A model-based approach to monitor complex road-vehicle interactions through first principles

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Abstract. The increasing availability of portable computing devices and their interaction with physical systems ask for designing compact models and simulations to understand and characterize such interactions. For instance, monitoring a road’s grade using accelerometer stationed inside a moving ground vehicle is an emerging trend in city administration. Typically the focus has largely been to develop algorithms to articulate meaning from that. But, the experimentation cannot provide with an exhaustive analysis of all scenarios and the characteristics of them. We propose an approach of modeling these interactions of physical systems with gadgets through first principles, in a compact manner to focus on limited number of interactions. We derive an approach to model the vehicle interaction with a pothole on a road, a specific case, but allowing for selectable car parameters like natural damped frequency, tire size etc, thus generalizing it. Different road profiles are also created to represent rough road with sharp irregularities. These act as excitation to the moving vehicle and the interaction is computed to determine the vertical/ lateral vibration of the system i.e vehicle with sensors using joint time-frequency signal analysis methods. The simulation is compared with experimental data for validation. We show some directions as to how simulation of such models can reveal different characteristics of the interaction through analysis of their frequency spectrum. It is envisioned that the proposed models will get enriched further as and when large data set of real life data is captured and appropriate sensitivity analysis is done.

1. Introduction
Portable computing devices are becoming ubiquitous and their interactions with the physical systems are increasing. These interactions can help analyze the characteristics of the interactions and their effects on the interacting systems. This would need modeling of specific interactions, but at the same time generalizing to allow for different types of interacting systems. To illustrate this modeling approach, we model the interaction between a road vehicle and a pothole on the road. Models are obtained from first principles due to the need for capturing of physical characteristics. We allow for variations in the parameters of a car like tire size, natural frequency, etc. We use this data to analyse the interaction’s frequency components.

Interaction analysis between a road vehicle and infrastructures have been analysed before, but in a different context. For instance, in [1], [2] the authors present a method to assess dynamic forces that occur after a vehicle passes a road surface irregularity and obtain the contact forces and its effect on bridge vibration. The usage of smart phone accelerometer for
pothole identification and road grade analysis have been widely experimented. See for instance, [3], [4]. These works were motivation to look at this specific interaction.

2. Modeling and Simulation of Vehicle road Interaction
In this section, we briefly describe the modeling approach for the pothole vehicle interaction. We consider that the pothole affects only one wheel and hence there is a vehicle tilt. The potholes modeled as a step deformation and the personal computing device accelerometer location is considered to be aligned to the roll center of the front axle. The computation of the acceleration has three phases, (i) the descent into the pothole (ii) the bounce inside the pothole (iii) the ascent from the pothole to the road.

The tire motion is modeled as a projectile. The initial descent is modeled as a horizontally launched projectile followed by a bounce inside the pothole and then by a projectile motion with an ascend and descend. This projectile based modeling is extensible to cover different step pothole scenarios with different length and internal gradient. In this paper we derive the idea of using a single bounce case.

2.1. Mathematical Model
For the equation of motion of horizontally launched projectile, we apply modification to account for the tilt between the two front wheels due to the descent. Apart from this, we also modify the ‘g’ value appropriately to take care of the characteristics of vehicle body and wheel. This results in vertical and lateral displacements (refer Figures 1 and 2).

\[ S_t = \frac{g_{db}}{2}(t - t_i)^2, \quad \phi = \tan^{-1}\left(\frac{S_t}{L}\right), \quad \Delta Z = \frac{L}{4}\sin(2\phi), \quad \Delta X = (H - \frac{L}{2\sin\phi})\sin\phi \quad (1) \]

where, we \( g_{db} \) is the \( g \) value corrected for the body natural frequency as, \( g_{db} = g - 2\pi f_n M_R \), where \( M_R \) is the Motion ratio factor of the vehicle body and \( f_n \) is its natural frequency. Here \( t_i \) is the initial time. Here \( L \) is the axle length and \( H \) is the position of the accelerometer above roll axis. The accelerations in the two directions are given by,

\[ A_z = \frac{2\Delta Z \cos\phi}{(t - t_i)^2}, \quad A_x = \frac{2\Delta X \sin\phi}{(t - t_i)^2} \quad (2) \]
Ascent  Similar to the descent case, we have the ascending of the tire expressed as,

\[ S_t = \text{Depth} - (V_{zf}(t - t_i)) - \frac{gdb}{2}(t - t_i)^2 \]  

