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MODELLING OF A MOTORCYCLE WITH A BIODYNAMIC PILOT AND A NEW INTEGRATION METHOD

Leonardo Roso Colpo
Alison Lima
Federal University of Rio Grande do Sul, Department of Mechanical Engineering, Sarmento Leite St., 425 - Room 202, 90040-001, Porto Alegre, RS, Brazil.
leonardo.colpo@ufrgs.br, alisonlima@gmail.com

Herbert Martins Gomes
Federal University of Rio Grande do Sul, Department of Mechanical Engineering, Sarmento Leite St., 425 - Room 202, 90040-001, Porto Alegre, RS, Brazil.
herbert@mecanica.ufrgs.br

José Luis Picoral
Federal University of Rio Grande do Sul, Department of Mechanical Engineering, Sarmento Leite St., 425 - Room 202, 90040-001, Porto Alegre, RS, Brazil.
picoralj@yahoo.com.br

Abstract. *The use of motorcycles as a mode of transportation has increased over the years, mostly as a more affordable and agile substitute for daily displacements. The design for the suspension of these vehicles requires the analysis of several factors, including the purpose of the motorcycle utilization, as well as aesthetic, ergonomic, comfort and safety aspects. The key factor affecting the pilot's comfort is the motorcycle vibration, caused by the road excitations, accelerations in the maneuvers and the engine vibration itself. In this sense, this work proposes a comparative study to verify which factors can most affect the vibration felt by the pilot and improve drivability, also comparing the integration algorithm used in the interpretation of the results. For that, it is proposed the modeling of the motorcycle suspension system, with 5 degrees of freedom for the vertical dynamics, 4-GDL for the lateral dynamics and a proposal of two biodynamic models, with 8 and 12-GDL. This work proposes the modeling of the dynamic vibrational behavior using two integration methods, traditional Newmark and quadratic Newmark. The other monitored variable was the route established by ISO 2631-1 (1997), which alternated between an irregular track, with a roughness and perfectly smooth. Then the motorcycle is held in a single lane change maneuver as per ISO 3888-2 (2011). The results can indicate the practical differences obtained when simulating the motorcycle with the 8 or 12 DOF biodynamic model in order to justify a more complex representation of the human body, as so the influence in the results caused by the road roughness. Also, the quadratic Newmark integration method can be compared with previous studies to verify its consistency, speed of calculation and accuracy. All the findings of this work can be assessment tools in the evaluation of motorcycle design, contributing to improve the motorcycle driving conditions and safety.*

Keywords: *Motorcycle Dynamics, Quadratic Newmark Method, Biodynamic Model, Lateral Dynamics, Comfort and Vehicle Safety.*

1. INTRODUCTION

With the pandemic, the way Brazilians move around has changed. Motorcycles have increased their participation in the market as an alternative to cars, which are more expensive, have higher maintenance costs and smaller range than motorcycles. According to ABRACICLO (2022), the Brazilian Association of Manufacturers of Motorcycles, Mopeds, Scooters, Bicycles and Similar Vehicles, the number of motorcycles registered in the country was 636.000 in the first half of 2021, an increase of 32% compared to the same period of the previous year. This number represents the best performance since 2015, proving that motorcycles have established themselves as an option to other means, mainly considering their practicality.

In March 2022, the sale of 0 km cars fell 23% while the sale of motorcycles raised 76%. One possible explanation for this discrepancy is the high fuel prices, since a motorcycle has a greater autonomy than a car, in some cases up to three times greater. Also, the number of category A driving licenses, i.e., for riding motorcycles, has also grown in recent years, rising from 23.3 million in 2012 to 35.2 million in 2021, an increase of 50.9% ABRACICLO (2022). This figure also includes the increase in the number of people who use motorcycles as their main job or as extra income, i.e., motoboys, mototaxis, delivery drivers, etc. People who spend many hours on the seat of a motorcycle.

However, this increases in the contingent of motorcycles on the streets represents more accidents, as a consequence. This becomes evident when one realizes how much it costs the public coffers, for in the year 2021 alone, more than 300 thousand motorcyclists required hospitalization, costing the public health system almost 280 million of Brazilian Reais.

In terms of vehicle safety as general, the study of suspensions has gained evidence in the literature, in view of the growing concern with users' ergonomics and safety. In this context, automotive suspension in particular has achieved greater relevance through models that can have from one or two degrees of freedom (GDL) to some more complex ones, up to 15 degrees of freedom, (DREHMER, 2017).

