Development of Computational Models of Roller Coaster Vehicles and Occupants for Injury Analysis

Extended Abstract

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Abstract

A roller coaster ride consists of a vehicle negotiating a track characterized by a sequence of curves with different spatial geometries. During the track negotiation, the vehicle occupants are subjected to accelerations that depend on the car speed variation which in turn are related to the instantaneous curvature of the track. These accelerations provide excitement to the occupants with a minimum risk of injury. The design of the roller coaster geometry requires reliable computational tools to simulate the roller coaster rides. An important ingredient for the realistic representation of the conditions of the occupant is the modelling of the vehicle-track interaction. This thesis, proposes an approach to model the car-track interaction, with the implementation of two new path motion constraints, allowing for the prescription of the path of each wheelset along the track rails. The rail geometries are generated based on the roller coaster geometry. Together with the multibody models that represent the roller coaster vehicle, a biomechanical model to represent the roller coaster passenger is also developed and implemented. In this work, two roller coasters models are analysed to demonstrate the procedures. The risk of injury of the occupant is analysed by relating the biomechanical model dynamic responses with the applicable injury criteria. For this purpose, a post-processor is implemented to evaluate the g-forces acting on the passenger and verify if they are within the human tolerance thresholds. Also regular injury criteria such as the HIC and the Result Head Acceleration (3ms) are evaluate and checked if they are within safe thresholds. The computational tools developed in this work are then used to analyse the risk of injury of an occupant in two different roller coasters, corresponding to an existing commercial roller coaster and to a new design not installed yet.

Keywords

Roller Coaster, Multibody Dynamics, Path Motion Constraint, Biomechanical Model, Injury Criteria

1 Introduction

Roller coaster/amusement parks are popular worldwide. The roller coaster rides attract and entertain a substantial numbers of visitors to these parks. Some guests particularly enjoy rides in vehicle traveling along a track, such as roller coasters, in which, one or more vehicles run along a complex track geometry.

Injuries of occupants in roller coaster rides are periodically reported for normal operation conditions. Contrary to common individuals that have occasional rides in fighter jets, roller coaster riders are not screened beforehand to ensure that they can withstand high g-forces nor they are trained to endure them. Amidst controversy in which evidence of fatal or serious injury in roller coasters [1] is opposed by data showing that high g-force roller coasters still lead to head accelerations far below the minimum thresholds [2, 3].

Roller coasters seem to be relatively simple mechanical systems when compared to modern railways or cars, but due to high nonlinearity their kinematics, standard design techniques for dynamic systems have limitations. Moreover, since most of the roller coasters represent unique designs, extensive testing and design of real world prototypes is not possible from an economical point of view. To avoid expensive testing before the final installation of the roller coaster track, reliable computer aided design tools are required. In order to support the engineering design of safe roller coaster rides this work presents the development of a computational tool for the dynamic analysis of roller coasters with the ability to evaluate the biomechanical injury thresholds [4-7] including those associated to g-forces.

The development proposed in this work address; the design, for creating a geometric model of the track and vehicle; and the simulation, for evaluating the system behaviour in general, and the occupant in particular.

In order to understand the behaviour of the roller coaster using numerical simulations, a detailed model of the roller coaster is required. The design of the system requires the knowledge of the human tolerances to injury [4-7]. In a way, the roller coaster cannot be boring, it must exciting and stimulating, but on the other hand, the roller coaster passenger should not be injured by riding it. The physiological excitement of the passenger is achieved through the roller coaster track, which assures the human body is subjected to accelerations in different directions, within the human tolerance thresholds [4, 5], but not any further.

The objectives of this work are the development of a proper roller coaster vehicle for use in roller coaster simulations, in the multibody dynamic analysis program DAP-3D and the development of a biomechanical model to evaluate the risk of injuries in different roller coasters.

