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## COB-2019-0128 ANALYSIS OF WHOLE-BODY VIBRATION EXPOSURE IN DRIVERS AND USERS OF BUS

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**Abstract.** *The main objective of this paper is to carry out an analysis of whole-body vibration exposure in drivers and users of bus, taking into account comfort and health for the bus driver and comfort for the passengers, when the bus is subjected to vibrations caused by traveling in irregular road profiles. For this, computational routines are developed in the Matlab software. The Newmark method, which is defined in the time domain, and the spectral analysis method, which is defined in the frequency domain, are adopted. The irregular roads profiles are generated through the procedure proposed by ISO 8608 (1995), and the comfort and health analyses are carried out according to ISO 2631-1 (1997). The results show that the bus driver is exposed to potential damage to his health when he drives in C class roads or above and the passengers of the bus will feel some discomfort even for A class roads, but the situation is worse for a seated person in the rear of the bus.*

**Keywords:** *Whole-Body Vibration (WBV), Bus, Comfort, Health, Irregular Road Profile, ISO 2631.*

### 1. INTRODUCTION

The possibility of predicting the dynamic behavior of vehicles subjected to irregular roads profiles using numerical methods is a subject of great interest to the automobile industry, as more and more the industry faces the challenge of allying economy and vehicles performance with the comfort and safety of their occupants. The use of numerical methods can increase the reliability and quality of vehicles and, in addition, decrease the cost of production processes and the time spent in the design stages. The irregularity of the roads profiles is not the only parameter that influences the dynamic response of a vehicle, parameters such as bodywork mass and the suspension system used are determining factors for the behavior of the vehicle.

The main objective of this paper is to carry out an analysis of whole-body vibration exposure in drivers and users of bus, taking into account comfort and health of the bus driver and comfort of the passengers, when the bus is subjected to vibrations caused by traveling in irregular road profiles, through numerical simulation. The first numerical method used is the Newmark (1959) method, which is defined in the time domain, while the second method adopted is defined in the frequency domain, in which the system response is determined directly from the power spectral density (PSD) of the excitation. The PSD of the irregular road profile is defined by ISO 8608 (1995), and its transformation for analysis in the time domain is performed by the procedure proposed by Shinokuza and Jan (1972). Finally, the analyses of comfort and health are carried out according to the criteria of ISO 2631-1 (1997).

### 2. THEORETICAL BASIS

#### 2.1 Vehicle Model

The vehicle model adopted in this paper is the bus model proposed by Sekulic *et al.* (2013), which has ten degrees of freedom: one representing the vertical displacement of the bus driver, two representing the vertical displacement of a seated person in the middle and in the bottom of the bus, one representing the vertical displacement of the bus, two representing the vertical displacement of the center of gravity of the axles, two representing the rotation of the axles, and two others representing the pitch and roll angles of the bus. The model is based on the Intercity bus IK-301 and is shown in Figure 1. The equation of motion can be written as:

$$M\ddot{z}(t) + C\dot{z}(t) + Kz(t) = f(t) \quad (1)$$

in which  $M$  is the mass matrix,  $C$  is the damping matrix,  $K$  is the stiffness matrix,  $f$  is the force vector and  $z$ ,  $\dot{z}$  and  $\ddot{z}$  are the displacement, velocity and acceleration vectors, respectively. For this paper, the velocity of the bus is constant and equal to 100km/h.

