INCLUSION OF TIRE LIFTING EFFECT IN TRAFFIC SIMULATION OF A COMMERCIAL LOAD CARRYING VEHICLE

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Abstract. *This work presents a methodology to take into account the effect of tire lifting in the numerical simulation of a commercial vehicle b-train. Firt, the basic equations of the vertical dynamics are showed, followed by the modifications suggested to be included into an existing numerical model of the vehicle (which does not consider the effect). Then, the use of the contact function of commercial software is explained for the tire lifting situation. A study is carried out for the simplified problem of a single wheel running on idealized surfaces. Once the correctness of the approach was asserted, the road obstacle benchmark was used to compare the results of both approaches in a full vehicle numerical simulation. The numerical results obtained with the inclusion of the tire/road separation agreed favorably to the available experimental results, what was demonstrated with graphical comparisons.*

Keywords*: Tire Lifting, Contact, Numerical Analysis, Traffic Simulation, Commercial Load Carrying Vehicle*

1. INTRODUCTION

In a country like Brazil, where the loads transportation depends fundamentally on the roads, researches that bring development of technology for this segment have a big relevance. For the grain transport, the vehicle combination known as “B-Train” is responsible for about 70% of the sales of the trailer companies. Because of that, it has already established a notable position in the national scenario.

Tight competition and increasing demand for higher quality and durability from customers push the producers to review their concepts of design constantly. Using virtual simulation tools in the design process is now essential, either for the cost reduction or the time savings when launching new products to the market.

Inside this context, a dynamic model was developed to obtain the loads acting in a traffic simulation (Peres, 2006). In despite of this model’s calibration, the numerical simulations presented some discrepancies when compared to experimental results at velocities higher than 10 km/h. The main reason is a phenomenon called tire lifting, which appears when the vertical acceleration of one body overcomes the gravity magnitude, making this body’s behavior essentially ballistic.

The initial stimulus for this work is to refine the tire/road interaction, including the lifting from the ground. Therefore, it will be possible to considerate the alterations that occurred in the calibration of the model in higher velocities, and, thus, make it more reliable.

Hence, the goal is to improve the b-train dynamic model, finding a way to simulate the tire lifting effect when passing over an obstacle. With this intention, a study was carried out where the movement input is applied through contact. To validate this suggestion, graphical comparisons with the real vehicle experimental results and the results obtained in Peres (2006) are shown.

2. TIRE LIFTING

When passing over an obstacle, like a hole or a ramp, the vertical acceleration of all parts in a vehicle are significantly changed. According to Cardoso and Marczak (1995), when the acceleration of the unsprung bodies (axles and associated components) overcomes gravity, their displacement profile becomes ballistic (parabolic). It is a phenomenon where the tire lifts from the ground. In this situation, the bodies behave like projectiles and their positions, velocities and accelerations are explained as such. Another way of seeing this effect is analyzing the springs that represent the tires in numerical models. When tensile forces appear, the tire/ground interaction is interrupted and the relevant bodies are only controlled by gravity acceleration.

2.1. Simplified model

Understanding the phenomenon was one of the first barriers to implement the tire lifting to the b-train numerical model. There is not an abundant specific literature about this subject – regarding vehicles, although the ruling equations are a well-known matter of the dynamics of rigid bodies (Wong, 2001).

For a better comprehension of the physical effect involved, the vertical dynamics equations are presented in this section. The system of equations for a mass-spring system is shown, representing the tire lifting in each wheel of the vehicle combination. The analytical model presents (Fig. 1): sprung mass (everything that is supported by the suspension - m_s), suspension (stiffness k_s and damping c_s), unsprung mass (axles and associated components - m_{ns}), tire (stiffness k_p and damping c_p) and pavement (the source of vertical inputs).

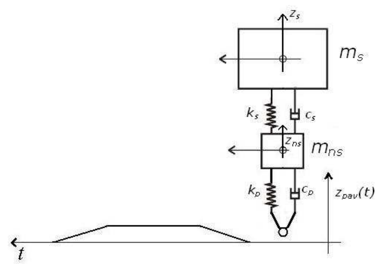


Figure 1. Analytical model.

