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Analyzing The Relationship Between The Road Surface Roughness And Vertical Loading On Automotive Wheels

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ABSTRACT: The significance of the contact force between the vehicle's tires and the road surface is two-folded. Firstly, the contact force is an important input parameter required to calculate the vertical loading onto the vehicle's parts. Secondly, the contact force also determines the damaging impact of vehicle's weight onto the road surface. Therefore, the understanding of the contact force between the vehicle's tires and the road surface is essential the design of both the vehicle and the road. This paper presents an analytical approach to calculate this contact force. The study includes a 7 degrees-of-freedom vehicle dynamics model. MATLAB Simulink is used to solve for the contact forces at four wheels of the vehicle. The analytical approach is then experimentally verified by using strain gauge at the vehicle's wheels during its operation. This analytical approach can be useful in reducing the time and effort comparing to the experimental approach.

KEYWORDS: Road Surface; Loading Vertically; Static Analysis; Dynamic Analysis.

INTRODUCTION

Road surface roughness is a parameter to quantify the quality of the road surface and it is always changing in the estimated road life. Roughness and road surface life, safe movement speed of vehicles are closely related, it is widely used in road surface management. The growth rate of roughness depends on the climate conditions, the initial structure of the road, the load of the vehicle involved in the traffic and the surface maintenance variable [1-2]. Method to evaluate loading wheels of vehicle to road surface dynamic interaction is based on the modal vehicle frequency response function and the statistical description of the geometry of the roughness. A half vehicle dynamic model base excitation and on the road surface roughness differences to the passenger comfort and can be used for design purposes [3]. Wheeled Mobile Driving Simulators (WMDS) for simulation to analysis conducted is restricted to a frequency of up to 100 Hz. the hypothesis is used: An surface without unevenness for the application of WMDS method. So, research with solid tires and a rigid connection between wheel and frame is assessed via computer simulation. Solid tires are many advantages compact dimensions and a high vertical stiffness, high slip values and slip angles are necessary to reach the maximum friction coefficient of about 0.8. So can using alternative to conventional pneumatic tires [4-5]. Analyses of the impact of the road micro-profile on the duration and the type of the vehicle wheel contact with the road surface driving at different speed are performed. The experiments measuring the vehicle suspension displacement and the body acceleration and frequency characteristics of suspension motion and regularities of vertical movement of the wheel were identified with road section according to driving modes. The analysis into the wheel contact with the road surface and identified correlations enable to determine the vehicle stability on selected quality roads [6-7]. Analyses of the effect of road roughness to determine the regularity with which the wheel of a vehicle moving at varying speed on the roughness of road pavement texture are performed. The vertical acceleration of the wheel and the body of a vehicle has been analyzed. At speeds over 60 km/h, the range of the wheel's displacements increases. At speed reaches 80 km/h, the wheel tends to contact with positive road surface, it partially loses contact with the road surface for approximately 6.9% of the vehicle's driving time [8].

VEHICLE MODELLING

A full vehicle representation for description of the dynamic vehicle. Seven degrees of freedom lumped parameter model describing relevant movements of the vehicle, as shown in Figure 1 [9-10].

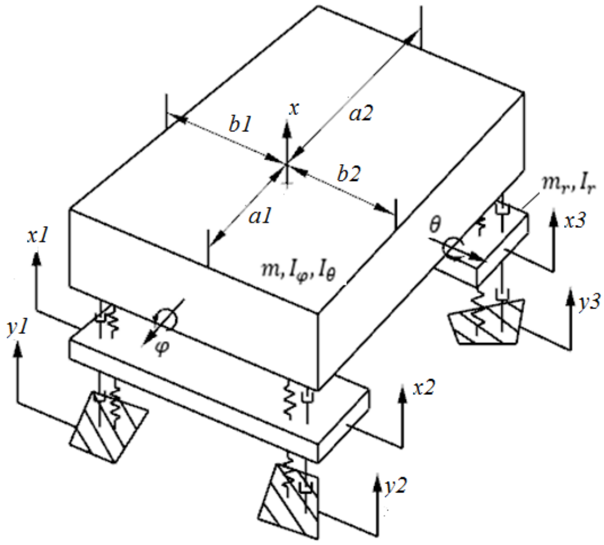

Figure 1. A full vehicle model seven degree of freedom

Where: x,φ,θ are the vertical displacement, roll and pitch angles of the hung masses; $x1,x2,x3,x4$ are the vertical displacements of the front and rear axles. G is the center of mass of the hung masses. kf,cf,ktf,ctf are the stiffness and damping coefficients of the front suspensions and front tires. kr,cr,ktr,ctr are the stiffness and damping coefficients of the rear suspensions and rear tires.