Zellner and Weir (1978) proposed to analyze the concept of a simple Lane Change (LC). This analysis is based on field data, with motorcyclists maneuvering in order to develop a standard procedure for maneuverability (Handling Test Procedures). Also in this year, Rice (1978) proposed field tests and pointed to the need to consider motorcycle performance as a whole, i.e., construction quality, vehicle design, etc. along with ride quality, and not just vehicle dynamics.

As for the available bibliographic material, this topic began to gain prominence in the optimization field only in the 1990s, with the great expansion of computer simulation methods. With the publication of the ISO 2631 (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 1997), which establishes some criteria and guide values for simulations and tests with focus on the design of vehicular suspension linked to comfort. This standard was published with some improvements in relation to the British BS-6841, 1987. The ISO-8608:2016 (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 1995) is among these standards the one that most focuses its rules on road profile, establishing data for research in vertical dynamics. Since some minimum criteria were established, many works have been developed in the area.

Baumal, McPhee, and Calamai (1998) worked on the optimization of a 5-GDL vehicle suspension using a global function optimization technique called genetic algorithm, considering two variables, pitch and vertical displacement of the driver's seat. This research concluded that road disturbances contribute very little to the acceleration of the driver's seat. Cossalter and Sadauckas (2006) evaluated an LCI (Lane Change Index) rolling index in comparison with the already known Koch index. They concluded that this new way of measuring better characterized the maneuverability of motorcycles precisely when changing lanes, and that the lower this index, the less torque is required on the handlebars of the motorcycle to obtain a satisfactory roll, giving more comfort to the vehicle. The authors also noted that they could simplify the model studied more adequately starting from the front wheel, as it is more sensitive to the variations suffered by the set.

An evolution of this maneuver is DLC (Double Lane Change), analyzed by Drehmer (2017), through multi-objective functions that could predict uncertainties in suspension manufacturing and other external factors, such as component assembly, track irregularities, and even rider human error in a complex 15-GDL model. In his research, he concludes that factors that may contribute to decreased vertical and lateral RMS acceleration can be reduced by the use of driver's head and back restraints.

Other parts of the motorcycle have also been studied, such as the tires, for example. Pacejka (2012) developed a mathematical model for simulation capable of describing with acceptable accuracy the geometry and shape of tires, while also considering their deformability. This model has become quite useful for further research, as it couples elastic material properties with properties of the medium, such as slip, allowing this approach to describe quite reliably tire behavior in the steady and transient state. The contributions of this work make it very present in vehicle dynamics literature as a basis in the study of tires.

Still in the field of simulation, a high-fidelity motorcycle driving simulator was proposed by Massaro et al. (2016), with the intention of allowing the development of vehicles to be done with more accuracy. Through this simulator, it was realized that the degree of freedom of the roll and the counter-steering behavior are very important for the complete evaluation of the motorcycle dynamics, and a very intuitive conclusion that professional drivers have, in terms of comfort, driving advantages over ordinary drivers, because professional drivers have high concentration, improving the response time in maneuvers and turns.

The evolution of this line of research is the development of a biodynamic model, presented by Zainal, Zakaria, and Baarath (2018), highlighting a human body that is represented by suspension masses, springs, and dampers, which in this case characterize aspects of human anatomy such as bones, muscles, and joints. However, the model proposed by Zainal, Zakaria, and Baarath (2018) featured 8 and 12-GDL, and was proposed for the purpose of analyzing the vibration relationship of the skull with the rest of the body while performing maneuvers. Their major conclusion was the fact that the relationship of vibration and impact are directly related, and that increased vibration can cause dangerous impacts on the brain, and can also generate injuries and trauma in this region.

In this work, a motorcycle with a biodynamic model is constructed, in order to evaluate the vibrations on the driver along a double lane change maneuver. Besides that, several comparisons are made with changes in the model and obstacle properties, as the use of different biodynamic models: one with 8-DOF and one with 12-DOF; the presence of roughness on the road or not and the integration method between the traditional Newmark and the quadratic Newmark.

2. MOTORCYCLE AND DRIVER MODELS

The models used in this work are now presented. In Fig.1 a), there is a representation of the 5 degree of freedom (DOF) motorcycle mode. For the driver models, two different biodynamic models are used: one with 8-DOF as in Fig. 1 b), and one with 12-DOF as in Fig. 1 c).

