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# APPLICATION OF THE NEWMARK INTEGRATION METHOD TO DETERMINE THE DYNAMIC RESPONSE OF A COMPLETE VEHICLE MODEL SUBJECTED TO THE EXCITATION OF A RANDOM ROAD PROFILE ACCORDING TO ISO 8608

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**Abstract.** When analyzing a vehicle traveling on a lane, irregularities in this lane can expose the driver to vibrations that can result in health damage. This implies the need for a suitable suspension system. This study is justified by the fact that the determination of the dynamic response of vehicles traveling on irregular lanes allows us to understand the behavior of the vehicle in terms of displacement, velocity and acceleration as a function of time. The general objective of this study is to determine the dynamic response of a complete vehicle model subjected to the excitation of a random road profile, according to the ISO 8608. The specific objectives are: (I) To reproduce a vehicle model; (II) Determine a random road profile; (III) Apply the Newmark method. The methodology of this study consists of simulating the vehicle in Matlab software and validating this model. Apply the random road profile as road excitation. Determine the dynamic response using the Newmark Method. As a result, the dynamic response of the vehicle subjected to the excitation of a random road profile was obtained. It is concluded that it was possible to complete the specific objectives, reaching the general objective.

**Keywords:** Dynamic response, Complete vehicle model, ISO 8608, Newmark method.

## 1 Introduction

Discomfort and damage to the passenger's health can be the result of exposure, over a long period and in high magnitudes, to vibrations imposed by the ground when a vehicle is traveling in an irregular road. This implies the need for a suitable suspension system.

Thus, this study is justified by the fact that the determination of the dynamic response of vehicles traveling on irregular lanes allows us to understand the behavior of the vehicle in terms of displacement, velocity and acceleration as a function of time.

The general objective of this study is to determine the dynamic response of a complete vehicle model subjected to the excitation of a random road profile, according to ISO 8608 - “Mechanical Vibration – Road Surface Profiles - Reporting of Measured Data”. The specific objectives are: (I) To reproduce a vehicle model present in the literature; (II) Determine a random road profile according to ISO 8608; (III) Apply a Newmark integration method on the vehicle model subjected to random road profile excitation.

This article is organized as follows. Section 2 presents the materials and methods used. Section 3 presents the results obtained. And finally, Section 4 presents the main conclusions.

## 2 Materials and methods

This section presents the vehicle model used, the irregular road profile according to ISO 8608 and the input data used.

## 2.1 Complete vehicle model

Jazar [1] proposes a solid theoretical basis related to the dynamics, modeling and simulation of transport vehicles, presenting a complete vehicle model with seven degrees of freedom, namely: body bounce (x), body roll (φ), body pitch (θ), left front wheel vertical displacement ($x_1$), right front wheel vertical displacement ($x_2$), right rear wheel vertical displacement ($x_3$), left rear wheel vertical displacement ($x_4$). The model also takes into account independent road excitations ($y_1$, $y_2$, $y_3$, $y_4$), one on each wheel. It is also considered the mass of the vehicle body (m), the mass of the front wheels ($m_f$), the mass of the rear wheels ($m_r$), the longitudinal moment of inertia ($I_x$), the lateral moment of inertia ($I_y$), the front suspension stiffness ($k_f$), the rear suspension stiffness ($k_r$), the front tire stiffness ($k_{tf}$), the rear tire stiffness ($k_{tr}$), the antiroll bar stiffness ($k_R$), the front wheels damping ($c_f$) and the rear wheels damping ($c_r$). Finally, the model also considers the vehicle geometry, being specified by the distance from front to center of vehicle ($a_1$), distance from center to rear of vehicle ($a_2$), distance from center to left side of vehicle ($b_1$) and the distance from center to right side of the vehicle ($b_2$). Figure 1 presents this complete vehicle model.

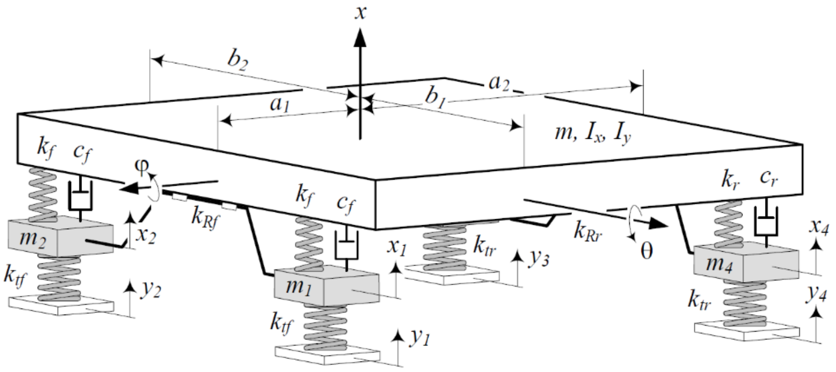


Figure 1. Complete vehicle model proposed by Jazar [1]

Jazar [1] also specifies in his model which mass, stiffness and damping matrices should be used. It also specifies displacement and force vectors that should be used to simulate the model.