2 Roller Coaster Dynamics

Due to the application requirements of this work, a roller coaster model, the trajectory of the wheelsets is based on the general spatial curve kinematic constraint, developed by Pombo [8]. However, to avoid over constrained wheels, a new path motion constraints is here developed. The original motion constraint forces a body to follow a given trajectory and to rotate with respect to a Frenet moving frame. The new kinematic constraint, the Prescribed Point Constraint, frees all rotations maintaining only the prescribed translation. The basis of the vehicle-track interaction in the roller coaster multibody system is the prescribed point motion joint. This approach is implemented in the computer program DAP-3D[9].

Let a curve be described using an n^{th} order spline segments, interpolating a set of control points, be defined as [10]:

$$\mathbf{g}(u) = \begin{Bmatrix} x(u) \\ y(u) \\ z(u) \end{Bmatrix} = a_0 + a_1 u + a_2 u^2 + a_3 u^3 + \ldots + a_n u^n \tag{2.1}$$

where $\mathbf{g}(u)$ is the vector locating a point on the curve, u is the local parametric variable and a_i are unknown algebraic coefficients that must be calculated using points with known coordinates. Although Eq. (2.16) is generic for any polynomial interpolation, in this work only cubic polynomials are considered.

2.1 Prescribed Point Constraint

The curve parameter u does not ensure that the polynomial exhibits a constant velocity. For the implementation of the prescribed point constraint, it is required that the piecewise polynomial parameter u is replaced by a curve arc-length parameter L with respect to which the interpolating polynomial has a constant velocity. Consider the parametric variable u^P, corresponding to a point P, located on the k^{th} polynomial segment to which a curve length L_k^P measured from the k^{th} segment origin is associated. The parameter u^P is obtained by [8]:

$$\int_0^{u^P} \sqrt{g_k^{u^T} g_k^u}\, du - L_k^P = 0 \tag{2.2}$$

In terms of its computer implementation, the non-linear equation (2.4) is solved in the program pre-processor, using Newton-Raphson method [9]. The prescribed point constraint is proposed to be used here as the basis for the definition of the vehicle-track interaction in the roller coaster multibody system. The wheelsets of the vehicle model move along the rails of the track and the kinematic constraint enforces each one of them to follow a given roller coaster rail. The wheel-rail contact forces of the roller coaster vehicle are not explicitly used during the dynamic analysis. It is considered that the wheelsets of the roller coaster cars are permanently in contact with the rails and follow exactly the track geometry, according with the restrictions imposed by the prescribed point constraint.

The objective of the prescribed point constraint is to define equations that enforce a certain point, of a rigid body to follow a reference path. Consider a point P, located on rigid body i, that is constrained to follow a specified path, as depicted in Figure 2.1. The path is defined by a parametric curve $\mathbf{g}(L)$, which is controlled by a global parameter L that represent the length travelled by the point along the curve from the origin to the current location of point P. The constraint equations that enforce point P to follow the reference path $\mathbf{g}(L)$ are written as [9]:

$$\mathbf{\Phi}^{(\text{pmc},3)} \equiv \mathbf{r}_i^P - \mathbf{g}(L) = \mathbf{0} \tag{2.3}$$

where $\mathbf{r}_i^P$ represents the coordinates of point P with respect to the global coordinate system (x, y, z), depicted in Figure 2.1.