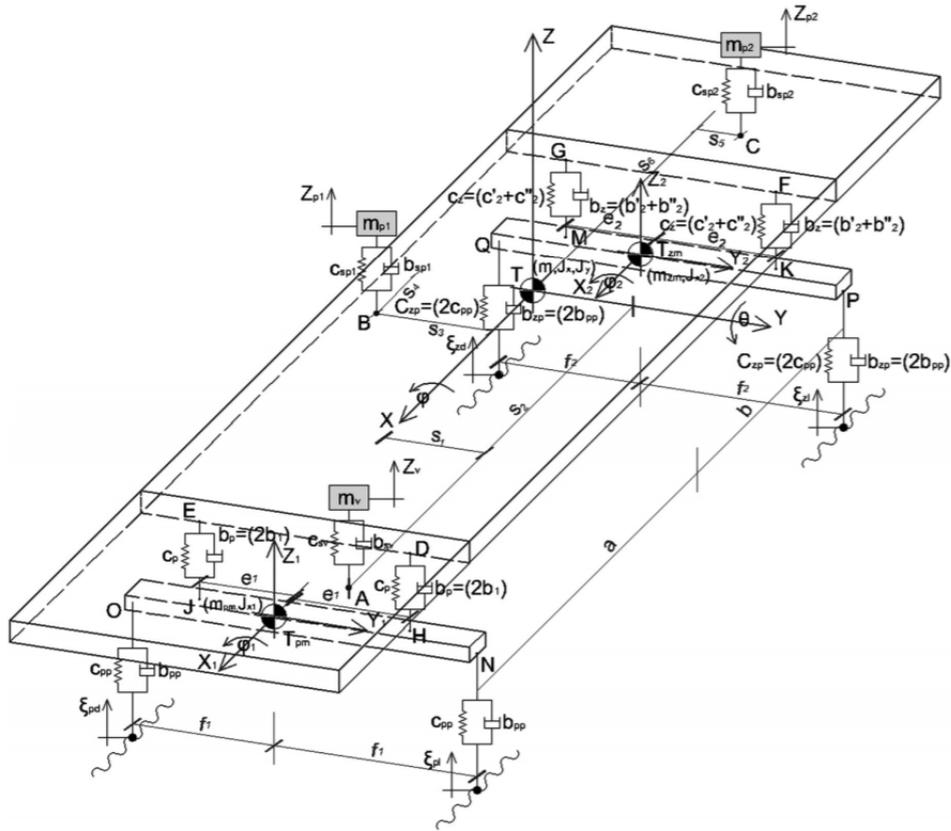


Figure 1. Oscillatory bus model proposed by Sekulic *et al.* (2013).

## 2.2 Irregular Road Profile

The generation of the irregular road profile is performed according to ISO 8608 (1995), through the standard is possible to make a representation of different road profiles using power spectral densities (PSDs). The standard divides the roads classes in ascending alphabetical order according to the roughness increase, thus the relation of the PSD of displacement and the spatial frequency is defined by:

$$G_d(n) = G_d(n_0) * \left(\frac{n}{n_0}\right)^{-w} \quad (2)$$

in which  $n_0$  is the reference spatial frequency in cycles/m,  $n$  is the spatial frequency in cycles/m,  $w$  is the coefficient that determines the slope of the adjusted PSD,  $G_d(n_0)$  is the reference PSD in  $m^3$  and  $G_d(n)$  is the displacement PSD as a function of the spatial frequency in  $m^3$ . The standard defines  $n_0$  as 0.1 cycles/m. In addition to this, when  $w = 2$  a PSD of constant speed is obtained, that is, it simulates that the vehicle is traveling at constant speed. ISO 8608 (1995) also determines that the range of spatial frequencies ( $n$ ) that represents the dynamic behavior of vehicles varies from 0.011 to 2.83 cycles/m. In order to obtain the displacement signals in the time domain, the method proposed by Shinozuka and Jan (1972) is used and it can be defined by Eq. (3):

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

in which  $z_e(t)$  is the displacement imposed by the road in m,  $N$  is the number of intervals of frequency range,  $\psi_k$  is the random phase angle in rad,  $\Delta f_k$  is the frequency range in Hz. The phase angle consists of a random variable with uniform distribution in the range of 0 to  $2\pi$ . This first signal is the displacement imposed on the left wheels of the vehicle. Sekulic *et al.* (2013) defined an equation that represents the profile where the wheels on the right side of the vehicle travels:

$$z_d(t) = \sum_{k=1}^N \sqrt{2 * G_{d_{ad_e}}(f_k) \Delta f_k} * \cos(2\pi f_k t + \psi_k) + \sqrt{2 \left( G_d(f_k) - G_{d_{ad_e}}(f_k) \right) \Delta f_k} \cos(2\pi f_k t + \beta_k) \quad (4)$$

in which  $G_{d_{ad_e}}$  is the cross power spectral density and  $\beta_k$  is a random variable with uniform distribution in the range of 0 to  $2\pi$ .