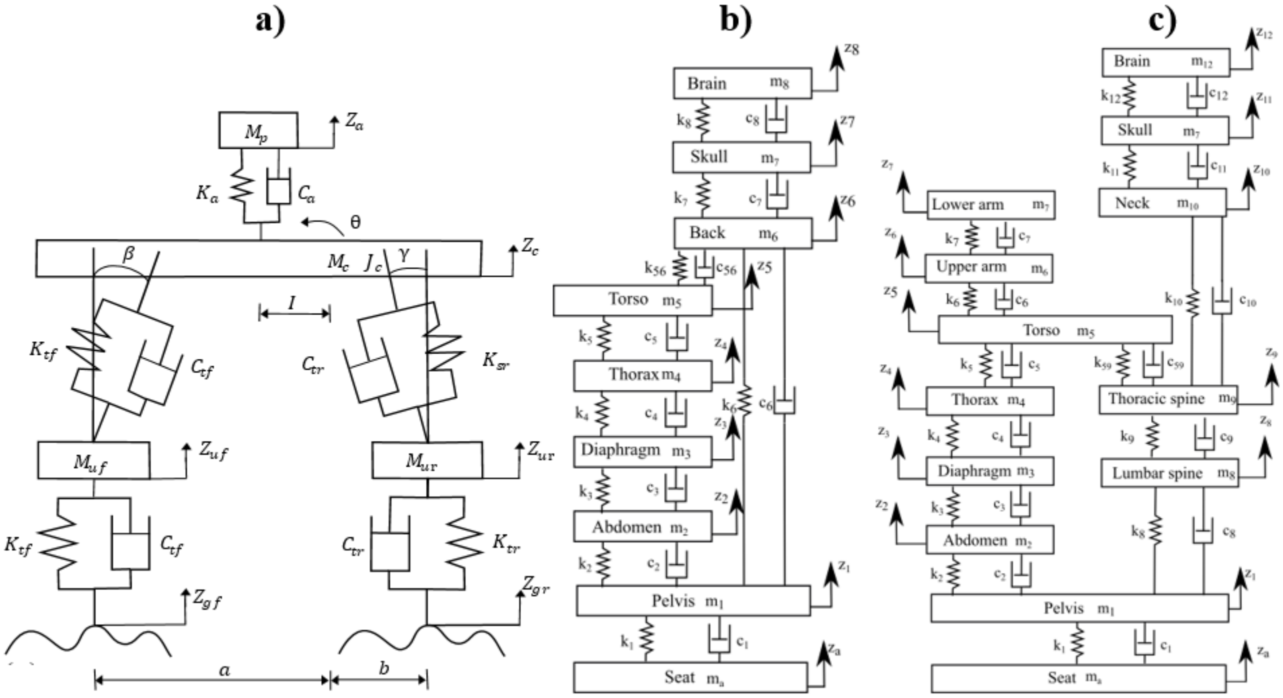

Figure 1 – a) Representation of the 5 DOF motorcycle model (ZOU et al., 2009). b) Representation of the 8-DOF biodynamic model (ZAINAL; ZAKARIA; BAARATH, 2018). c) Representation of the 12-DOF biodynamic model (ZAINAL; ZAKARIA; BAARATH, 2018)

The motorcycle parameters are contained in Tab. 1. The vehicle biodynamic models are coupled with the motorcycle model, creating a bigger system that will solve both driver and motortycle DOF displacements and etc. The properties of each biodynamic model are contained in Tab. 2, both representing a person with around 90 kg.

Table 1 - Motorcycle parameters

Symbol	**Variable**	**Value**	**Unity**
K_{tf}	Front tire stiffness	180000	N/m
K_{tr}	Rear tire stiffness	180000	N/m
C_{tf}	Front tire damping	250	Ns/m
C_{tr}	Rear tire damping	250	Ns/m
M_{uf}	Front unsprung mass	15	Kg
M_{ur}	Rear unsprung mass	20	Kg
K_{sf}	Front suspension stiffness	14000	N/m
K_{sr}	Rear suspension stiffness	30000	N/m
C_{sf}	Front suspension damping	2000	Ns/m
C_{sr}	Rear suspension damping	2200	Ns/m
M_c	Chassis mass	170,7	Kg
K_a	Seat stiffness	50000	N/m
C_a	Sear damping	500	Ns/m
M_p	Driver mass	91,3	Kg
l	Driver distance to CG	0	m
h	Distance between CG and roll center	0,3	m
a and b	Distance of front and rear axle to CG	0,70; 0,823	m

Table 2 – Properties of each biodynamic model (ZAINAL; ZAKARIA; BAARATH, 2018)