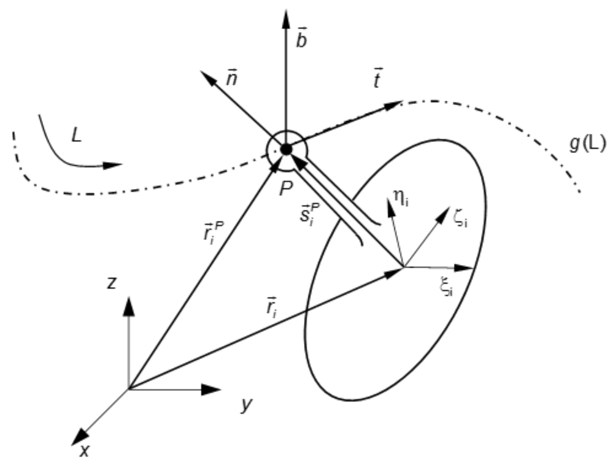

Figure 2.1: Prescribed Point Constraint

2.2 Track Geometry

The track geometry is part of the input information in the simulations performed in this work. It is composed by two rails, which can be viewed as two side-by-side defined in a plane that sits in the track centreline spatial curve, also called as the reference path. The two rails are independent, right and left, being discretised by independent sets of nodal points. The position of each point is defined by vector $\mathbf{r}$, being its coordinates measured with respect to the global reference frame (x, y, z), and its orientation defined by the tangent, $\mathbf{t}$, normal, $\mathbf{n}$, and binormal, $\mathbf{b}$, vectors. The three orientation vectors compose an orthogonal referential attached on the nodal points in which the rail profile is defined.

To achieve the proper parameterization, it is necessary to use an appropriate modelling approach. A pre-processor, similar to that one implemented by Pombo [11], is used to define the curve parameterization. As input data to each track, it is necessary to consider the three coordinates (x, y, z), the normal and binormal vectors, $\mathbf{n}$ and $\mathbf{b}$, respectively, in each nodal point of the track centreline. These points are used in the interpolation procedure of the centreline, using cubic splines, being their spacing defined by the user taking into account for the accuracy required for the geometric description of the tracks. The pre-processor evaluates the position of each rail and the orientation of its Frenet Frame using the track centreline, based on the gauge defined by D, that corresponds to the distance between the centres of the left and right rails.

After the roller coaster track database is built, the track model is completely defined. This is used in the multibody model of the track to roller coaster vehicle interaction during the dynamic analysis of the whole system. A three dimensional representation of two complete roller coaster tracks is displayed in Figure 2.2. It is depicted the track centreline with respective representation of the unitary vectors **n** and **b** to allow better visualization of the track torsion and of its smoothness. Figure 2.3 presents zooms of two selected sections of the tracks to show how the visualizations are used for visual inspection.

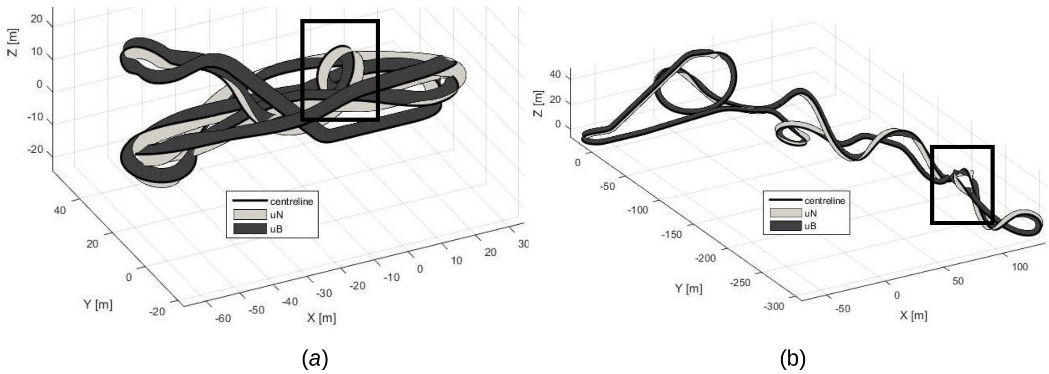

Figure 2.2: Three-dimensional representation of the track centreline and a sweep of the unitary normal and binormal vector. (a) Looping Star (b) Gate Keeper