Rao [2] states that based on the mass matrix and the stiffness matrix, it is possible to perform modal analysis, determining the natural frequencies and vibration modes. Natural frequencies are basically the frequencies at which the system oscillates in the absence of external excitation. Vibration modes are the ways in which the system vibrates at each natural frequency. During the vibration of the system at one of its natural frequencies, the shape of the deformed configuration does not change over time, only its amplitude is modified.

## 2.2 Irregular road profile according to ISO 8608

In 1995, ISO 8608: “Mechanical Vibration - Road Surface Profiles - Reporting of Measured Data” was created. The creation of this standard enabled uniformity in the methodology used to represent irregularities on the surface of roads and highways and, consequently, facilitated the comparison of studies by different authors.

According to ISO 8608 [3], the general equation representing the power spectral density (PSD) of vertical displacements, in terms of spatial frequency, is given by:

$$G_d(n) = G_d(n_0) \cdot \left(\frac{n}{n_0}\right)^{-w} \tag{1}$$

Where $G_d(n)$ is the PSD of vertical displacements, in $m^3$, $G_d(n_0)$ is the PSD of reference in terms of vertical displacements, in $m^3$, $n$ is the spatial frequency, in cycles/m, $w$ is the exponent of the PSD of vertical displacements and $n_0$ is the spatial frequency of reference, with a value equal to 0.1 cycles/m.

ISO 8608 [3] states that the relationship between the reference PSD and the spatial frequency can be approximated by a descending line on a logarithmic scale plot, for the range of spatial frequencies between 0.011

cycles/m and 2.83 cycles/m. To obtain a PSD of constant vertical velocities, the exponent of the PSD of vertical displacements equal to 2 is used. This means that the velocity of the vehicle traveling on the road is constant.

Reza-Kashyzadeh et al. [4] shows that the vertical displacement PSDs, in terms of spatial and temporal frequency, are related as follows:

$$G_d(f) = \frac{G_d(n)}{v} \tag{2}$$

Where $G_d(f)$ is the PSD of vertical displacements in terms of time frequency, in $m^2s$, and $v$ is the vehicle velocity, in m/s.

ISO 8608 [3] proposes a road classification system that divides the road classes in ascending alphabetical order, according to the increasing degree of irregularity. Table 1 presents the intervals and geometric averages of the reference PSD in terms of vertical displacements for different classes of roads, in spatial frequency units.

Table 1. Intervals and geometric averages of the reference PSD in terms of vertical displacements for different classes of roads, in spatial frequency units, proposed by ISO 8608

| Road Class | Degree of irregularity | | |
|---|---|---|---|
| | $G_d(n_0)^{(1)}(10^{-6}\ m^3)$ | | |
| | Lower limit | Geometric average | Upper limit |
| A | - | 16 | 32 |
| B | 32 | 64 | 128 |
| C | 128 | 256 | 512 |
| D | 512 | 1024 | 2048 |
| E | 2048 | 4096 | 8192 |
| F | 8192 | 16384 | 32768 |
| G | 32768 | 65536 | 131072 |
| H | 131072 | 262144 | - |

$^{(1)}$ $n_0 = 0{,}1\ \text{cycles/m}$

Shinozuka and Jan [5] proposed a method that uses random signals from road surface irregularities to describe the vertical displacements of the road as a function of time:

$$\vec{z}(t) = \sum_{k=1}^{N} \sqrt{2G_d^*(f_k)\Delta f_k}\cos(2\pi f_k t + \psi_k) \tag{3}$$

Where $\vec{z}(t)$ is the vector of vertical displacements of the road, in m, $N$ is the number of components of the frequency interval, $G_d^*(f_k)$ is the PSD of vertical displacements of the road, in $m^2s$, $\Delta f_k = f_{k+1} - f_k$ is the frequency resolution, in cycles/s, $t$ is the time, in seconds, and $\psi_k$ is an independent random variable with uniform distribution in the range between 0 and $2\pi$ rad.