Model	Mass (kg)		Damping (Ns/m)		Stiffness (N/m)	
8-DOF	m_1=27.230	m_2=5.291	C_1=371.0	C_2=292.0	k_1=25 500.0	k_2=877.0
	m_3=0.455	m_4=1.362	C_3=292.0	C_4=292.0	k_3=877.0	k_4=877.0
	m_5=32.762	m_6=6.820	C_5=292.0	C_6=3 580.0	k_5=877.0	k_6=52 600.0
	m_7=3.500	m_8=1.500	C_7=450.0	C_8=340.0	k_7=800 000.0	k_8=156 000.0
			C_{56}=3 580.0		k_{56}=52 600.0	
12-DOF	m_1=27.230	m_2=5.906	C_1=370.8	C_2=292.3	k_1=25 016.0	k_2=877.0
	m_3=0.454	m_4=1.362	C_3=292.3	C_4=292.3	k_3=877.0	k_4=877.0
	m_5=32.697	m_6=5.470	C_{54}=292.3	C_{59}=3 581.6	k_5=877.0	k_{59}=52 621.0
	m_7=5.297	m_8=2.002	C_6=3 581.6	C_7=3 581.6	k_6=67 542.0	k_7=67 542.0
	m_9=4.806	m_{10}=1.084	C_8=3 581.6	C_9=3 581.6	k_8=52 621.0	k_9=52 621.0
	m_{11}=3.500	m_{12}=1.500	C_{10}=3 581.6	C_{11}=450.0	k_{10}=52 621.0	k_{11}=1 800 000.0
			C_{12}=340.0		k_{12}=156 000.0	

2.1 Lateral Dynamics

The model according to Drehmer (2017) presents 3-GDL, however one more degree of freedom will be included in this work. This dynamic, unlike the vertical one, represents the efforts in the x and y axes of the motorcycle, coming from the effects exerted by the tires and their reactions when decomposed. The original GDL are the longitudinal displacement of the motorcycle body (x_b), the lateral displacement of the motorcycle body (y_b) and the yaw angular displacement, given in radians (ψ) and the last GDL included in this work will be the rolling angular displacement, also in radians (φ).

Also, according to what can be observed in the original thesis of Drehmer (2017), as well as the development of these equations and their meanings, Eq. (1) describes the motion in the longitudinal direction, Eq. (2) describes the lateral motion, Eq. (3) details the dynamics of the yaw of the motorcycle body, and lastly Eq. (4) represents the rolling dynamics of the vehicle body.

$$m_t\ddot{x}_b = F_{x_1} + F_{x_2} + m_b h\varphi\ddot{\psi} + m_t\dot{y}_b\dot{\psi} - m_b h\dot{\varphi}\dot{\psi} - f_r m_t g - \frac{1}{2}C_D A_f \rho \dot{x}_b^{\,2} \tag{1}$$

$$m_t\ddot{y}_b = F_{y_1} + F_{y_2} - m_t\dot{x}_b\dot{\psi} - m_b h\ddot{\varphi} \tag{2}$$

$$I_z\ddot{\psi} = aF_{y_1} - bF_{y_2} + m_b h\varphi\ddot{x}_b - m_b h\dot{\varphi}\dot{x}_b + I_{xz}\ddot{\varphi} \tag{3}$$

$$I_x\ddot{\varphi} = m_t\ddot{z}_b - m_t gh \tag{4}$$

2.2 Tire modelling

The tire modelling is made accordingly to Pacejka (2012). Two of the proposed equations are used in this work, in order to evaluate the longitudinal force in Eq. (5) and the lateral force of the motorcycle tires in Eq. (6).

$$F_{L,x_i} = F_{Z_i} D_i \sin\left\{C_i \tan^{-1}\left[B_i\kappa_i - E_i\left(B_i\kappa_i - \tan^{-1}\left(B_i\kappa_i\right)\right)\right]\right\} \tag{5}$$

$$F_{L,y_i} = F_{Z_i} D_i \sin\left\{C_i \tan^{-1}\left[B_i\alpha_i - E_i\left(B_i\alpha_i - \tan^{-1}\left(B_i\alpha_i\right)\right)\right]\right\} \tag{6}$$

These equations are very similar, differing only by the coefficients κ and α, which represents the longitudinal slipping and the slip angle, respectively. The other parameters (B, C, D and E) are determined for motorcycle tires, and the "i" subscript means the front and rear tire.

3. NUMERICAL PROCEDURES

Two integration methods are used to be compared in terms of efficiency and accuracy: The traditional Newmark and the quadratic Newmark.

