DYNAMIC BEHAVIOUR OF TYPICAL HEAVY VEHICLES SUBMITTED TO ROAD IRREGULARITIES

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Abstract. *In this paper a mathematical model is developed for the dynamical analysis of typical heavy vehicles chassis submitted to road irregularities. The mathematical model simulates the chassis of a front engine urban bus, using a finite element representation. The vehicle uses leaf-spring front and rear suspension system. The passengers and the vehicle engine are represented by discreet systems of mass-spring-damper. The suspension of the vehicle is modelled using four discreet systems, one for each tire, simulating a suspension made of leaf-springs. In the present investigation, a more realistic model for the road irregularities is incorporated to the analysis methodology. Such a model considers that the pavement irregularities are defined in a non-deterministic model. The pavement roughness is modelled by a weakly stationary, second order and ergodic random process. In this way, a direct relationship between the mean square values of the irregular profile and the roughness power spectrum density (PSD) can be obtained. The dynamic response of the system, when submitted to the crossing of irregular surfaces associated to different types of pavements is compared with limits of human comfort proposed by code recommendations.*

Keywords. *heavy vehicles, road irregularities, non-deterministic model, dynamical analysis, human comfort*

1. Introduction

The use of mathematical models with increasing complexity for the analysis of important factors related to vehicles design such as safety, passenger comfort and vehicle performance represents the main motivation for this work, (Karlsson and Boman, 1987; Dokainish and Elmadany, 1980).

In general the dynamic behaviour of a ground vehicle can be divided in three categories: longitudinal, lateral and vertical dynamics. These three components must be studied together considering the interaction among them and their influence on vehicle handling, ride, braking and powering forces.

On the other hand, in the modelling process, some simplifying hypothesis can be made according to the type of analysis performed. In this work a mathematical model is developed for the dynamical analysis of typical heavy vehicles chassis taking into account only the vehicle vertical behaviour.

The mathematical model simulates the chassis of a front engine urban bus, using a finite element representation. Modelling strategies are developed using different types of three-dimensional elements for the numeric simulation of the bus chassis.

The vehicle uses leaf-spring front and rear suspension system. The passengers and the vehicle engine are represented by discrete systems of mass-spring-damper. The suspension of the vehicle is modelled using four discrete systems, one for each tire, with the objective of distributing the reaction force between two chassis points, simulating a suspension made of leaf springs. The main numerical tool is the Finite Element Method (FEM).

In the present investigation, a mathematical model is developed for the dynamical analysis of typical heavy vehicles chassis submitted to road irregularities. The work proposes a more realistic model for the road irregularities, which is incorporated to the analysis methodology. Such a model considers that the pavement irregularities are defined in a non-deterministic model.

The pavement roughness is modelled by a weakly stationary, second order and ergodic random process. In this way, a direct relationship between the mean square values of the irregular profile and the roughness power spectrum density (PSD) can be obtained.

The equations of motion of the vehicle-irregularities system follow a standard procedure in which the effect of the pavement roughness is introduced considering that, for the vehicle, it acts as a base motion. For each surface quality grade cases a series of pavement surface profiles is generated. This series of 10 (Ten) profiles were used to excite the vehicle-irregularities system along all the parametric study.

The dynamic response of the system, when submitted to the crossing of irregular surfaces associated to different types of pavements is compared with limits of human comfort proposed by code recommendations. The adequacy of the chassis to the conditions of human comfort is verified.

2. Structural model

Existent models in the market of vehicles of urban transport motivated the choice of the employed chassis in the present analysis. The chosen model is based on a chassis of a typical urban bus. The vehicle frame is composed by two longitudinal members with channel section and six cross members with I section. The members are welded and made of steel. The member material and cross section characteristics are obtained from technical information available in commercial publications. The steel used in the analysis is SAE-1020 with modulus of elasticity, $E=2.07\times10^{5}$MPa, and specific mass, $\rho = 7800$kg/m^3. Figure 1 shows a detailed representation of the chassis, (Roberto and Carvalho, 2001).