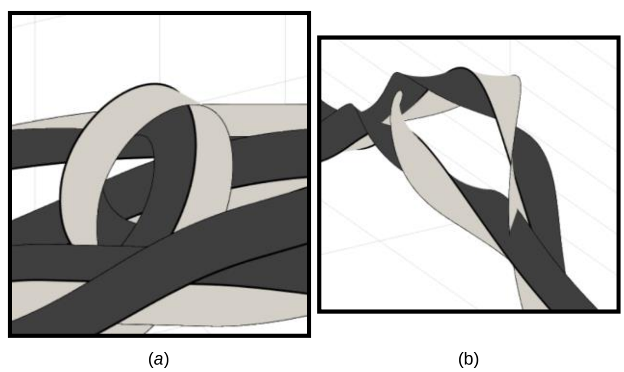

Figure 2.3: Zoom on selected sections of the roller coaster tracks: (a) Loop in Looping Star; (b) Screw in Gate Keeper.

2.3 Vehicle Model Development

A three dimensional model of the roller coaster vehicle is developed and presented. It must be noted that not only the vehicle does not exist but also it is not intended to represent any existing roller coaster vehicle. In a roller coaster track, not always it is possible to ensure that four points seat in the same plane, so, in order for the four wheelsets to follow their respective rails path, it is necessary an hinge mechanism, intra-vehicle, that allows a relative rotation between the front and the rear vehicle wheelsets. The solution for fitting the wheelsets on the track, i.e, on the rails, is achieved by a revolute joint between the rear axle and the frame of the vehicle, depicted in Figure 2.4, which allows that these two bodies rotate relatively to each other. So there is only one relative degree of freedom between the front and rear of the vehicle, allowing the vehicle wheelsets to seat in different tangent planes, which is what is necessary for the vehicle describe a curve without either the wheelsets to be out of contact with the rail or the vehicle structure to have to widstand torsion deformations.

The wheelsets are modelled as prescribed point constraints that force the reference local frames origins, of each one of the wheelsets, to coincide with the rail path. When there are four points to be prescribed along a roller coaster track, it is necessary to have three relative degrees of freedom between the wheelsets and the rails, allowing the three relative rotations. It is not only necessary to allow the three relative rotations between the vehicle and the rails, so that the vehicle follow the curve without bending, but also to allow for the wheelsets in the same axis to separate or to come closer to allow a proper insertion on the curve.

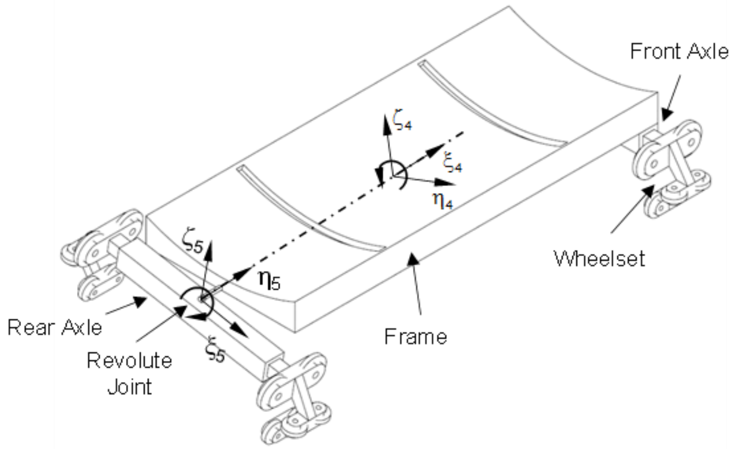

Figure 2.4: Primary Suspension System: Perspective

The solution is to allow the separation between the wheelsets of the same axis, as seen in Figure 2.5, so that the vehicle not only is able to follow the track without locking but also is not prevented from running due to geometric defects of the track. This same mechanism also allows for the wheelsets to overcome eventual track imperfections that can be reflected in gauge variations.