3.1 Traditional Newmark

The traditional Newmark method consists in a linear response for the differential equations of the movement. The recurrence equations that define the Newmark method are the Eq. (7) for displacements, Eq. (8) for velocities and Eq. (9)

for accelerations. The two parameters α and β must obey certain rules to assure the accuracy for the method, and in literature the values of 0.25 to α and 0.5 to β are accepted to assure the method unconditionally stable.

$$\mathbf{z_{i+1}} = \left[\frac{1}{\alpha(\Delta t)^2}\mathbf{M} + \frac{\beta}{\alpha(\Delta t)}\mathbf{C} + \mathbf{K} \right]^{-1} \times \left\{ \mathbf{F_{i+1}} + \mathbf{M}\left(\frac{1}{\alpha(\Delta t)^2}\mathbf{z_i} + \frac{1}{\alpha(\Delta t)}\dot{\mathbf{z}}_\mathbf{i} + \left(\frac{1}{2\alpha} - 1\right)\ddot{\mathbf{z}}_\mathbf{i} \right) + \mathbf{C}\left(\frac{\beta}{\alpha(\Delta t)}\mathbf{z_i} + \left(\frac{\beta}{\alpha} - 1\right)\dot{\mathbf{z}}_\mathbf{i} + \left(\frac{\beta}{\alpha} - 2\right)\frac{\Delta t}{2}\ddot{\mathbf{z}}_\mathbf{i} \right) \right\} \tag{7}$$

$$\ddot{\mathbf{z}}_\mathbf{i+1} = \frac{1}{\alpha(\Delta t)^2}\left(\mathbf{z}_{i+1} - \mathbf{z}_i\right) - \frac{1}{\alpha(\Delta t)}\dot{\mathbf{z}}_i - \left(\frac{1}{2\alpha} - 1\right)\ddot{\mathbf{z}}_i \tag{8}$$

$$\dot{\mathbf{z}}_\mathbf{i+1} = \dot{\mathbf{z}}_\mathbf{i} + \left[(1-\beta)\ddot{\mathbf{z}}_i + \beta\ddot{\mathbf{z}}_{i+1}\right]\Delta t \tag{9}$$

3.2 Quadractic Newmark

The quadratic method is very similar to the traditional one, but treats the variation of the acceleration as non-linear. This guarantees a bigger accuracy using the same time step, due to the raise of terms in the Taylor Series (AKBAR GHOLAMPOUR; GHASSEMIEH; KARIMI-RAD, 2013). The resulting expression for the displacement is Eq. (10) and for the velocity is the Eq. (11).

$$\mathbf{z_{i+1}} = \mathbf{z}_i + (\Delta t)\dot{\mathbf{z}}_i + \left[\left(\alpha - \frac{1}{12}\right)\ddot{\mathbf{z}}_{i-1} + \left(\frac{1}{2} - 2\alpha\right)\ddot{\mathbf{z}}_i + \left(\alpha + \frac{1}{12}\right)\ddot{\mathbf{z}}_{i+1} \right](\Delta t)^2 \tag{10}$$

$$\dot{\mathbf{z}}_\mathbf{i+1} = \dot{\mathbf{z}}_i + \left[\left(\delta - \frac{1}{4}\right)\ddot{\mathbf{z}}_{i-1} + (1-2\delta)\ddot{\mathbf{z}}_i + \left(\delta + \frac{1}{4}\right)\ddot{\mathbf{z}}_{i+1} \right](\Delta t) \tag{11}$$

4. TESTS CONDITIONS

The conditions that the model is exposed are now discussed. The motorcycle will perform a double lane change maneuver in two conditions: a smooth road and a road with roughness accordingly to (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 1995).

4.1 Double Lane Change (DLC)

The Double Lane Change (DLC) maneuver is designed for cars, but in lack of a specific maneuver for motorcycles, the DLC is used as a reference for the vibration analysis. The maneuver is made through a steering input in the motorcycle handlebar, as shown in Fig. 2. The δ_1 is the angle of steer of the front tire, and δ_2 is the angle of the rear tire.