### 2.3 ISO 2631-1 (1997)

ISO 2631-1 (1997) sets general requirements for evaluation of exposure to whole-body vibrations, and according to it, the evaluation of the effects of exposure to whole-body vibrations should be done using the weighted r.m.s. acceleration in the three axes for vibrations with crest factor below or equal to nine. The crest factor is defined as the modulus of the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration to its r.m.s. value. The vibration total value of weighted r.m.s. acceleration can be calculated as follows:

$$a_v = k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2 \quad (5)$$

in which  $a_v$  is the total value of weighted r.m.s. acceleration,  $a_{wx}^2$ ,  $a_{wy}^2$  and  $a_{wz}^2$  are the weighted r.m.s. acceleration with respect to x, y and z axes respectively, and  $k_x$ ,  $k_y$  and  $k_z$  are multiplying factors. In this paper, the vibrations in the longitudinal (x) and lateral (y) axis are disregarded. Then the comfort can be evaluated according to Tab. 1:

Table 1. Comfort according to weighted r.m.s. acceleration.

Acceleration	Comfort
Less than 0.315m/s <sup>2</sup>	Not uncomfortable
0.315m/s <sup>2</sup> to 0.63m/s <sup>2</sup>	A little uncomfortable
0.5m/s <sup>2</sup> to 1m/s <sup>2</sup>	Fairly uncomfortable
0.8m/s <sup>2</sup> to 1.6m/s <sup>2</sup>	Uncomfortable
1.25m/s <sup>2</sup> to 2,5m/s <sup>2</sup>	Very uncomfortable
Greater to 2m/s <sup>2</sup>	Extremely uncomfortable

For health evaluation, the standard defines a health guidance caution zone, for exposures within the zone caution with potential health risks are likely and above the zone health, risks are likely, (Figure 2).

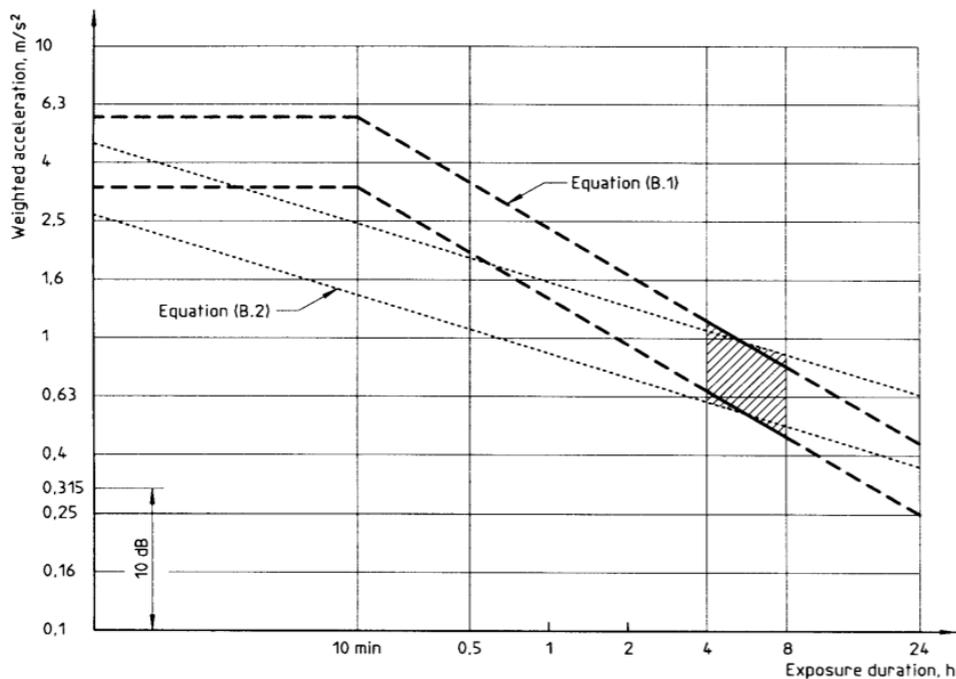


Figure 2. Health Guidance Caution Zones (from ISO 2631-1/1997).

### 3. VALIDATION OF THE ROAD PROFILE GENERATION

In order to validate the generation of irregular road profiles through the implemented routine, the behavior of the power spectral density generated in the presented paper is compared with those provided by the ISO 8608(1995) itself. In Fig 3.a is possible to see the graph of  $G_d(n) \times n$  in a logarithmic scale obtained in the present paper for a C road class, and the data presented in the standard can be seen in Fig 3.b.