The equations of motion of this particular masses - springs - dampers system, a system of ordinary differential equations (ODE's) written in matrix form, can be deduced by applying the Lagrangian equations of the second kind. Based on the equations for road profiles, the road excitations are derived and the matrix-form equation of motion of this 7-DOF system shown in equation (1).

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F\} \tag{1}$$

$\{F\}$ is loading matrix shown in equation (2).

$$\begin{Bmatrix} 0 \\ 0 \\ 0 \\ k_{tf}y_1+c_{tf}\dot{y}_1 \\ k_{tf}y_2+c_{tf}\dot{y}_2 \\ k_{tr}y_3+c_{tr}\dot{y}_3 \\ k_{tr}y_4+c_{tr}\dot{y}_4 \end{Bmatrix} \tag{2}$$

The profiles of the road cause excitation on the tires of the vehicle, which will in turn be transferred as dynamic loads onto the suspension and chassis of the vehicle, creating stress on the chassis. The vehicle traveling on a straight path, the road surface roughness profile at each tire can be expressed in terms of the one dimensional wave equation (3).

$$\left.\begin{aligned} y_1 &= Y_1\sin\left(-\frac{2\pi v}{\lambda_0}t\right) \\ y_2 &= Y_2\sin\left(-\frac{2\pi v}{\lambda_0}t\right) \\ y_3 &= Y_3\sin\left(-\frac{2\pi v}{\lambda_0}t+\frac{2\pi}{\lambda_0}(a_1+a_2)\right) \\ y_4 &= Y_4\sin\left(-\frac{2\pi v}{\lambda_0}t+\frac{2\pi}{\lambda_0}(a_1+a_2)\right) \end{aligned}\right\} \tag{3}$$

Where: Y_1, Y_2, Y_3, Y_4 are the vertical road surface roughness of the front and rear wheels.

RESULTS OF SIMULATION

Using Matlab Simulink to virtually simulate the dynamical behaviors of the entire vehicle, including road profile, tires, suspensions and chassis. As we can notice, since the profiles at the two rear wheel is exactly the same, yet are shifted from those of the front wheels, a delay factor that is dependent on the vehicle's length is introduced. The road profile represents a road profile with varying elevation and friction properties. As a vehicle travels, the axle parameters and the position of the center of gravity (G) determine the position of the front and rear axles. Using the axle positions to compute vehicle angle and, optionally, tire friction coefficients.

The parameters of vehicles as: Total mass is 700 kg, Inertia moment 360 kgm2, stiffness coefficient K is 26.65 kN/m and damping coefficient C is 1230 Ns/m.

Modal Analysis

The modal system properties characterize mode shape of vibration due to the non-diagonal constitution of the system matrix. The vehicle modal response has 7 natural frequencies of vehicle body shown in table 1.

Table 1. Natural frequencies of vehicle

Mode Number	Nature frequency (Hz)
1	5.304
2	8.442
3	8.772
4	54.89
5	56.54
6	79.91
7	98.5

Road Surface Roughness

The profiles of the road cause excitations (in the form of forced displacements) on the tires of the vehicle, which will in turn be transferred as dynamic loads onto the suspension of the vehicle, creating stress on the vehicle body. Thus, the first step in analyzing the chassis harmonics is to formulate a mathematical model for the general sinusoidal road profile. A considered vehicle traveling on a straight path, the road profile at each tire can be expressed in terms of the one dimensional wave. The result simulation of road surface roughness shown in Figure 2.