While the vertical acceleration is $\ddot{Z} \leq g$, displacement equations are represented by the translational accelerations, referring to each degree-of-freedom of the model, obtained from the bodies dynamic equilibrium. For the unsprung mass, the acceleration of the model in Fig. 1 is given by:

$$\ddot{Z}_{ns} = -\frac{K_p}{m_{ns}}\left(Z_{ns} - Z_{pav}\right) - \frac{C_p}{m_{ns}}\left(\dot{Z}_{ns} - \dot{Z}_{pav}\right) - \frac{K_s}{m_{ns}}\left(Z_{ns} - Z_s\right) - \frac{C_s}{m_{ns}}\left(\dot{Z}_{ns} - \dot{Z}_s\right) \tag{1}$$

But when the tires lift from the ground, only the gravitational acceleration must be considered (besides inertia). Therefore, in this time period, the unsprung mass acceleration is given by:

$$\ddot{Z}_{ns} = -g \tag{2}$$

The use of Eqs. (1) or (2) is determined by an appropriated algorithm, which detects the contact loss. Equation (2) is used when the tire lifting occurs, otherwise, Eq. (1) remains valid.

2.2. Detailed model

In his work, Peres (2006) developed a numerical model of the b-train vehicle combination to be used in traffic simulations (Fig. 2). The idea was to obtain the loading conditions for the vehicle's durability study. The dynamical validation was done by passing the real vehicle and the numerical model over an obstacle that provoked a vertical pulse in each axle of the vehicle, which had sensors for posterior comparisons with the numerical model.

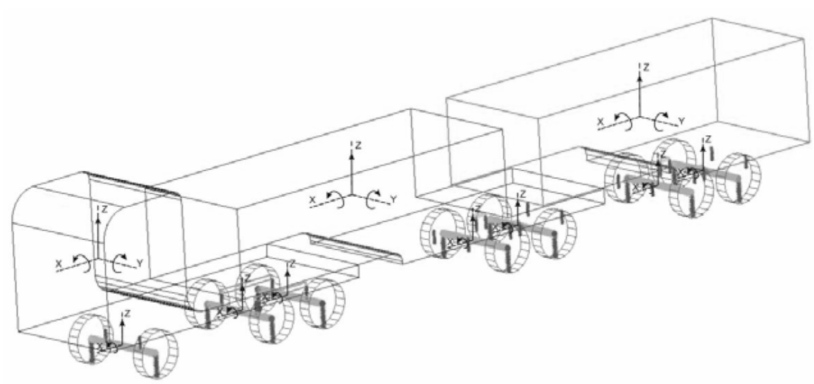


Figure 2. Numerical model of the b-train (Peres, 2006).

To measure the accelerations, four accelerometers were installed at the points where the biggest amplitudes of swinging and gallop would appear in the vehicle structure (Peres, 2006).

Experimental tests were carried out on a plane road, at the following velocities: 10, 15, 20 and 25 km/h. Each axle was passing over two obstacles at the same time (two ramps were used – one for the left wheels and another for the right wheels), without phase displacement.

The comparisons between the numerical simulations and the experimental tests had good results for the 10 km/h velocity. However, for higher velocities, some problems appeared in the comparison graphics. Analyzing the tests with the real vehicle, the tire/road lifting effect was noted. This phenomenon, for some velocities, also provoked "rebounds" of the tires on the pavement.

The model used in that dynamic analysis was not including this effect, especially because its input was generated by a movement function applied directly to the tires. This was 'obligating' the numerical tire to follow the exact excitation (ramp profile), disregarding the possibility of 'lift-off'. According to the author, this way of simulation was correctly representing reality for velocities up to 10 km/h, on obstacles with the same height (0,1m). Above that speed, it would present a sensible discrepancy when compared to the experimental tests.