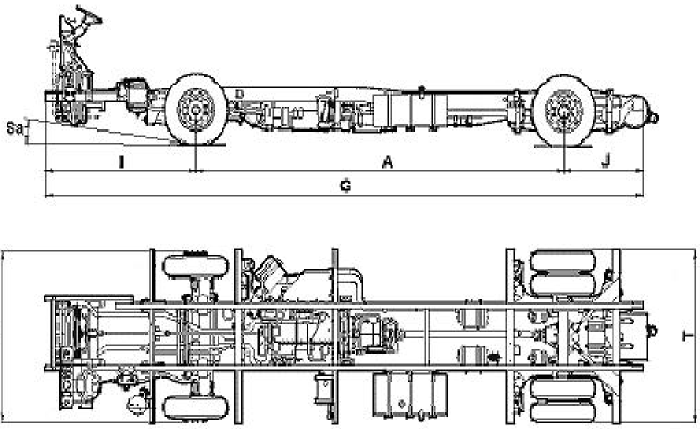

Figure 1. Chassis of a typical urban bus.

The bus chassis analysed in this work has a total weight of 57kN, 31kN are supported by the front axle and 26kN by the rear axle. Its total load capacity is 177kN, 72kN are supported by the front axle and 105kN by the rear axle, Table 1 presents the related technical information, (Roberto and Carvalho, 2001).

Table 1. Geometric characteristics of the chassis.

Geometry	Dimensions (m)	Geometry	Dimensions (m)
Wheel base (A)	6.000	Front width (K)	2.448
Front overhang (I)	2.350	Rear width (T)	2.460
Rear overhang (J)	1.300	Angle (Sa)*	8.20º
Length (G)	9.650	*Angle (Sa) in degrees.	

3. Mathematical model

The mathematical model is conceived to simulate the vertical dynamic behaviour of a typical heavy vehicle with flexible chassis. There is the participation of masses and stiffness coefficients associated to the engine, suspension components and passenger in the determination of the model frequencies. The model developed in this work simulates the chassis of an urban bus with front engine. Figure 2 presents the vehicle physical model used in this work.

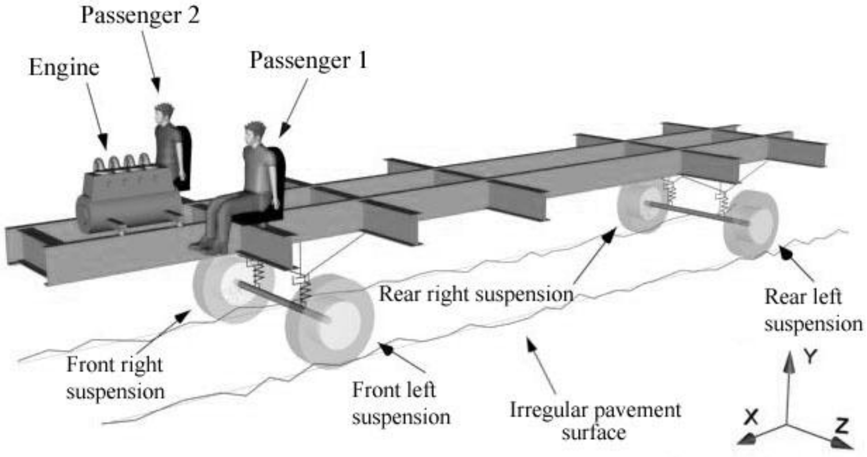

Figure 2. Bus chassis model.

3.1. Model of the flexible frame

In the developed mathematical model, it is considered that the vehicle frame just plays its structural function. Starting from usual techniques of discretization, using the finite element method, the frame members, shown in Fig. 2, are modelled using beam elements.

The beam elements used in the model present three nodes. Each node of the beam element has three degrees of freedom, which are: vertical displacement, u_y, rotation due to bending, θ_z and rotation due to torsion, θ_x. The discretized model has 172 beam elements and 530 nodes, with a total of 1034 degrees of freedom. Figure 3 presents the beam element used in the frame model.

