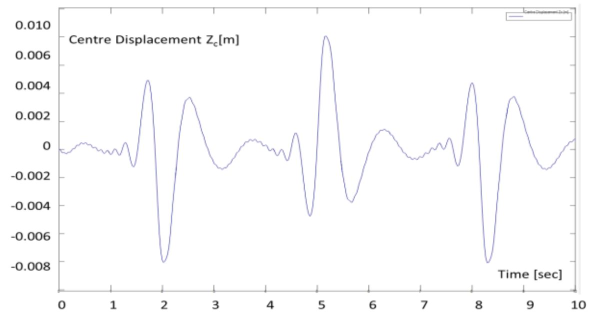

Figure 8. Vibrations Z_c for the speed of *20 m/s*

Analyzing those three scenarios we could see that the amplitude of vibrations is changing, from *0.013 m* when the vehicle speed is *5 m/s* down to *0.008 m* when the speed is higher, i.e. for *20 m/s.* Depending on the road imperfections and on the kinodynamic characteristics of the vehicle, including the passengers and the load, there is a set of optimal ground speeds. Driving with the optimal speed will ensure the maximum passenger comfort for the given scenario on the road.

VI. Active Suspension

In order to achieve better ride comfort an active suspension system is applied. It is using force sensors to detect road imperfections and initiate actuators to produce opposite forces acting on each wheel suspension subsystem. Elements of the system can be seen from the Fig. 9. Actuators are simulated by controlled current sources. As already mentioned, current corresponds to the force in physical systems approach. Delay line is used to simulate processing delay introduced by the hardware and the electro-mechanical components, i.e. motors /actuators.

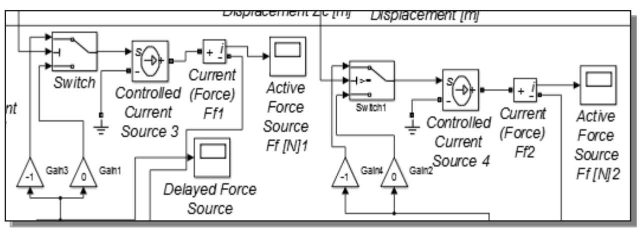

Figure 9. Active suspension subsystem

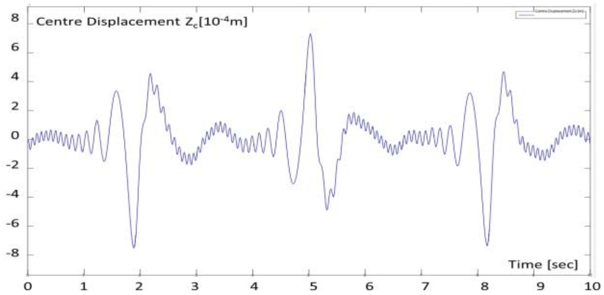

Figure 10. Vibration Z_c when active suspension is appied

Fig. 10 shows magnitude of vibrations in the center of mass when active suspension is applied and the vehicle speed is *20 m/s*. Compering with the same vehicle speed scenario, when the active suspension was not engaged, we can see that the major amplitude of the vibration is 10 times smaller, being *0.0008 m*. Active suspension is controlled through a single variable, taking values *0* or *1*, and two switch blocks.

Comprehensive research, theoretical and practical is conducted in the RMIT University School of Engineering. Vibration lab set up for vehicle behavior testing was already shown previously in [3]. Simulations models are going to be used as controllers for hardware in the loop testing.

The whole *vehicle on the road* Simpower-Systems Model is shown in Fig. 11. It includes bicycle model of the vehicle, as well as, gravel road input model. There is also large number of display scopes presented, used to monitor network variables in different parts of the system. Two main system variables are velocity and the force. Velocity, as an *across* variable is measured in reference to the systems ground, i.e. *0 m/s*, while the force is measured by placing measurement device in the network, i.e. in the Simpower circuit. Displacements are derived as integral of vertical velocities in the monitoring points placed in front and at the rear of the vehicle.

VII. Conclusion

Ride comfort is comprehensively investigated from many different points of view. Vibrations are one of the major factors influencing personal experience when driving. They can appear in different directions. In this research report we have concentrated on pitch and bounce type of disruptions, taking place around pitch axis. Using physical networks approach, a Simulink model, designed and upgraded, is used to investigate performances of a vehicle when driving over the gravel road. Compering to single step obstacles this scenario is more complex and demanding for the vehicle designers. Although that an optimal speed could be found, in each case, the best results are achieved applying active suspension.

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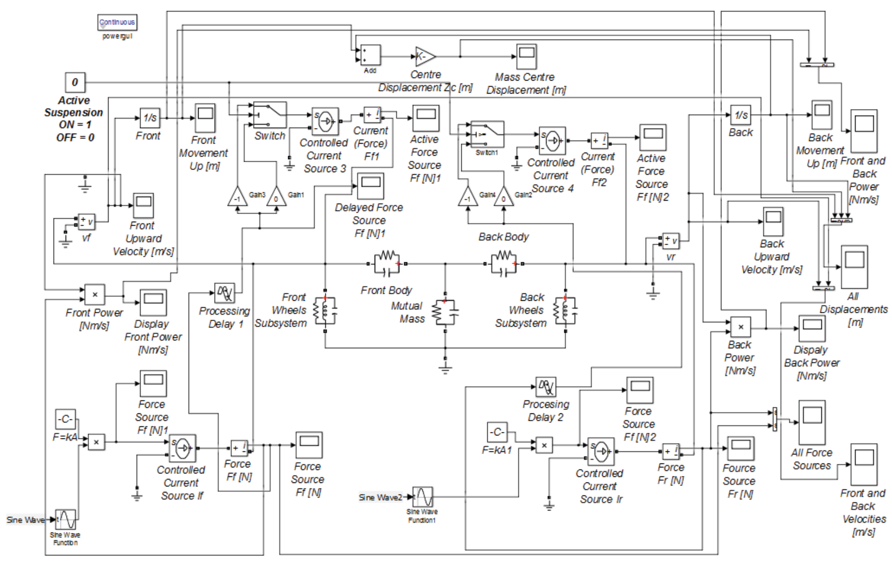

Figure 11. SimpowerSystems Model: Vehicle with active suspension driving over the gravel road