The intention of the present work is to improve the b-train dynamic model, finding a way to simulate the tire lifting effect on obstacles. On these terms, the loading conditions obtained in traffic simulations, that will use this 'improved' model, will agree even more with reality.

3. NUMERICAL MODELING

The purpose of the numerical modeling developed here is simulating the b-train's vertical dynamics, which is imposed to the vehicle composition through the roughness and obstacles of the road. To represent the tire lifting effect in the analysis, it was decided to use a contact function. This choice relies on the fact that contact has been studied to represent the real interaction of rigid bodies, and its applications have been a constant theme in the last decades.

The numerical simulations in this work were run in the commercial software MSC.ADAMS, which is based on multibody dynamics.

According to Barbosa (1999), the Multibody Systems – MBS had its birth in the early 60's, but it was introduced to the field of mechanics and road transportations only in the beginning of the following decade.

The multibody systems are made of solid bodies connected to each other through joints, which restrict their relative movement. The method is based on the substitution of real systems for equivalent models, elaborated with discrete bodies, in which elastic and inertial properties are known. Summarizing, the study is about an analysis of how these mechanisms react under the influence of excitations.

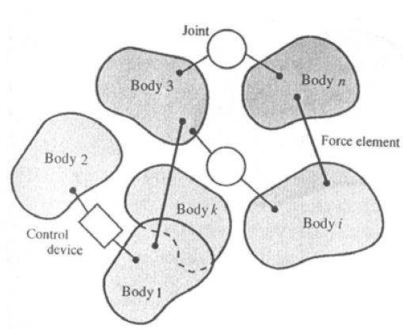


Figure 3. Schematic representation of a multibody system.

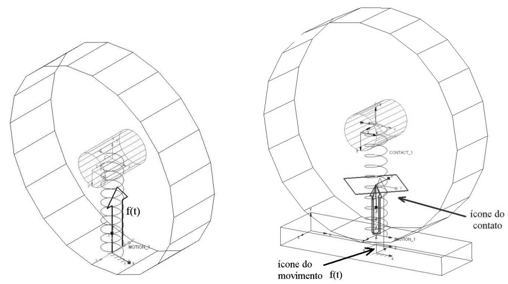
Because of high computational costs in transient finite elements simulations for problems with the complexity found in this work, it is rather common the use of rigid bodies systems to simulate vehicle traffic (Peres, 2006). From this analysis, the relevant loads on the structure are extracted, which are then used for a strength and fatigue study on critical points.

3.1. Improved numerical model

Trying to approximate the numerical model behavior to the real vehicle one, the option of generating the obstacle input with a contact function was considered interesting. For that, blocks were added right under each of the b-train wheels of the initial model, imitating a pavement. The idea of using one only big block under the whole vehicle composition was discarded, since the excitation of passing over the obstacle had to be applied to each axle independently.

Differently from what was previously happening, in the new model the movement inputs, which derive from the passage over the ramp, are applied to the blocks, not longer to the tires. Through the contact function, the blocks push the tires and the whole vehicle combination, according to pre-established contact parameters. Figure 4 illustrates the situations described above.

This way, the obstacles used in the experimental tests can be dynamically simulated for an unrestricted band of velocities (what was impossible in the previous model), which is one of the contributions of the present work.



(a) (b)

Figure 4. (a) Actual model, with the pavement excitation f(t) applied to the tire; (b) Proposal of new numerical model, where the excitation f(t) is imposed to the block and the contact is applied in the tire/block interaction.

3.2. Contact Inclusion

The contact function of the software used in the tire lifting simulation in this work applies the impact function model for the normal forces calculations. Like the restitution coefficient, this model uses a penalty rule for the normal contact restrictions.

The contact between rigid bodies theoretically requires that the two bodies do not penetrate each other. This can be expressed as an unilateral restriction (inequality). The contact force is the force associated to the imposition of this restriction. Dealing with these auxiliary conditions of restriction is usually achieved by two ways: introducing Lagrange multipliers (Vaz, 2001) or penalty rule.