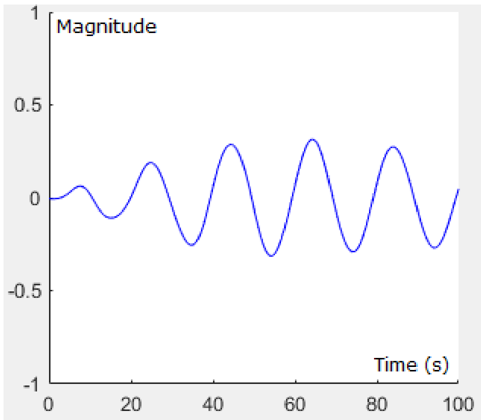

Figure 2. Road surface roughness

Vertical Reaction Forces

A Simulink algorithm is also developed to solve of the problem are the forces or displacements acted on the wheels (with determined amplitude and frequencies). Given the harmonic criteria and the design/control parameters, again after solving the system of ODE's, such vertical reaction forces can be found. The vertical reaction forces on the tires of the vehicle running on the road paved track at 54 km/h (15 m/s) in time domain is shown in Figure 3.

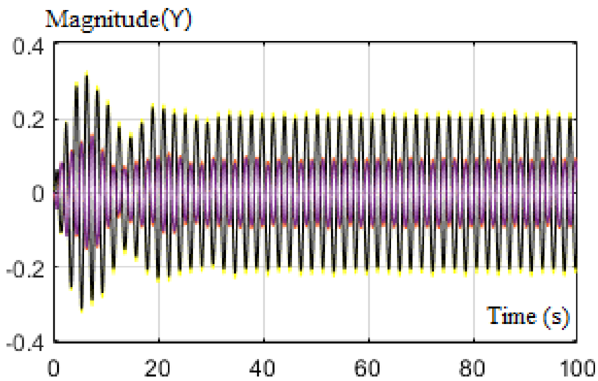

Figure 3. Reaction forces on the tires

The loads (either forces or displacements) from the road onto wheels should be designed far away from the structure's natural frequencies to avoid resonance. The vertical forces of vehicle modal transfer function depends on T that is a speed function T=L/Vx). Therefore, the FRF shape will be speed-dependent of vehicle. Using FFT analysis in Matlab Simulink to determine the frequencies of excitation force for 54 km/h (15 m/s) we obtain the results in frequency domain shown in Figure 4.

The magnitude of vertical force reaction depends on the axle front and rear distance L (1.8 meters) and vehicle's speed. For the vertical mode, they occur at every integer, resulting in peaks around 1, 2, 3, 4, 5, 6 mode shape.

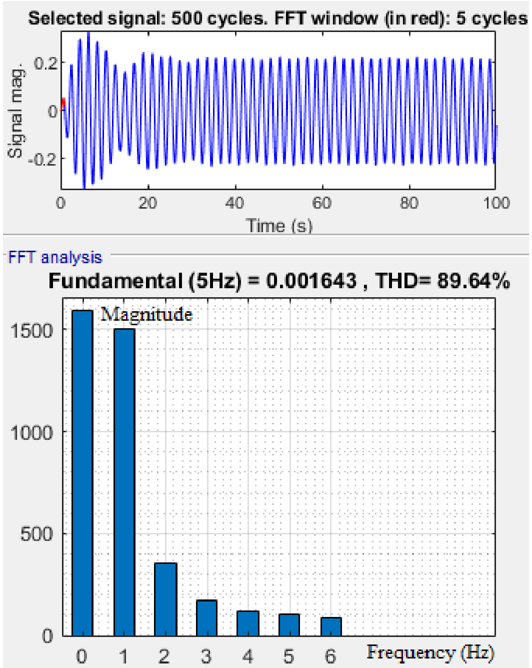

Figure 4. Vertical force Reaction on the automotive Front right wheel

In the same way will simulate the vertical force reaction in the remaining wheels as front left, rear right , rear left wheels.

EXPERIMENT

The physical interface to the acceleration generating road excitation to tires, therefore, the tire modelling is of high relevance for the vertical behavior. Vertical reactions at contact points between tire and road surface show load distribution on vehicle. When the vehicle is moving due to the acceleration of gravity, it will affect the accuracy of the measurement. Kalman Filter is used as the estimator for both on simulation and on the experimental vehicle to reduce these errors.