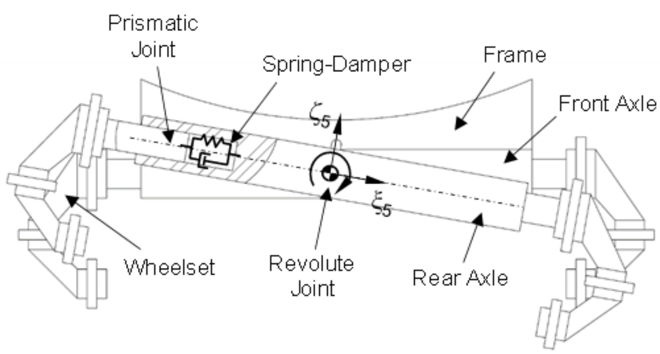

Figure 2.5: Primary Suspension System: Back View

A vehicle moving along a circular curve is subjected to an inertial centrifugal acceleration, which is perceived by the passenger as lateral acceleration. This lateral acceleration is not only felt by the passengers as an uncomfortable sensation, but it presents some level of physiological danger for the roller coaster user that, if not kept inside healthy limits eventually leading to the need to stop the roller coaster operations. The secondary suspension mechanism or passive tilting mechanism, has the objective of reducing the uncomfortable sensation, or even motion sickness, that can occurs to a passenger when the roller coaster vehicle is moving along a circular curve. The parameter used to assess the level of discomfort of the passengers is the non-compensated lateral acceleration, NCA [12]. The NCA is defined by a relation between the centrifugal and gravitational accelerations applied on the carbody in its local lateral direction. The NCA, depicted in Figure 2.6, is obtained by:

$$NCA = a_c \cos(\varphi + \theta) - g \sin(\varphi + \theta) = a_{\varphi+\theta} - a_{\mathbf{g}} \tag{2.4}$$

where $a_{\varphi+\theta}$ is the local lateral acceleration of the carbody due to the centrifugal acceleration a_c, φ is the torsion angle, θ is the roll angle between the carbody and the chassis, due to the passive tilting mechanism, as depicted in Figure 2.6 and g is the gravitational acceleration.

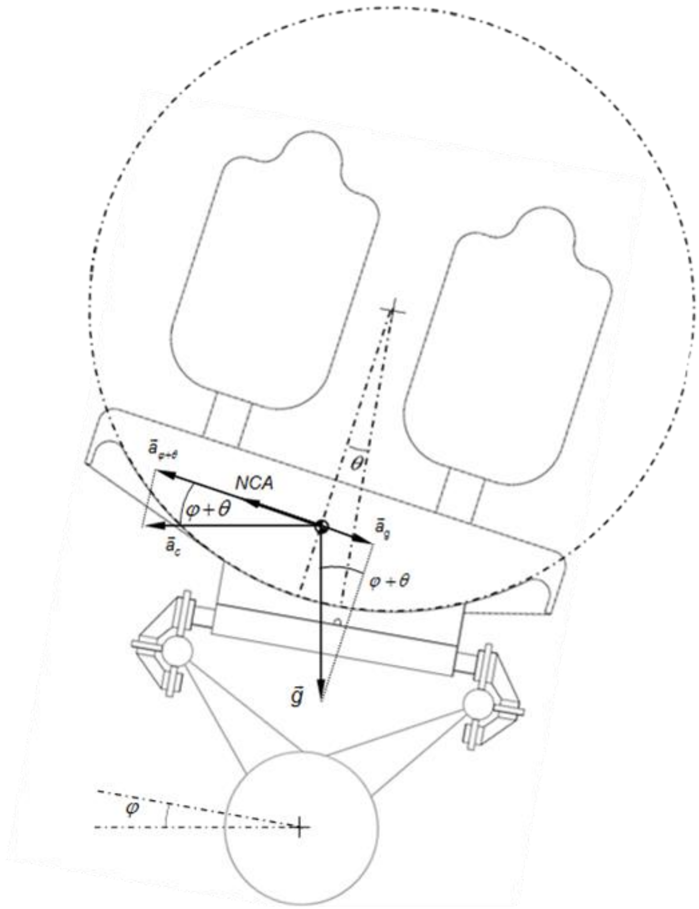

Figure 2.6: Graphical scheme to show the non-compensated acceleration (NCA)