Penalty rule is a technique where a restraint is mathematically imposed, applying forces along of the restriction gradient. The contact force magnitude depends on the violation of this restraint. As an example, the magnitude of the contact reaction force is equal to the product of material stiffness and bodies' penetration, like a spring force. The disadvantage of the penalty rule, however, is that the software user is responsible for setting an appropriate penalty parameter, what means the stiffness of the materials. Besides that, a high value for the stiffness or for the penalty parameter can cause integration difficulties.

The contact restrictions used are as follow:

$g \geq 0$ – a positive value for g indicates that there is penetration of the bodies.

$F_n \geq 0$ – a positive value of the contact normal force represents a separation force between the bodies in contact.

$F_n * g = 0$ – requirement so that the contact normal force is different than zero only when the contact occurs.

$F_n * \frac{dg}{dt} = 0$ – the normal force is different than zero only when the separation rate of the bodies is zero.

This last restriction is important especially when the interest is on the conservation or dissipation of the energy.

The impact force model is obtained when the three first auxiliary conditions are replaced by the following expression, known as 'Hertz Law' (Hertz, 1896):

$$F_n = k * g^e \tag{3}$$

Where: k (stiffness) is a penalty scalar parameter, so that the penalty becomes exact when k approaches infinity.

To incorporate the materials constitutive relations, the software extends the previous expression with non-linear viscous damping terms that depend on displacement. The general form of the impact force becomes:

$$F_n = k * g^e + Step\left(g, 0, 0, d_{\max}, c_{\max}\right) * \frac{dg}{dt} \tag{4}$$

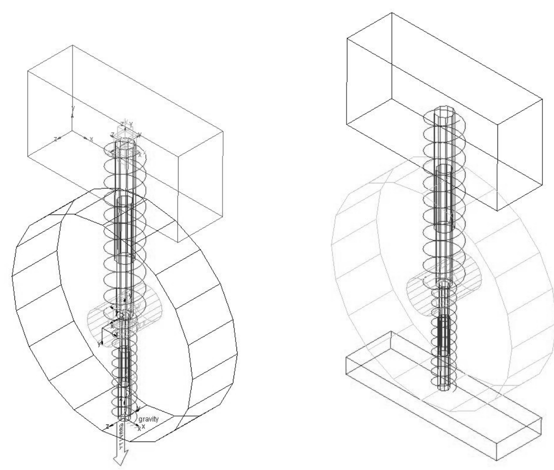
Where: *g* represents the penetration of one geometry into another, *dg/dt* is the penetration speed at the contact point, *e* is a positive real value that represents the force exponent, and *dmax* is a positive real value specifying the limit penetration in order to apply the maximum damping coefficient *cmax*.

To apply the software's contact resource (based on the impact function), it is necessary that the user sets the following parameters: stiffness, contact force exponent, damping and penetration depth.

3.2. Simplified Model

In order to evaluate the dynamic behavior of the contact function when representing the tire/pavement lifting, before going to the b-train complete model, it was decided to simulate a simplified model of the phenomenon (Fig. 5). This simplification represents one wheel of the vehicle only, with the sprung mass (all the components supported by the suspension), the unsprung mass (axle and associated components), the tire, the suspension and the pavement (Fig. 6).

The parameters used in this simulation were determined to reproduce the reality. They depend on the materials and the geometry of the contact region. In the literature, it was noticed a hard time in the acquisition of these values, such that some authors opted by experimental determination (Bartha, 2001).



(a) (b)

Figure 5. Simplified numerical models: (a) without contact; (b) with contact.

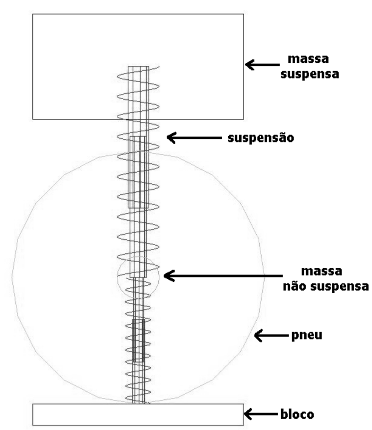


Figure 6. Representation of the mass-spring system used.