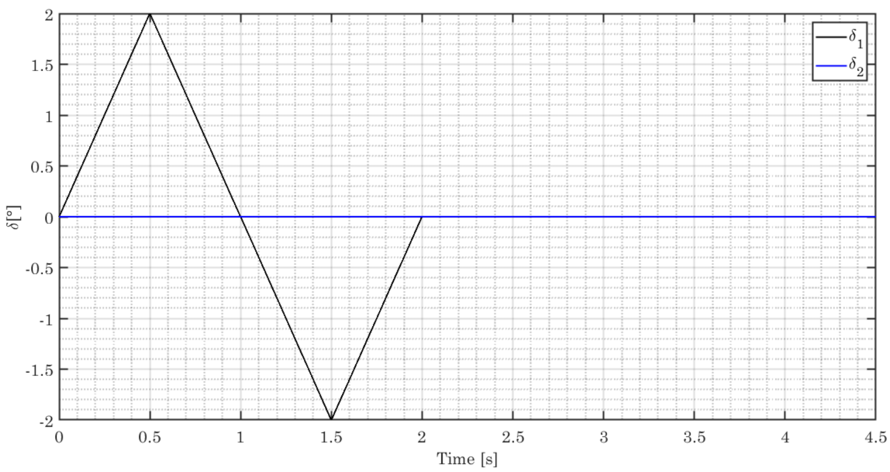

Figure 2 - Steering input in the handlebar

4.2 Road roughness

The International Organization for Standardization (1995) establishes some parameters to represent a certain level of roughness accordingly to the road category and quality. The standard proposes 8 different classes, categorized by letters of A to H. In this work, the A class road is chosen, representing a very smooth asphalt.

5. RESULTS AND DISCUSSIONS

The results of the simulations are now presented and discussed.

5.1 Simulation outputs

The main outputs of the motorcycle maneuver are presented below. It can be seen in Fig. 3 a) the longitudinal results of the chassis and in Fig. 3 b) the lateral results. The DLC is executed as expected, maintaining the physical logic and expected behaviors. This is also confirmed by the lateral forces on the tires, seen in Fig. 4.

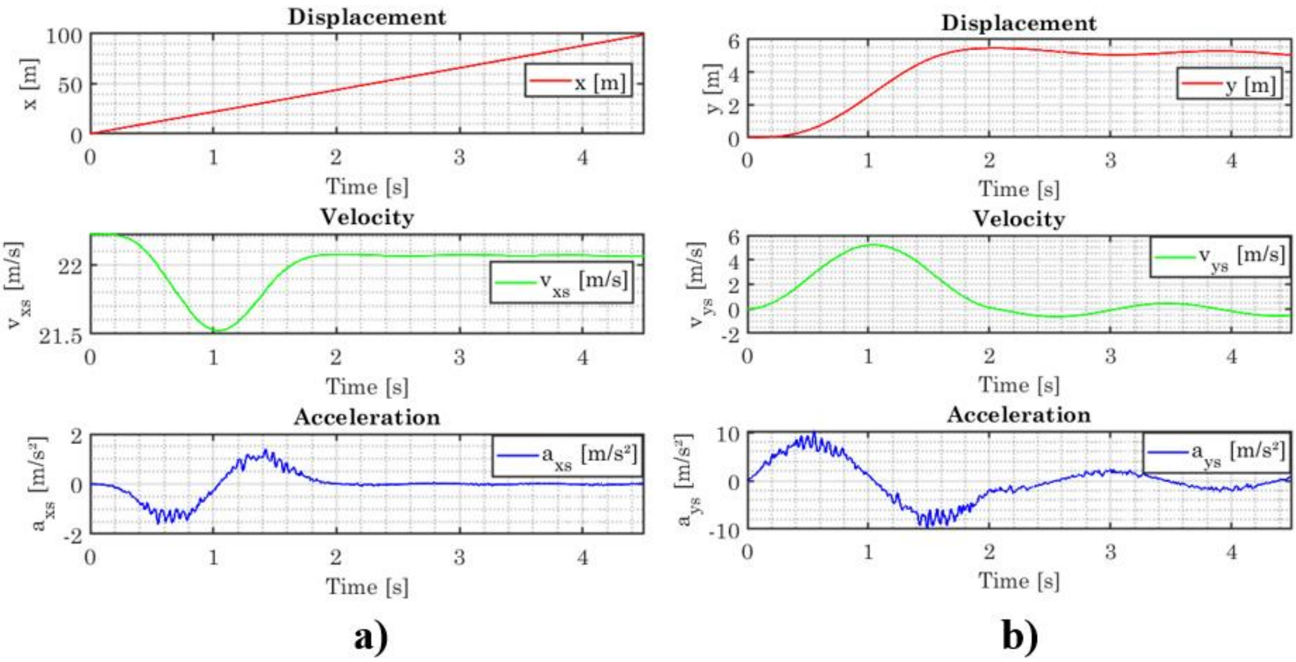

Figure 3 - Results of the chassis movements in: a) longitudinal dynamics and b) lateral dynamics