The vehicle is set in such a way that the wheelsets reference local frames are coincident with the path that each rail describes, so, the reference local frame origin of each wheelset is the point to be prescribed. In the prescribed constraint, this point is the basis for the definition of the vehicle-track interaction. The prescribed point constraint enforces this point, the wheelset reference local frame origin, to move along the rail path, therefore, there are four prescribed point constraints, each one applied to a wheelset. It is considered that the wheelsets of the roller coaster vehicle are permanently in rigid contact with the rails and follow exactly the track geometry, according with the restrictions imposed by the prescribed point constraint. The wheel-rail contact forces are related to the Lagrange multipliers associated to the prescribed point constraint and are obtained by post-processing the dynamic analysis response of the vehicle.

A local reference frame (ξ,η,ζ) is rigidly attached to the centre of mass (CM) of each body. The spatial orientations of the local reference frames are such that they are aligned with the principal inertia directions of the respective rigid body. The mass and the inertia properties, with respect to the three principal local axes, of each body are Table 2.1. The geometric representation of each body and of its body fixed frames is shown in

Figure 2.7. In this figure, it is not possible to see the wheelset that correspond to the body number 7, in Table 2.1, since it is covered by the carbody.

ID	Rigid Bodies	Mass	Inertia Properties $(Kg.m^2)$		
		(Kg)	$I_{\xi\xi}$	$I_{\eta\eta}$	$I_{\zeta\zeta}$
1	Wheelset Front Left	10.1	0.14115	0.13446	0.93322
2	Wheelset Front Right	10.1	0.14115	0.13446	0.93322
3	Front Axle	51.5	0.097884	2.3432	2.34232
4	Frame	245	13.0706	77.8762	90.9305
5	Rear Axle	51.5	0.097884	2.3432	2.34232
6	Wheelset Rear Left	10.1	0.14115	0.13446	0.93322
7	Wheelset Rear Right	10.1	0.14115	0.13446	0.93322
8	Carbody	280	30.7503	127.8009	145.6759

Table 2.1: Physical properties of each body

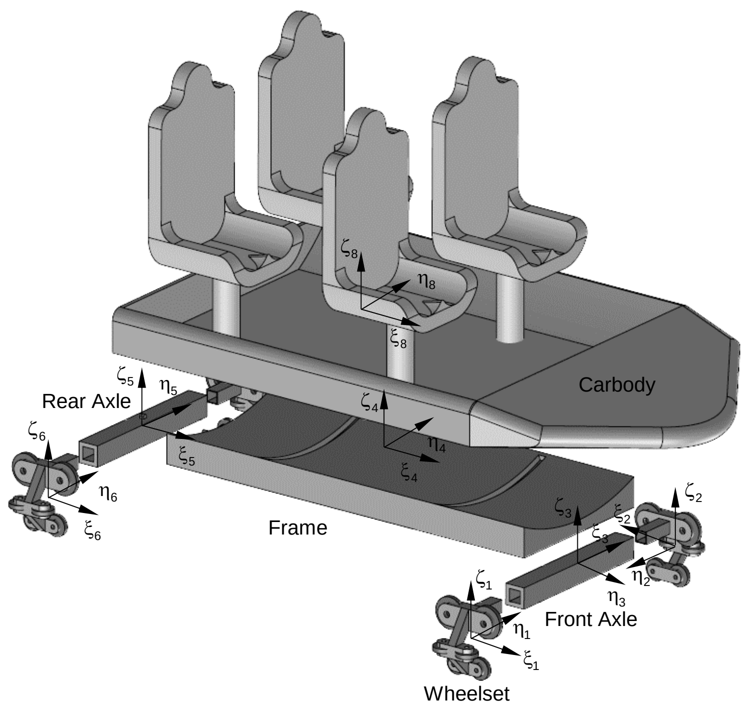

Figure 2.7: Geometric representation of body fixed frame for each individual body in the vehicle

The initial positions, orientations and velocities of each body are presented in Table 2.2. The initial position of each rigid body is given by the location of its body fixed frame origin, coincident with its centre of mass, with respect to the global reference frame (x, y, z). Note that the initial velocity of 26 m/s is used to take the vehicle to the top of the highest point of the roller coaster track, so that if reaches such point at an almost null velocity. In reality, such guidance is achieved with other type of control, not modelled in this work.