Since the objective here was to validate the use of contact to represent the tire lifting situation, in the first trials software recommended values were used, because they were not different in magnitude from the values found in literature (Alamo, 2006). The stiffness and damping of the tire and the suspension were given by the producers.

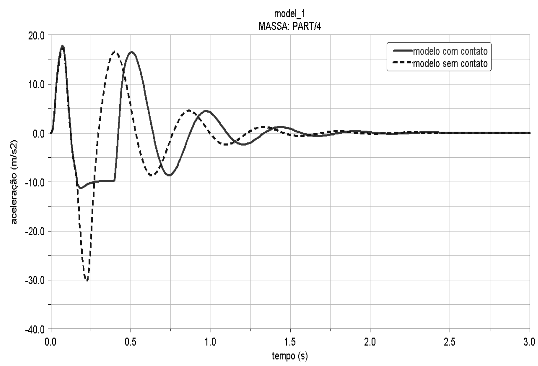
Table 1. Parameters values used in the simplified model simulation.

	Suspension	Tire	CONTACT
Stiffness (N/m)	2.0 E+6	4.0 E+6	1.0 E+10
Damping (N.s/m)	9.5 E+4	5600	1.0 E+8
Force exponent	---	---	2.2
Penetration depth (m)	---	---	1.0 E-5

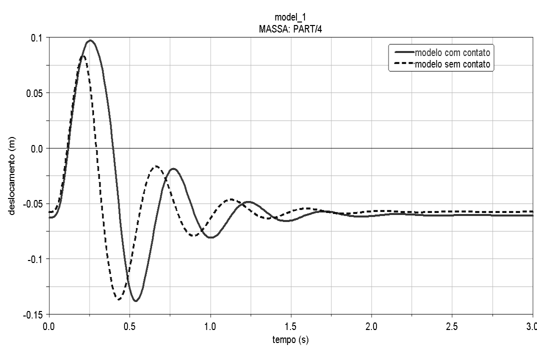
4. RESULTS

4.1 Simplified Model

For the simplified model of one isolated wheel, the following plots (Fig. 7) compare the models with and without contact. Figures 7a and 7b indicate the behavior of the sprung mass (acceleration x time and displacement x time, respectively), while the Figs. 7c and 7d represent the unsprung mass (acceleration x time and displacement x time, respectively).



(a)



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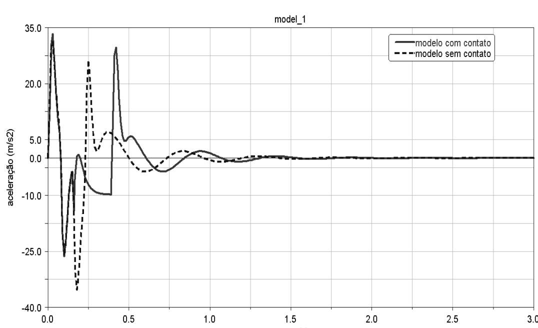
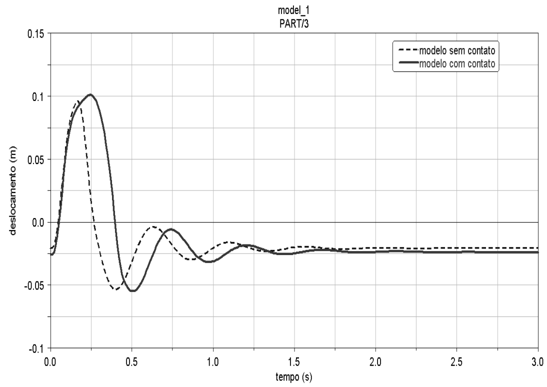


(c)



(d)

Figure 7. *Sprung mass*: (a) acceleration x time; (b) displacement x time.
Unsprung mass: (c) acceleration x time; (d) displacement x time.