There are two methods of measuring vertical loading on tires. One method is an indirect measurement method, using accelerometer sensors. In this case, the measured parameter will be the acceleration of the suspension-hung masses under the impact of the force between the wheel and the road surface. As a result, the acceleration is multiplied by the mass of the hung masses on the quarter-oscillating model. Other method of measuring vertical loading on tires (used in this research) is an direct using tenzo deformation. Each vertical load on the tire will have a deformation of tenzo corresponding. Tenzo is fastened to a axle cover position close to the wheel to be measured. Performance a calibration to get the load value (kg) on tenzo corresponding. Graph of calibration between the standard load (represented on the horizontal axis) and the voltage on the device (represented on the vertical axis) is a non-linear relationship. Use regression coefficients to determined the linear relationship with R = 0.83 is the calibration line of the experiment. We get measurement calibration factor is k = 0.83, Figure 5.

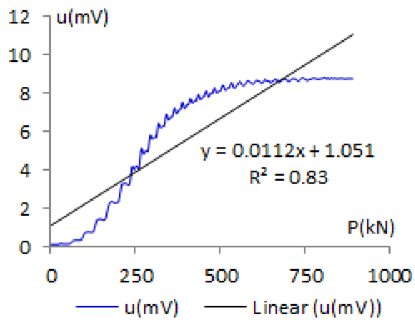

Figure 5. Calibration for vertical force on the rear right wheel

The study uses the experiment vehicle to evaluate its performance in real condition. During the test, the experiment vehicle was conduit on the expressway Lang-Hoalac. The test takes the total distance is about 10 km and speed during this period of 120 seconds corresponding. To present experimental results more clearly, we divided the experimental distance into many sections, each length of 2000 m long of the experimental data to analyze. Each length of the experiment will allow the vehicle to run at different speeds according to the increasing speed, the first section is 40 km/h, the second section is 60 km/h, the third is 800 km/h, the fourth paragraph is 100 km, the last section is to reduce the vehicle speed and stop, because the speed limit specified for this expressway is 100 km/h maximum speed.

From the Figure 6, we can see these results confirming that of vertical forces on road experimental in case of speed vehicle driving 40km/h. In this case, two points per meter were sampled. Wavelengths up to 2000 m of each section were considered in the anti-aliasing processes.

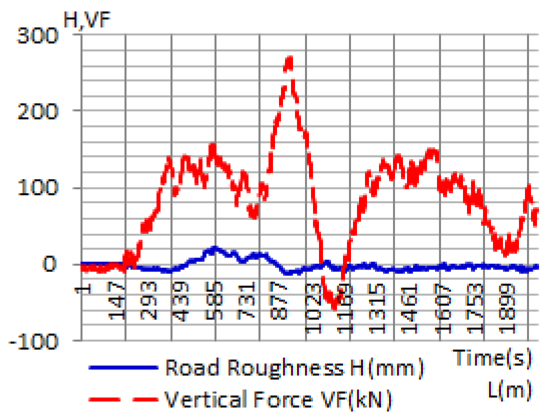

Figure 6. The paragraph of road roughness and vertical force on the rear right wheel at 40 km/h

Because the test is based on the direct measurement method, using tenzo deformation, two parameters can be measured at the same time when the vehicle is running. This is very important for analyzing results in real time.

The blue line represent the measured value of roughness road surface symbolized as H (mm) over time (s). The red line represent the measured value of roughness road surface symbolized as H (mm) over time (s). The vertical forces has underwent big variation during the experiment. That is caused by the speeds of the vehicle and road surface. The dash space blue lines represent the measured value of vertical forces on the tire symbolized as VF (kN) over length of section road measured vehicle running L(m).

The continuous sections road of the vehicle accelerate and run stability in that length. The measurement results are shown in Figures 7 corresponding to the speed of 60 km/h, in Figure 8 corresponding to the results of 80 km/h and the last section is the measurement result when the vehicle running at a speed of 100 km/h shown in Figure 9.