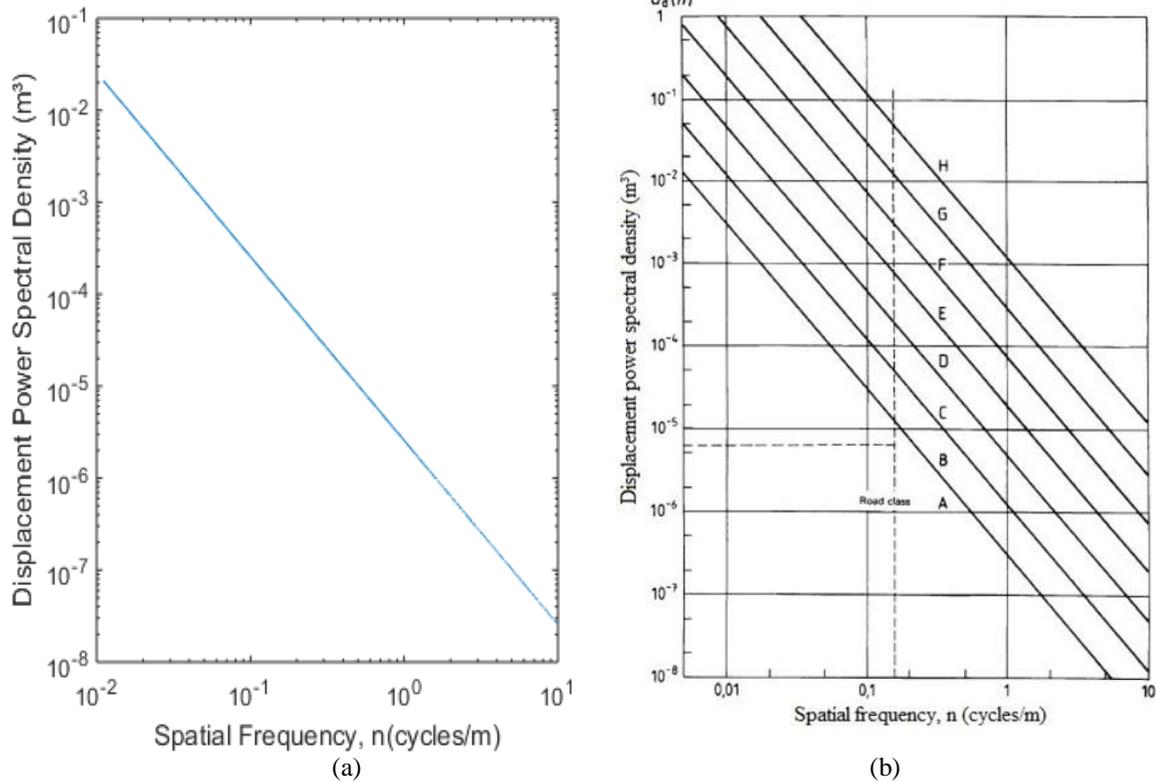


Figure 3. (a) C road class Displacement Power Spectral Density obtained in the present paper in a log-log scale.  
 (b) Displacement Power Spectral Density (from ISO 8608/1995).

Analyzing Fig. 3, it is possible to see the similarities of the obtained curve and the presented by ISO 8608 (1995), both have a maximum value of  $G_d(n)$  between  $10^{-2}$  and  $10^{-1}$  and a minimum value between  $10^{-8}$  and  $10^{-7}$ , then the irregular road profile generation is validated.

### 4. EVALUATION AND COMPARISON OF RESULTS

In Tab. 2, it is possible to see the imposed accelerations to the Bus Driver. According to Fig. 2 for an exposure of 4 hours in the roads A and B, the accelerations are below the caution zones, for a C road profile the acceleration is within the zone and so the bus driver is exposed to potential health risks. If the bus is traveling in D and E roads profile, the bus driver is exposed to accelerations above the caution zones, and so, he is exposed to greater health risks. If the exposure duration is 8 hours the situation is worse, for an A and B roads profile the accelerations are below the caution zone, but for a C, D and E roads, the accelerations are all above the caution zones. In matter of comfort, the A road is comfortable, B road is a little uncomfortable, C road is fairly uncomfortable, D is very uncomfortable and E extremely uncomfortable. The Crest Factor is below to nine and so the weighted r.m.s. acceleration are calculated according to Eq. (5). In Fig. 4 is possible to see the weighted acceleration imposed to the bus driver for an A class road profile.

Table 2. Accelerations imposed to the bus driver.