It is interesting to notice the behavior of the bodies at the moment where their acceleration overcomes gravity (~ 9,81 m/s2). In the ‘acceleration x time’ plots (Figs. 7a and 7c), the phase delay is easily noticed when comparing the outputs with contact and without it. Also, in the ‘displacement x time’ comparisons (Figs. 7b e 7d), the parabolic profile becomes obvious in the movement of the bodies.

These results are indications that the numerical representation of the tire lifting was obtained. Therefore, during this time period (from 0.2s to 0.4s, approximately) the bodies behave like projectiles. After that, gravity is again higher than the bodies’ acceleration, so that the model output is back to the pattern that doesn’t use contact (one particular case of the present analysis)

4.2 Detailed Model

Relying on the simplified model results, the use of the contact function in the b-train complete model is validated. The stiffness and damping parameters are the same as the ones in the simplified model. The force exponent and the penetration depth (dependent on the contact materials and geometry) are determined by trials, representing reality as close as possible, since very few combinations of these factors allow the simulation to run completely. Figure 8 presents the new proposal for the numerical model, already with the suggested alterations.

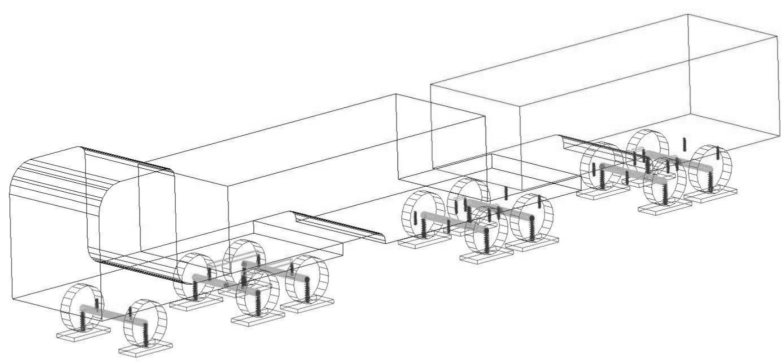


Figure 8. B-train complete numerical model with contact.

For point 4 (Fig. 9), Figures 10 and 13 plots present the comparisons between the experimental data, the numerical results without contact and the ones from the new model (that uses contact). This point suffers the biggest influence of the tire lifting, because it is located at the back portion of the second trailer. The behaviors for the velocities of 10, 15, 20 and 25 km/h are showed, for a loaded vehicle.

The top plots are from the accelerations in the time domain, while the inferior plots show the same comparisons in the frequency domain, with spectral density. In the time domain, the signals’ magnitudes are compared, and in the frequency domain, we look for the similarity of the signals.