In the roller coaster vehicle model, four prescribed point constraints are used to guide each wheelset on a rail path. These kinematic constraints are defined between the vehicle wheelsets and the rails centerlines, in order to enforce the wheelsets to move along the roller coaster, with their spatial position prescribed according to the track geometry.

ID	Initial Position (m)			Orientation			Velocity (m/s)		
	x_0	y_0	z_0	e_1	e_2	e_3	v_{x_0}	v_{y_0}	v_{z_0}
1	-2.1	0.5	0	0	*0*	*1*	-26	0	0
2	-2.1	-0.5	0	0	*0*	*0*	-26	0	0
3	-2.1	0	0.125	0	0	-0.7071	-26	0	0
4	-1.1	0	0.185	0	0	1	-26	0	0
5	-0.1	0	0.125	0	0	-0.7071	-26	0	0
6	-0.1	0.5	0	0	0	1	-26	0	0
7	-0.1	-0.5	0	0	0	0	-26	0	0
8	-1.175	0	0.48	0	0	1	-26	0	0

Table 2.2: Initial positions, orientations and velocities

The remaining kinematic constraints are used to assemble the roller coaster vehicle model, all kinematic constraint data is presented in Table 2.3, which includes the number of the bodies connected and the local coordinates of the attached points.

ID	Kinematic Constraint	Bodies		Attachment Points Local Coordinates (m)			
		i	j	$s_P^{'i}$	$s_Q^{'i}$	$s_P^{'j}$	$s_Q^{'j}$
1	Prescribed Point	1	Rail	[0;0;0]	-	-	-
2	Prescribed Point	2	Rail	[0;0;0]	-	-	-
3	Prescribed Point	6	Rail	[0;0;0]	-	-	-
4	Prescribed Point	7	Rail	[0;0;0]	-	-	-
5	Prismatic	3	1	[0.1;0;0]	[0.2;0;0]	[0;0.1;0.125]	[0;0.2;0.125]
6	Prismatic	3	2	[-0.1;0;0]	[-0.2;0;0]	[0;0.1;0.125]	[0;0.2;0.125]
7	Prismatic	5	6	[-0.1;0;0]	[-0.2;0;0]	[0;0.1;0.125]	[0;0.2;0.125]
8	Prismatic	5	7	[0.1;0;0]	[0.2;0;0]	[0;0.1;0.125]	[0;0.2;0.125]
9	Revolute	4	5	[-1;0;0]	[-1.1;0;0]	[0;0;0.06]	[0;0.1;0.06]
10	Revolute	4	8	[1.05;0;1.05]	[1.075;0;1.05]	[0.975;0;0.755]	[0.95;0;0.755]
11	Rigid	3	4	[0;0;0]	-	[0;0;0]	-

Table 2.3: Kinematic Joints

The flexible links, or force elements, correspond to spring-damper systems, and all their characteristics, bodies connected and local coordinates of the attachment points are presented in Table 2.4.

ID	$K\ (N/m)$	$c\ (N.s/m)$	l_0 (m)	Bodies		Attachment Points Local Coordinates (m)	
				i	j	$s_P^{'i}$	$s_P^{'j}$
1	8×10^5	4×10^4	0.1	3	1	[0.2;0;0]	[0;0.2;0]
2	8×10^5	4×10^4	0.1	3	2	[-0.2;0;0]	[0;0.2;0]
3	8×10^5	4×10^4	0.1	5	6	[-0.2;0;0]	[0;0.2;0]
4	8×10^5	4×10^4	0.1	5	7	[0.2;0;0]	[0;0.2;0]
5	2×10^4	1×10^3	0.7577	3	1	[-0.9;0.35;0]	[-0.975;-0.35;0.00505]
6	2×10^4	1×10^3	0.7577	3	2	[-0.9;-0.35;0]	[-0.975;-0.35;-0.00505]