Road Profile	$a_v$ (m/s <sup>2</sup> ) (Newmark)	$a_v$ (m/s <sup>2</sup> ) (Average of 30 runs - Newmark)	$a_v$ (m/s <sup>2</sup> ) (Spectral Analysis)	Crest Factor
A	0.2367	0.2289	0.2293	2.5731
B	0.4623	0.4599	0.4586	2.6339
C	0.9242	0.9146	0.9172	3.2119
D	1.8237	1.8327	1.8345	2.8605
E	3.8927	3.6720	3.6689	3.1367

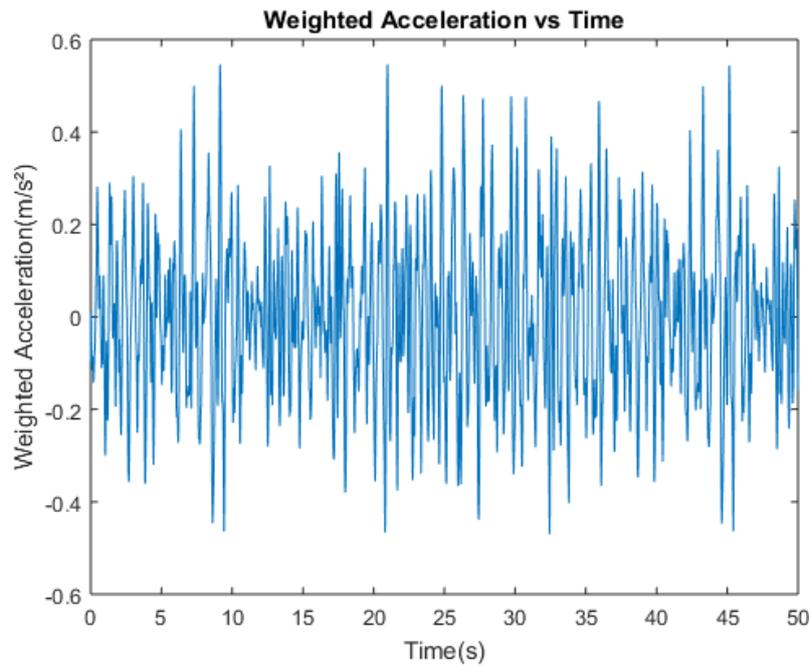


Figure 4. Weighted acceleration imposed to the bus driver for an A class road profile.

For a person seated in the middle of the bus, according to Tab. 3, the comfort for an A road profile is a little uncomfortable, for a B road profile the passenger feels fairly uncomfortable, for a C road profile the passenger feels very uncomfortable, and for a D and E roads profile the passenger feels very uncomfortable. The crest factor is below nine and so the analysis can be made according to Eq. (5). In Fig. 5 is possible to see the weighted acceleration imposed to a seated person in the middle of the bus for an A class road profile.

Table 3. Accelerations imposed to a seated person in the middle of the bus.

Road Profile	$a_v$ (m/s <sup>2</sup> ) (Newmark)	$a_v$ (m/s <sup>2</sup> ) (Average of 30 runs - Newmark)	$a_v$ (m/s <sup>2</sup> ) (Spectral Analysis)	Crest Factor
A	0.4676	0.4478	0.4452	3.3122
B	0.8711	0.8897	0.8905	3.3031
C	1.7806	1.7823	1.7810	3.5483
D	3.2924	3.5631	3.5619	3.0451
E	7.1100	7.1266	7.1238	3.2732