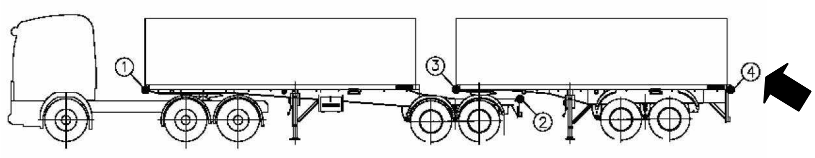


Figure 9. Location of the accelerometers in the real vehicle

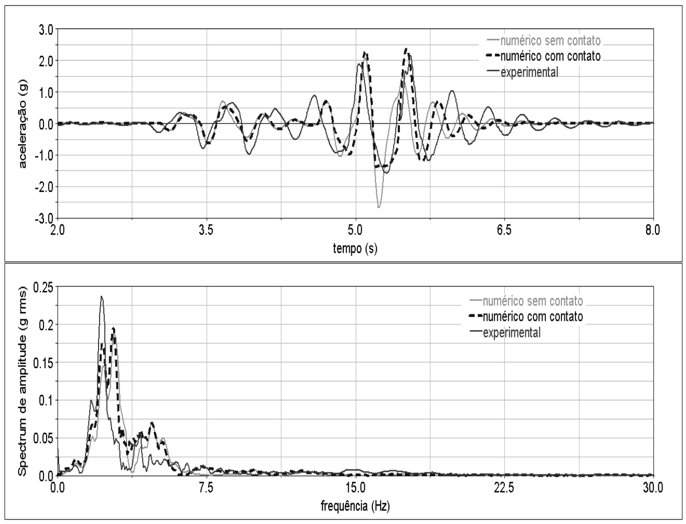


Figure 10. Comparison of the accelerations in the time domain (top) and in the frequency domain for the point 4, with a loaded vehicle at 10 km/h.

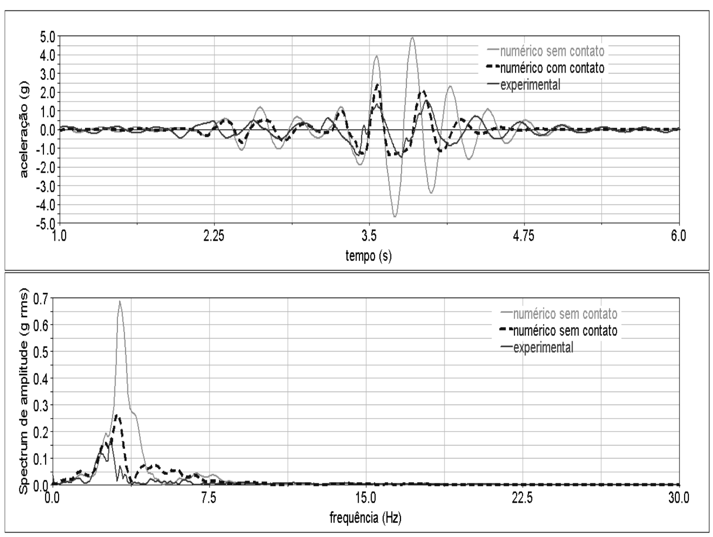


Figure 11. Comparison of the accelerations in the time domain (top) and in the frequency domain for the point 4, with a loaded vehicle at 15 km/h.

Comparing the accelerations in the time domain, significant improvements were obtained in the similarity of the numerical and experimental signals. Especially at the maximum peaks, where the axles next to the measured point where passing over the obstacle. In the rest of the signal, the model with tire lifting presented a result close to the 'old' model. This was expected, since the contact has its biggest effect in the moment where the tire lifting is imposed to the blocks.

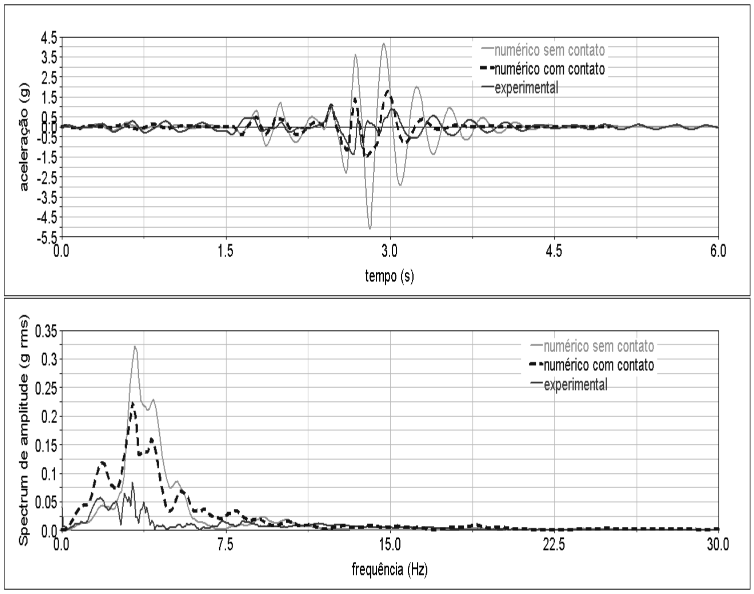


Figure 12. Comparison of the accelerations in the time domain (top) and in the frequency domain for the point 4, with a loaded vehicle at 20 km/h.