Thus, the road vertical displacement vectors can be used as road excitations in the complete vehicle model.

### 2.3 Input data used

Jazar [1] presented a solved example that provides input data like mass of the vehicle body ($m = 840\ kg$), mass of the front wheels ($m_f = 53\ kg$), mass of the rear wheels ($m_r = 76\ kg$), longitudinal moment of inertia ($I_x = 820\ kg \cdot m^2$), lateral moment of inertia ($I_y = 1100\ kg \cdot m^2$), distance from front to center of vehicle ($a_1 = 1{,}4\ m$), distance from center to rear of vehicle ($a_2 = 1{,}47\ m$), distance from center to left side of vehicle ($b_1 = 0{,}7\ m$), distance from center to right side of the vehicle ($b_2 = 0{,}75\ m$), front suspension stiffness ($k_f = 10000\ N/m$), rear suspension stiffness ($k_r = 13000\ N/m$), front tire stiffness ($k_{tf} = 200000\ N/m$), rear tire stiffness ($k_{tr} = 200000\ N/m$) and antiroll bar stiffness ($k_R = 2500\ N \cdot m/rad$). To apply the Newmark integration method, the following input data were adopted: zero time displacement ($\vec{x}(t = 0) = 0\ m$), zero time velocity ($\dot{\vec{x}}(t = 0) = 0\ m/s$), time variation ($\Delta t = 0{,}005\ s$), front wheels damping ($c_f = 1260\ N \cdot s/m$) and rear wheels damping ($c_r = 1638\ N \cdot s/m$).

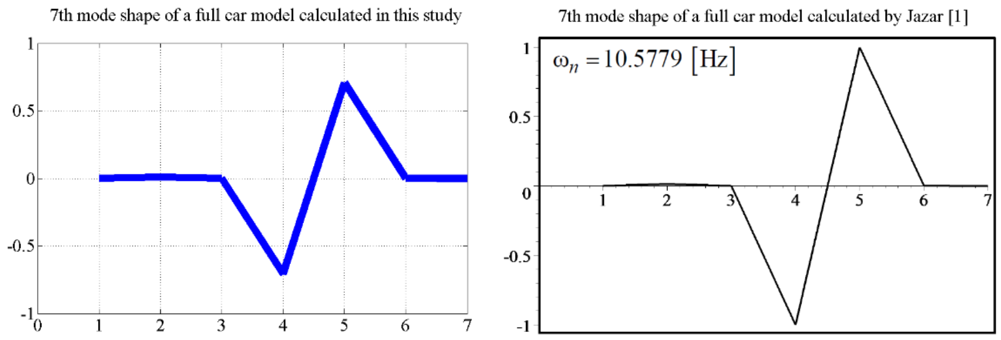
# 3 Results

This section presents the results obtained in the validation of the complete vehicle model, in the implementation of the irregular road profile and in the determination of the dynamic response through the Newmark integration method.

## 3.1 Complete vehicle model validation

A routine was produced in Matlab software capable of reproducing the complete vehicle model proposed by Jazar [1]. When applying the input values of the solved example by the same author, the following natural frequencies were found: $\omega_1 = 1{,}1128$ Hz; $\omega_2 = 1{,}1541$ Hz; $\omega_3 = 1{,}4640$ Hz; $\omega_4 = 8{,}4272$ Hz; $\omega_5 = 8{,}4334$ Hz; $\omega_6 = 10{,}0219$ Hz; $\omega_7 = 10{,}5779$ Hz. These values of natural frequencies in Hz obtained coincide with the values obtained by Jazar [1] in the solved example.

In addition, a graphical analysis of the obtained vibration modes was performed, comparing the graphs by the author with the graphs generated by the Matlab routine created in this study. Just like natural frequencies, all vibration modes also coincide. Therefore, it can be affirmed that the validation of the complete vehicle model elaborated in this study was successfully completed. Figure 2 presents the graphical comparison between the seventh mode shape calculated in this study and obtained in the example solved by Jazar [1].


7th mode shape of a full car model calculated in this study

7th mode shape of a full car model calculated by Jazar [1]

Figure 2. Comparison between the 7th mode shape calculated in this study and calculated by Jazar [1]

## 3.2 Implementation of irregular road profile according to ISO 8608

Adopting a constant vehicle velocity of 20 m/s and applying the methodology proposed by the ISO 8608 [3] together with the method proposed by Shinozuka and Jan [5], it was possible to describe the vertical displacements of each road class as a function of the time, as shown in Fig. 3.