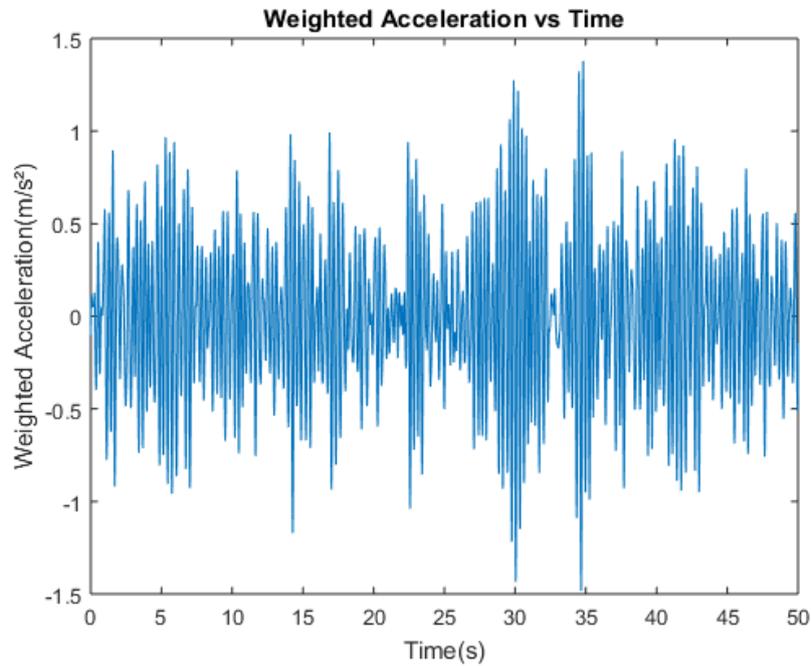


Figure 5. Weighted acceleration imposed to the passenger seated in the middle of the bus for an A class road profile.

The worst case is for a seated person in the rear of the bus, according to Tab. 4, for an A road profile the acceleration imposed to the passenger is fairly uncomfortable, for a B road profile the acceleration imposed is uncomfortable, and for C, D and E roads the acceleration imposed to the passenger is extremely uncomfortable. Again, the crest factor is below nine and so the analysis can be made according to Eq. (5). In Fig. 6 it is possible to see the weighted acceleration imposed to a seated person in the rear of the bus for an A class road profile.

Table 4. Accelerations imposed to a seated person in the rear of the bus.

Road Profile	$a_v$ (m/s <sup>2</sup> ) (Newmark)	$a_v$ (m/s <sup>2</sup> ) (Average of 30 runs - Newmark)	$a_v$ (m/s <sup>2</sup> ) (Spectral Analysis)	Crest Factor
A	0.6104	0.6432	0.6402	3.2425
B	1.2968	1.2817	1.2841	2.6298
C	2.7569	2.5677	2.5681	2.9737
D	4.5604	5.1337	5.1363	2.9963
E	10.2232	10.2750	10.2726	3.3555

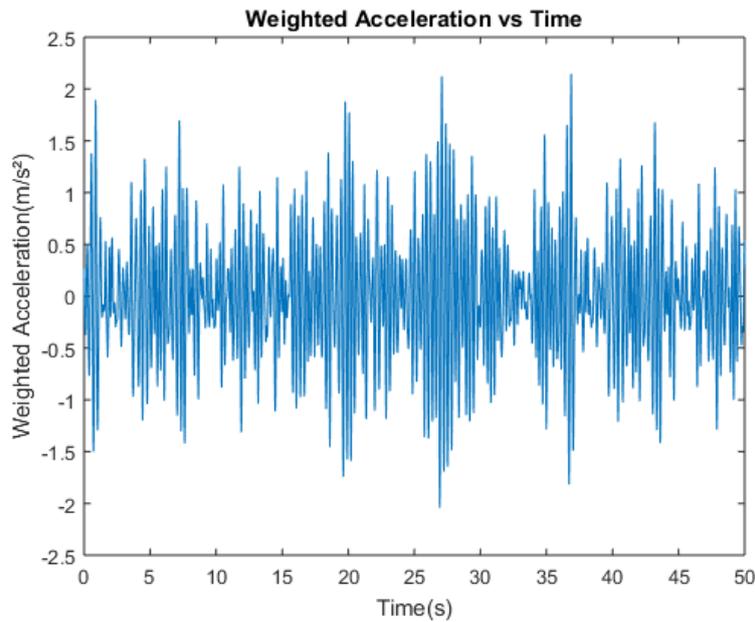


Figure 6. Weighted acceleration imposed to the passenger seated in the rear of the bus for an A class road profile.

## 5. CONCLUSIONS

Analyzing all the data it is possible to note that for roads with C profile and above, the dangers to the bus driver health grows, this is worrisome as many roads in Brazil have this road profile or even worse. For good roads with A and B road profiles the dangers to the bus driver health are reduced even for an exposure of eight hours, and the bus driver feels comfortable driving in an A road profile. The accelerations imposed to the passengers are worse than the accelerations imposed to the bus driver, and so, for a good road with roughness profile A, a passenger seated in the middle of the bus already feels a little uncomfortable. The situation for a passenger seated in the rear is worse as the passenger feels fairly uncomfortable for an A road profile. The divergences in results obtained in the Newmark method and Spectral analysis method is due to the randomness of the responses in the time domain due to random phase angles used in the Shinozuka and Jan (1972) method. For a large number of executions is possible to see that the average of the responses obtained in the Newmark Method converge to the value obtained by the Spectral analysis method.

## 6. ACKNOWLEDGEMENTS

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