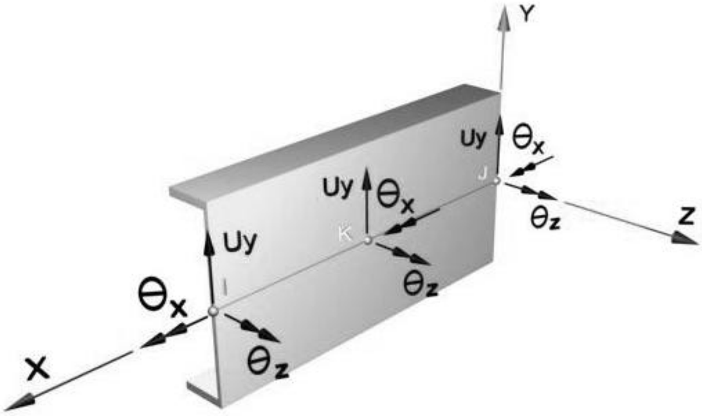

Figure 3. Beam element used in the frame model.

3.2. Model of the passenger and vehicle engine

In this investigation, discrete systems of mass-spring-damper were adopted for passenger and engine models. They consider only vertical displacements associated to the passenger and engine masses. However, it must be emphasized that the vibration levels on the human body can change significantly with variation of the dynamical properties related to the stiffness and damping of the passenger and driver seats. Figure 4 presents the mass-spring-damper system used as the analysis model.

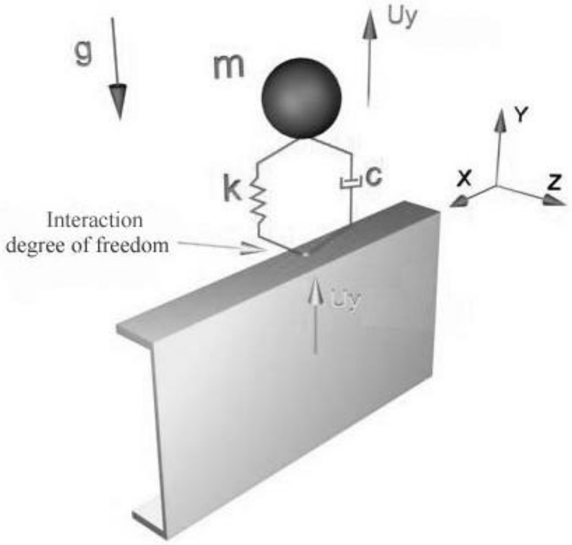

Figure 4. Passenger and engine models.

In the sequence of the paper, Tab. (2) shows the physical parameters used in the model of the passenger and vehicle engine, (Rocha, 1998).

Table 2. Physical parameters: passenger and engine models.

MASS-SPRING-DAMPER	MASS m (kg)	STIFNESS k (N/m)	DAMPING c (N.s/m)
Passenger	100	19620	1400
Engine	500	1226250	24761

3.3. Model of the vehicle suspension and tires

The vehicle suspension was modelled using four discrete systems, one for each tire, with the objective of transmitting the forces originated on the ground to the joining points in the frame, simulating a leaf-spring type of suspension.

The vehicle suspension model is constituted by a spring coupled to two rigid bars, considered without mass, in one of its ends. The rigid bars without mass are coupled directly to the frame longitudinal members. The dampers (shock absorbers) associated to each wheel are connected directly to the frame. Discrete systems of mass-spring-damper were adopted for the vehicle tire model. They consider only vertical displacements associated to the tires mass. Figure 5 presents the suspension and the tires model.