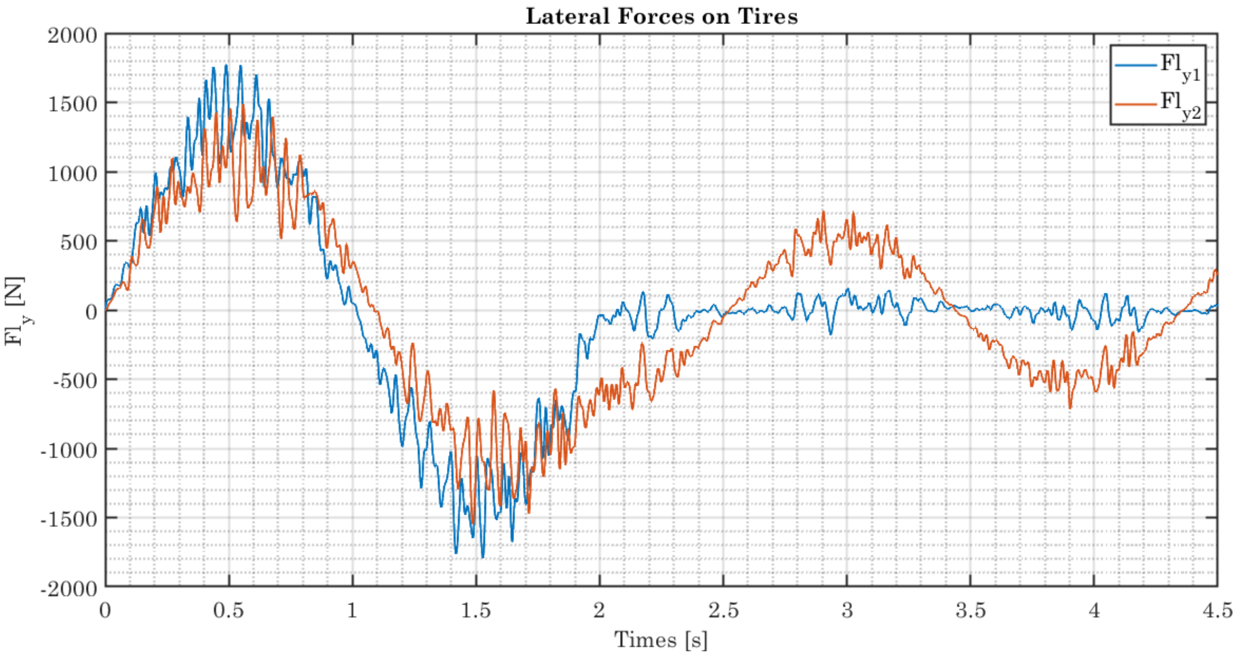

Figure 4 - Lateral forces on tires

The motorcycle is performing as proposed in the maneuver, so the analyzes can now be presented.

5.2 Performance of the integration methods

Using a class A road, the traditional and quadratic Newmark results are compared in 12 DOF defined to be comparison points. In Tab. 3, the results of each integration method in those points are presented. The maximum difference between both is less than 1%, but the quadratic method is much faster to solve due to the advantages already discussed. The quadratic method will be used in the next simulations.

Table 3 – Results for traditional Newmark and quadratic Newmark

Symbol	Variable	Unity	Traditional	Quadratic	Dif. (%)
a_x	Chassis longitudinal acceleration	m/s²	0,507	0,508	-0,197
a_y	Chassis lateral acceleration	m/s²	3,880	3,885	-0,129
$\ddot{\psi}$	Chassis yaw acceleration	rad/s²	1,919	1,923	-0,208
$\ddot{\varphi}$	Chassis roll acceleration	rad/s²	0,871	0,879	-0,918
$\ddot{\theta}$	Chassis pitch acceleration	rad/s²	2,483	2,482	0,040
a_c	Chassis bounce acceleration	m/s²	0,584	0,584	0,000
a_{uf}	Front unsprung mass acceleration	m/s²	4,036	4,041	-0,124
a_{ur}	Rear unsprung mass acceleration	m/s²	3,461	3,464	-0,087
a_a	Seat acceleration	m/s²	0,407	0,407	0,000
a_1	Pelvis acceleration	m/s²	0,146	0,146	0,000
a_6	Lumbar spine acceleration	m/s²	0,140	0,140	0,000
a_8	Brain acceleration	m/s²	0,150	0,150	0,000

5.3 Effects of the road roughness

The results for each case, for a class A and a smooth road, are presented in Tab. 4. The longitudinal and lateral accelerations are essentially not affected, what is expected since using a smooth and a rough profile and keeping the same friction coefficient will not lead to big differences in the analysis.