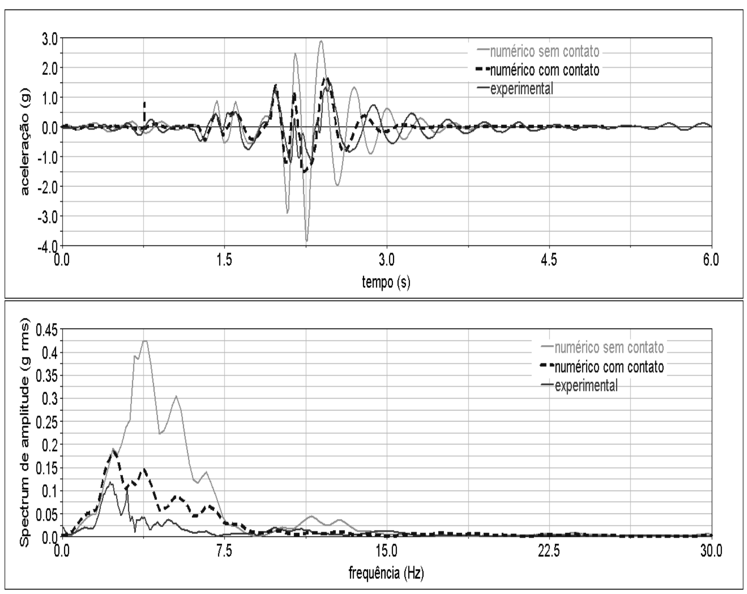


Figure 13. Comparison of the accelerations in the time domain (top) and in the frequency domain for the point 4, with a loaded vehicle at 25 km/h.

In the frequency domain, satisfying results were also reached, especially at the excitation peaks. These maximums, which were caused by the imposition of the movement profile to the numerical model, were strongly reduced in the excitation with contact.

Some simplifications used in the dynamic modeling, in the calibration of the modeled suspension (the condition of end of course - backstop) and in the acquisition of the b-train geometrical properties, are probable reasons for the small discrepancies we still see in the graphics.

Being the main objective of the simulation the ‘reproduction’ of the pavement excitations, the numerical model with contact was successful. The representation of the real vehicle behavior had its fidelity increased, when looking at the vertical dynamics. Therefore, the use of contact is recommended to obtain the structure loadings.

5. ACKNOWLEDGEMENTS

To the initial challenge of improving the reliability of the numerical model, which was developed for a b-train's traffic simulation, a successful solution was presented. Besides the absence of specific literature about the tire lifting effect, which could help the theoretical founding and be useful as source for other options of resolution for this problem, and the obvious difficulties of representing a complex physical phenomenon in the numerical environment, the application of contact resulted in some very interesting outputs.

According to the comparisons, either in the simplified or in the complete model, in the time or in the frequency domains, contact was presented as an excellent option to represent situations that deal with rigid bodies' interaction. A sensible improvement in the fidelity of the real phenomenon numerical representation was obtained, using a highly non-linear resource and still not much used in real cases (contact function).

The agreement of the results reached with the tire lifting inclusion, added to the numerical model calibration, founds the use of the new model to obtain the vertical dynamic loadings of future traffic simulations. This would make the analysis of accelerations/forces more quantitative and less qualitative for higher velocities. Even more important, a following fatigue analysis would have more benefits from the new model results, since the frequencies and amplitudes of the stress history would be more faithfully represented.

For the continuation or development of new researches related to the subject of this work, the following topics are recommended:

- optimizing the values of the contact parameters in the numerical model, approaching an even higher approximation with experimental data.
- adjusting the numerical model with tire lifting developed in this work to include the lateral dynamics provoked by road profiles with lateral phase difference.
- adapting the methodology for other types of vehicles.
- a theoretical formulation of the contact function, with more degrees-of-freedom, can be applied for this tire lifting situation.

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