(3)

with the rest of the equations as given by (1). Here \( V_{zf} = R_{vel}V_{zf} \), is corrected final velocity after the tire hits the pothole, where \( R_{vel} \) is the translation factor between velocity final velocity on the tire to that as experienced at the pothole (after accounting for tilt and other factors).

Bounce and Transmissibility  The transmissibility factor is computed with a sinusoidal road profile \( p = P\sin\left(\frac{2\pi z}{L}\right) \) to quarter car model as discussed in [5]. We use the transmissibility factor given by [5], and obtain the \( A_z \) measured at the phone as,

\[ TR = \frac{\sqrt{1 + (2\zeta\beta)^2}}{\sqrt{(1 - \beta^2)^2 + (2\zeta\beta)^2}} \quad A_{z-bounce} = \frac{2TRV_{zf}\cos\phi}{\delta t} \]  

(4)

where, \( \beta = \omega/\omega_n \), with \( \omega \) is the frequency of the road profile is considered and \( \omega_n \) is the natural frequency of the vehicle. \( \zeta \) is the body damping factor of the vehicle. We consider the radius of tire \( (R_{tire}) \) and the velocity of the vehicle \( (U_x) \) to compute the impact interval \( (\delta t = K\pi R_{tire}/U_x) \), where \( K \) is an empirical value changing from very small for smooth and hard surface to close to 1 muddy surface.

Roadgrade modeling and Simulation  To represent a road with irregularities, the modeled pothole should be augmented with the profile of a road. The ISO 8608:1995 classifies road profiles based on their degree of roughness given by the Power Spectral Density of the surface roughness. We use the sinusoidal approximation as described in [6], [7] and the generated road surface is input to a quarter car model to obtain the acceleration as discussed in [8].

2.2. Results  In this section, we briefly discuss the results obtained from simulations and their comparisons with experimental results (performed using a TATA Nano car). A comparison of the Z-direction acceleration of the measured and the generated pattern are shows in Figure 3. To illustrate the different modes of this approach, the Figure 4 we illustrate how different cars going on a 50m Type C road with a randomly placed pothole, will give out signatures in the Z-axis acceleration, with a sampling frequency of 20 Hz.

3. Analysis of Modeled Interaction  In this section we briefly discuss how the simulated data can be put to use. In Figure 5, we compare the PSD of experimental and simulated data of the jerk \( (m/s^3) \). The amplitude difference and absence of second peak is due to the modeling limitations, which can be overcome using more accurate modeling. In Figure 6, we look at the frequency response impact for an increasing pothole size for a medium saloon car (sampled at 50 Hz), which shows a unique response signature for different potholes in the form of number of peaks. Such analysis can give a deeper understanding of the interaction without performing elaborate experiments.

4. Concluding Remarks  In this paper, we discussed the preliminary results of a modeling approach to suit the increasing interaction of mobile computing device with various physical and engineering systems. We have illustrated this by modeling the interaction between a vehicle and a pothole on a road and analysing the characteristics of this interaction. Indirectly, the data generated through this
Figure 3. Z-direction acceleration at 30 kmph over a 10cm deep pothole (18 Hz)

Figure 4. Simulation of a vehicle on road with different type of cars

Figure 5. Comparison of PSDs of Simulated and Experimental Data for a 7cm pothole

Figure 6. PSD of Jerk (simulated at 50Hz) for different pothole depths

Simulation can also aid in evaluating algorithms used to identify potholes. This work can be enhanced by modeling the interaction with further details and analysing their implications. This approach can be used in different applications where a mobile computing device are put to use.

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