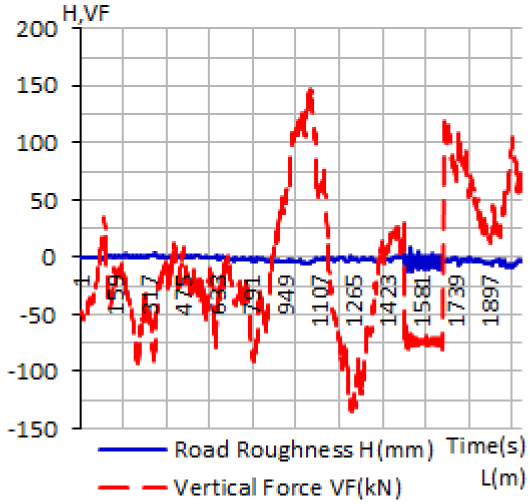

Figure 7. The paragraph of road roughness and vertical force on the rear right wheel at 60 km/h

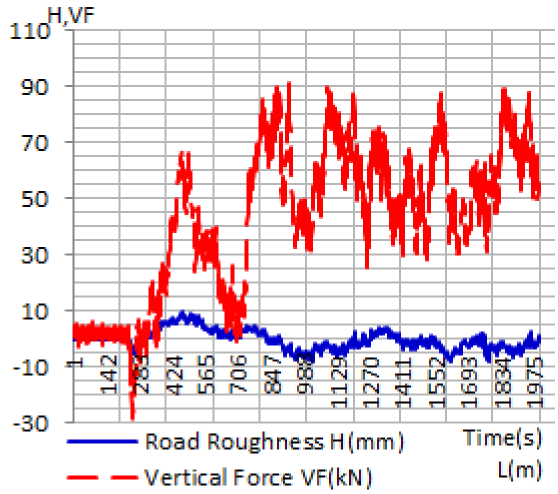

Figure 8. The paragraph of road roughness and vertical force on the rear right wheel at 80 km/h

We get two problems, the first is when the vehicle speed increases, the amplitude of force decreases. In case the car runs at a speed of 40 km/h, the maximum impact force is about 150 kN, at a speed of 60 km/h, the maximum impact force is about 130 kN, while at the speed of 100 km/h the largest force about 90 kN. The second problem is road roughness directly affect the force acting vertically on the wheel. This problem is very difficult to calculate but can be obtained by experiments real time of vehicle testing.

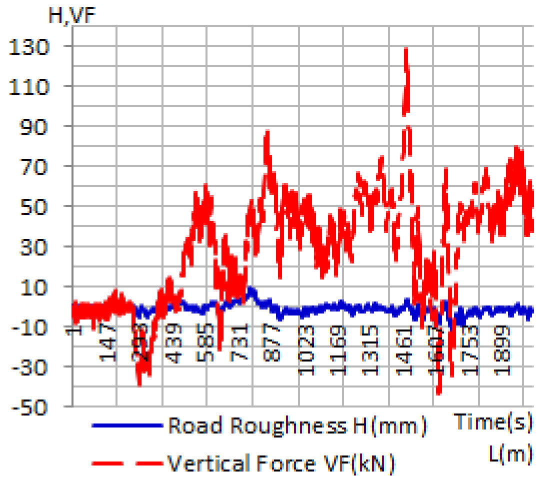

Figure 9. The paragraph of road roughness and vertical force on the rear right wheel at 100 km/h

CONCLUSION

The article presents the analysis of the relationship of road surface roughness to vertical force on wheels when vehicle running in real time. By simulation method in Matlab Simulink software, the natural oscillation frequency of the vehicle is found in the range of 5.3 Hz to 98.5 Hz, this range of frequencies affects the smoothness moving of the vehicle. Analyzing the roughness of the pavement, the vertical force on the wheel, these two parameters are related to each other through simulation results.

By conducting experiment when the car runs on the road, the real-time analytical results are reliably achieved because the method of the experiment is directly measured by using deformed tenzo. The results show that the surface roughness and vertical forces is closely related. When the road surface is more rugged, it is that vertical force increases also.

However, in practice, some parameters are considered to have changed during driving. To improve the accuracy of the test, we need to accurately determine the physical parameters of the vehicle, such as the position of the center of gravity, the stiffness of the body, the stiffness of the suspension and so on to choose the set location of measuring equipment as well as the most suitable driving method.

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