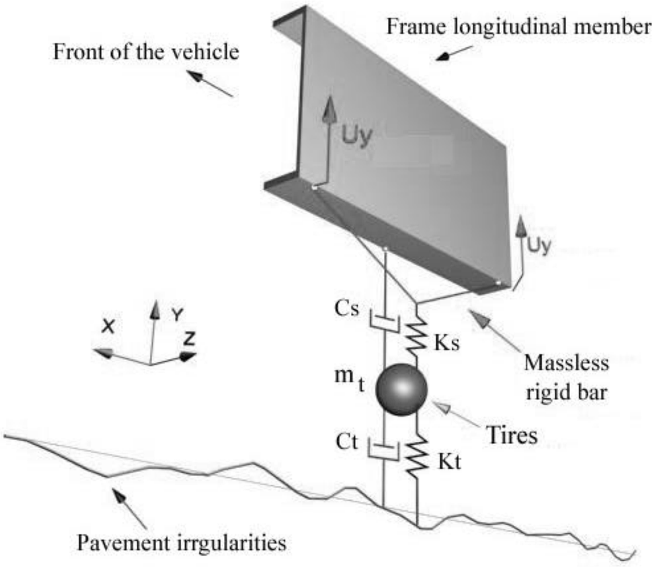

Figure 5. Leaf-spring suspension model.

Following the present investigation, Tab. (3) and Tab. (4) present the physical parameters used in the suspension and tires, (Rocha, 1998).

Table 3. Physical parameters: leaf-spring suspension system.

SUSPENSION SYSTEM	STIFFNESS k (N/m)
Front right	193256
Front left	193256
Rear right	313595
Rear left	313595
SUSPENSION SYSTEM	DAMPING c (N.s/m)
Front right	12872
Front left	12872
Rear right	19828
Rear left	19828

Table 4. Physical parameters: tires system.

MASS-SPRING-DAMPER	MASS m (kg)	STIFFNESS k (N/m)	DAMPING c (N.s/m)
Front Tires	1200	1932560	1000
Rear Tires	1200	3135950	1000

4. Pavement irregularities model

The pavement roughness is modelled by a weakly stationary, second order, and ergodic random process. In this way one can write the relation between the mean square values of the irregular profile, $E[v_b{}^2]$, and the roughness power spectrum density, (PSD), $\Phi_{vb\ vb}(\omega)$, as illustrated in Eq. (1).The PSD function presents the characteristics of road surface roughness along the longitudinal direction.

$$E\left[v_b^2\right] = \int_{-\infty}^{+\infty} \Phi_{v_b v_b}(\omega)\, d\omega \tag{1}$$

The PSD function is written, by its turn, following Eq. (2), which has been used by most of the people who made studies on this area, (Dodds and Robson, 1973; Silva, 1999 and Silva, 2000). In the Eq. (2), $\Phi(\omega_0)$ is an amplitude coefficient associated with the pavement quality, made equal to 10^{-6}m³ (1cm³) and ω_0 is a basic frequency, made equal 1m^{-1}, (Dodds and Robson, 1973; Silva, 1999 and Silva, 2000).

$$\Phi_{v_b v_b}(\omega) = \Phi(\omega_0)\left[\frac{\omega}{\omega_0}\right]^{-2} \tag{2}$$

The equations of motion of the vehicle-pavement irregularities system follow a standard procedure in which the effect of the pavement roughness is introduced considering that, for the vehicle, it acts as a base motion. The effect of the rough pavement is introduced in the vehicle mathematical model as a load vector analogous to what would be considered if the vehicle were subjected to a base movement equal to the irregular pavement profile (Silva, 1999 and Silva, 2000). The irregular pavement profiles are generated based on a standard procedure as the sum of a series of harmonics, based on a random phase angle normally distributed in the interval [0-2π] (Silva, 1999 and Silva, 2000). Figure 6 shows four samples of these profiles used in this analysis, for very good quality surface.