However, the accelerations are very different between these conditions. A smooth road will mostly not identify vibrations in the driver body, as seen in the results. Even with the higher quality pattern in the ISO 8608, the differences are quite clear and ensure that the roughness of the road must be taken into account.

Table 4 – Results for the class A road and the smooth road

Symbol	Variable	Unity	Class A road	Smooth road
a_x	Chassis longitudinal acceleration	m/s²	0,508	0,504
a_y	Chassis lateral acceleration	m/s²	3,885	3,858
$\ddot{\psi}$	Chassis yaw acceleration	rad/s²	1,923	0,535
$\ddot{\varphi}$	Chassis roll acceleration	rad/s²	0,879	0,389
$\ddot{\theta}$	Chassis pitch acceleration	rad/s²	2,482	0,001
a_c	Chassis bounce acceleration	m/s²	0,584	0,002
a_{uf}	Front unsprung mass acceleration	m/s²	4,041	0,000
a_{ur}	Rear unsprung mass acceleration	m/s²	3,464	0,000
a_a	Seat acceleration	m/s²	0,407	0,003
a_1	Pelvis acceleration	m/s²	0,146	0,004
a_6	Lumbar spine acceleration	m/s²	0,140	0,004
a_8	Brain acceleration	m/s²	0,150	0,004

5.4 Biodynamic models comparison

Finally, the comparison of both biodynamical models is in Tab. 5.

Table 5 – Results of accelerations in both biodynamic models

Symbol	Variable	Unity	8-DOF	12-DOF	Dif. (%)
a_x	Chassis longitudinal acceleration	m/s²	0,508	0,508	0,000
a_y	Chassis lateral acceleration	m/s²	3,886	3,885	0,026
$\ddot{\psi}$	Chassis yaw acceleration	rad/s²	1,923	1,923	0,000
$\ddot{\varphi}$	Chassis roll acceleration	rad/s²	0,879	0,879	0,000
$\ddot{\theta}$	Chassis pitch acceleration	rad/s²	2,482	2,482	0,000
a_c	Chassis bounce acceleration	m/s²	0,584	0,584	0,000
a_{uf}	Front unsprung mass acceleration	m/s²	4,041	4,041	0,000
a_{ur}	Rear unsprung mass acceleration	m/s²	3,463	3,464	-0,029
a_a	Seat acceleration	m/s²	0,408	0,407	0,245
a_1	Pelvis acceleration	m/s²	0,154	0,146	5,195
a_6	Lumbar spine acceleration	m/s²	-	0,140	-
a_8	Brain acceleration	m/s²	0,165	0,150	9,091

The utilization of the 12-DOF model does not change the responses on the motorcycle itself. In comparison with the 8 DOF model, a few differences were spotted in the brain and pelvis acceleration. However, these differences are lower than 10%, what can indicate that both models are returning consistent results of the human body acceleration. This means that any of the models could be applied in a human body analysis of vibration, but with de 8-DOF being easier to implement and estimates its parameters.

6. CONCLUSIONS

In this work, a motorcycle model was developed in order to analyze the vibrations on the driver along a double lane change maneuver, as well as make comparisons about some parameters of the maneuver. The DLC conditions were constructed by inputting a steer angle on the front tire of the motorcycle, leading to the desired path. The results of displacements, tire forces and reactions confirm that the maneuver is well executed along with the standards.

It was found that the quadratic Newmark method can be used as an alternative for faster results or bigger time steps without losing accuracy compared to the traditional Newmark method. Differences lower than 1% were found between the two integrations methods.

In terms of road roughness, even for lateral dynamics it was shown that the road surface plays a key role in the vibrations that the driver will experiment. An irregular track increases the vibrations felt by the driver in comparison with a smooth road, reinforcing that the roughness should be taken into account in numerical simulations, since they can modify the analysis scenarios. The modeling of the road roughness according to the ISO 8608 standard is an efficient way to consider these effects in vehicle analysis.

One point that did not show great asymmetry was the number of degrees of freedom for the biodynamic model. Both the 8-GDL model and the 12-GDL model yielded very similar values, differing less than 0.1% between them in the motorcycle variables. For the pilot, there were greater disproportions, of 5 and 9% for the pelvis and for the brain, respectively. These differences can be explained by the way in which the weight was distributed between the model with fewer degrees of freedom so that they maintained the same mass among themselves. However, even so, the difference presented was minimal, not justifying its implementation (12-GDL), as it will increase the complexity of the problem.

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