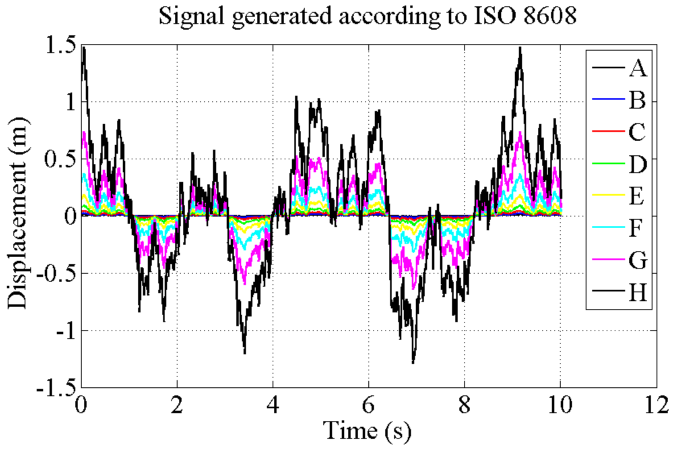


Figure 3. Vertical displacements of each road class as a function of time calculated in this study

### 3.3 Dynamic response through the Newmark integration method

Ngwangwa et al. [6] states that the class C profile corresponds to a well-maintained unpaved road or a road with some deep depressions and with frequent shallow depressions. Therefore, a class C profile was chosen for the dynamic analysis, as shown in Fig. 4.

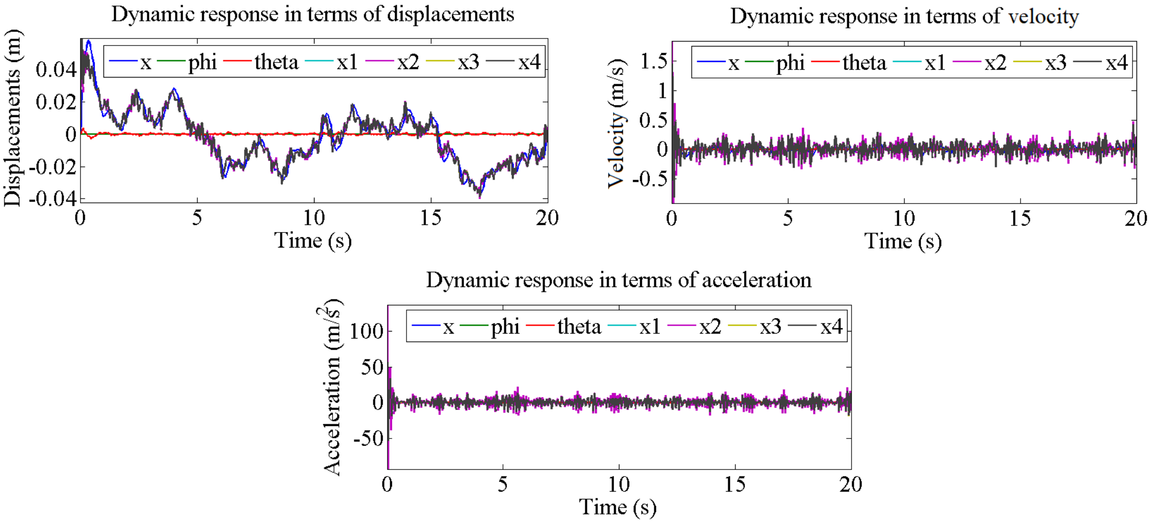


Figure 3. Dynamic analysis in terms of displacements, velocities and accelerations

As we can see, the displacements are maintained, approximately, within a range of amplitudes of -0.04 and 0.06 m. The velocities remain approximately within a range of -0.5 and 0.5 m/s. And the accelerations remain, approximately, within a range of amplitudes of -50 and 50 $m/s^2$.

# 4 Conclusions

Based on the results obtained, it can be concluded that it was possible to reproduce a complete vehicle model present in the literature and validate it, determine a random road profile according to the ISO 8608 and apply the Newmark integration method in the vehicle model subjected to random road profile excitation.

In general, it is concluded that it was possible to determine the dynamic response of the complete vehicle model subjected to the excitation of the random road profile in terms of displacement, velocity and acceleration as a function of time.

As a suggestion for future works, the addition of a lateral and longitudinal dynamic analysis is indicated, allowing a complete evaluation of the behavior of a vehicle in use.

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