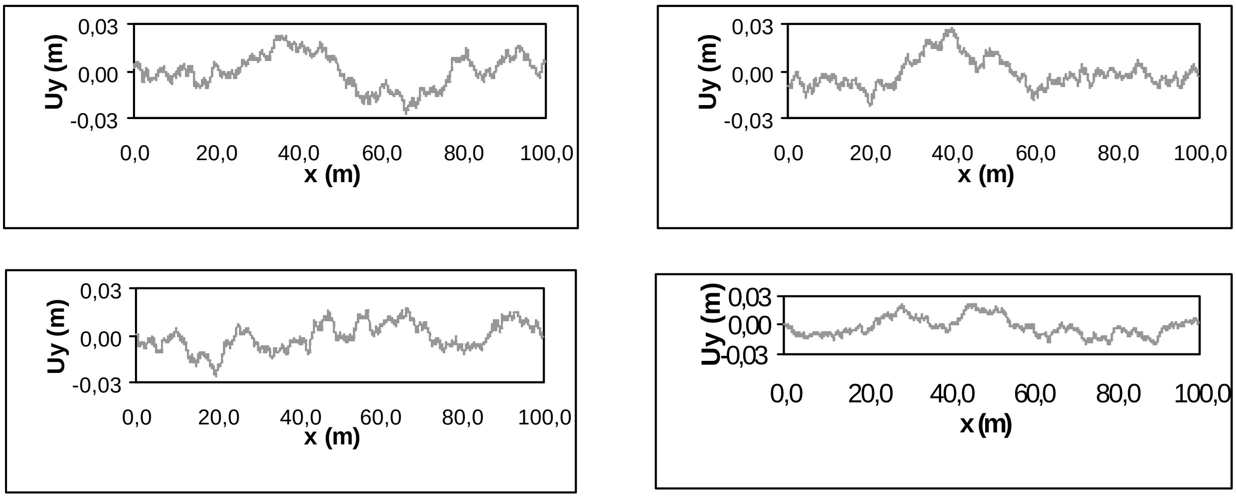

Figure 6. Typical irregular pavement profiles. Pavement quality: very good. $\Phi(\omega_0) = 10^{-6}$m³ (1cm³).

5. Result analysis and discussion

In order to better evaluate the quality of the results obtained by the developed analysis methodology for the simulation of the dynamic behaviour of the vehicle, natural frequencies and vibration modes of the model were calculated.

With this, the characterization of the vertical dynamic behaviour of the vehicle is intended as well as the evaluation of the coherence of the results obtained from the developed mathematical model. It is, also, an objective of this paper, the evaluation of the dynamical response of the vehicle when submitted to road irregularities, in order to verify the adequacy of the chassis to the conditions of human comfort.

5.1. Analysis of the frequencies and vibration Modes of the flexible frame

Using the beam element mentioned previously natural frequencies and vibration modes of the flexible frame were calculated with the use of ANSYS software (ANSYS, 1998). Table 5 presents the first five natural frequencies with a detailed description of the correspondent vibration mode.

Table 5. Natural frequencies and detailed description of the vehicle vibration modes.

FREQUENCIES AND VIBRATION MODES	DESCRIPTION OF THE VIBRATION MODES
f_{01}=2,05Hz - First Mode	Passenger's seat displacement and chassis roll mode.
f_{02}=3,83Hz - Second Mode	Front suspension displacements and chassis bounce mode
f_{03}=7,80Hz - Third Mode	Engine displacements and frame torsion mode.
f_{04}=9,40Hz - Fourth Mode	Rear suspension displacements and frame bending mode.
f_{05}=16,80Hz - Fifth Mode	Chassis pitch and frame bending mode.

5.2. Road irregularities effect

In this analysis methodology the pavement irregularities follow a non-deterministic strategy and are modelled by a weakly stationary, second order, and ergodic random process defined by a profile spectral density (PSD). In sequence, one approximates the irregularity surface by a gaussian ergodic harmonic series and generates a couple of profiles to be the input of a time domain analysis.

The generation of a number of pavement surface profiles sufficiently large to sustain a statistical treatment of the results is intended. For each surface quality grade cases a series of pavement surface profiles is generated. This series of 10 profiles were used to excite the vehicle-irregularities system along all the parametric study.

The vehicle dynamical response is obtained by the integration of its equations of motion, in the time domain, considering the excitation produced by the interaction of the vehicle wheels with the irregular pavement surface. The vehicle is considered running at constant velocity equal to 110km/h (30.6m/s) on a very good pavement quality surface and the time difference between successive front and rear wheel encounter is equal to 0.2s. The irregular pavement profiles present an extension of 100m, as shown in the Fig. (6).

The adequacy of the chassis to the conditions of human comfort is verified. The dynamic response of the system, when submitted to the crossing of irregular surfaces associated to different types of pavements is compared with limits of human comfort proposed by code recommendations (ISO, 1997).

Table 6 illustrates the mean maximum values of acceleration of the driver's seat due to the interaction of the vehicle wheels with an irregular pavement surface. This table presents the results in terms of the, mean maximum acceleration of the driver's seat, μ_a, and quadratic mean, $E[a^2]$. The variance and the standard deviation are both presented.

Table 6. Extreme acceleration of the driver's seat. Pavement quality: very good. $\Phi(\omega_0) = 10^{-6}m^3$ (1cm³).

Irregular Profiles	Mean Maximum Acceleration μ_a (m/s^2)	Quadratic Mean $E[a^2]$ (m/s^2)^2	Variance σ_a^2 (m/s^2)^2	Standard Deviation $\sqrt{\sigma_a^2}$ (m/s^2)	$\frac{\sqrt{\sigma_a^2}}{\mu_a}$
10	0.95	1.00	0.098	0.31	0.33

In the present investigation, the norm adopted was ISO 2631/1/1997, (ISO, 1997), for the analysis of the comfort provided by the vehicle to the passenger. The referred norm establishes that the acceptable values of vibration aiming passenger's comfort depend on different factors that vary in each application. The code recommends the employment of acceptable values described in its Appendix C, which relate the human reactions at different vibration levels in public transportations, as shown in Tab. (7), (ISO, 1997).

Table 7. Human reactions at different vibration levels in public transportations. ISO 2631/1/1997. Appendix C.

DIFFERENT VIBRATION LEVELS	ACCEPTABLE VALUES ISO 2631/1/1997
Smaller than 0,315m/s^2	Not uncomfortable
0,315m/s^2 a 0,63m/s^2	A little uncomfortable
0,5m/s^2 a 1,0m/s^2	Quite uncomfortable
0,8m/s^2 a 1,6m/s^2	Uncomfortable
1,25m/s^2 a 2,5m/s^2	Very uncomfortable
Larger than 2,0m/s^2	Extremely uncomfortable

Table 6 shows that the coefficient of variation, defined as the ratio between the standard deviation and the mean maximum acceleration of the driver's seat, is equal to 0.33 (33% of the mean maximum acceleration). This number could indicate that the generation of a number of pavement surface profiles, larger than 10 (ten) profiles, sufficiently large to sustain a statistical treatment of the results must be used.

The preliminary results obtained in this work indicate that the passenger's maximum acceleration is out of acceptable limits, Tab. (6) and Tab. (7). According to technical recommendations, (ISO, 1997), the results obtained indicate that the passenger's maximum acceleration does not meet comfortable levels for most of the investigated irregular roads.

6. Final Considerations

The present work presents an initial contribution to the development of a mathematical model for the dynamic analysis of typical heavy vehicles with flexible chassis submitted to road irregularities. The paper proposes a more realistic model for the road irregularities, which is incorporated to the analysis methodology. Such a model considers that the pavement irregularities are defined in a non-deterministic model.

The pavement roughness is modelled by a weakly stationary, second order and ergodic random process. In this way, it can be obtained a direct relationship between the mean square values of the irregular profile and the roughness power spectrum density (PSD).

The adequacy of the chassis to the conditions of human comfort was verified. The dynamic response of the system, when submitted to the crossing of irregular surfaces associated to different types of pavements was compared with limits of human comfort proposed by technical norms.

According to those technical recommendations, the results obtained indicate that the passenger's maximum acceleration does not meet comfortable levels for most of the investigated irregular pavement profiles. In the sequence of that investigation, one intends to consider the generation of a number of pavement surface profiles sufficiently large to sustain a statistical treatment of the results.

Based on each surface quality grade cases a series of pavement surface profiles must be generated up to be reached a statistical regularity in terms of the vehicle mean maximum response quantities. This series of almost 50 (Fifth) profiles must be used to excite the vehicle-irregularities system along all the parametric study.

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