Table 2.4: Characteristics of the spring-damper systems

3 Biomechanical Model and Injury Criteria

The anthropometric model is considered to be a representation of the static body geometry, in which relevant dimensions and physical properties are described [13]. These relevant dimensions and physical properties include, among others, the body size, shape and proportion as well as the mass, inertia and centres of mass location of its principal anatomical segments [14]. The anthropometric model used here is based on the one presented in the computer simulation code SOMLA [15], regarding the uniform mass distribution and body size of the 50th percentile dummy. The model considers the human body divided in sixteen anatomical segments.

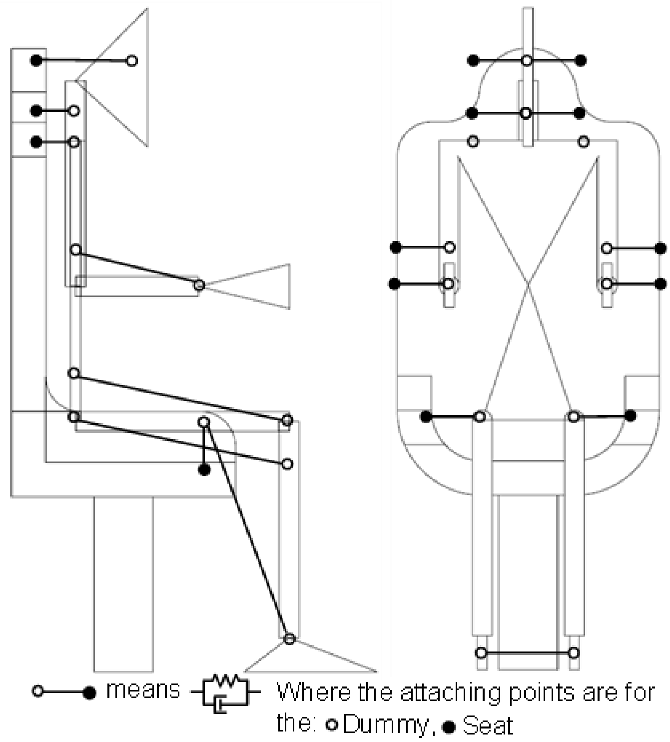

Figure 3.1: Biomechanical model seated

The objective here is to maintain the biomechanical model seated and slightly stuck to the seat, only allowing small movements, as for a roller coaster vehicle occupant that is restrained to the seat. The objective is to represent the natural resistance of the relative motion between anatomical segments as an occupant of a roller coaster, by using spring-damper restraints, as shown in Figure 3.1. It is assumed that for the passenger safety system there are shoulder restraints applied. To represent such restrictions, the lower torso is fixed to the seat by a kinematic rigid joint. The other links between the biomechanical model and the seat are all simulated by spring-damper systems. Spring-damper systems also represent the passive resistance of the biomechanical joints due stiffening that results from muscles resistance, because of muscle bracing.

The understanding of the injury mechanisms is of great importance for passive safety improvement. The existence of some injury scales such as AIS (Abbreviated Injury Scale) [16], together with loading conditions during this external actions are important qualification that the result from medical observation of real life injuries that complement the injury criteria classification and fill the information bridge between engineers and medical doctors. As the human body tolerance to g-forces varies with direction, magnitude and time durations, Figure 3.2 (a) depicts the limits of human tolerance for almost every directions for different time intervals and durations. In Figure 3.2 (b), it can be understood the nomenclature used in the accelerations components. The injury criteria implemented in this work are:

- Head Injury Criterion (HIC);
- Result Head Acceleration (3ms);
- G-force induced loss of consciousness (GLOC).

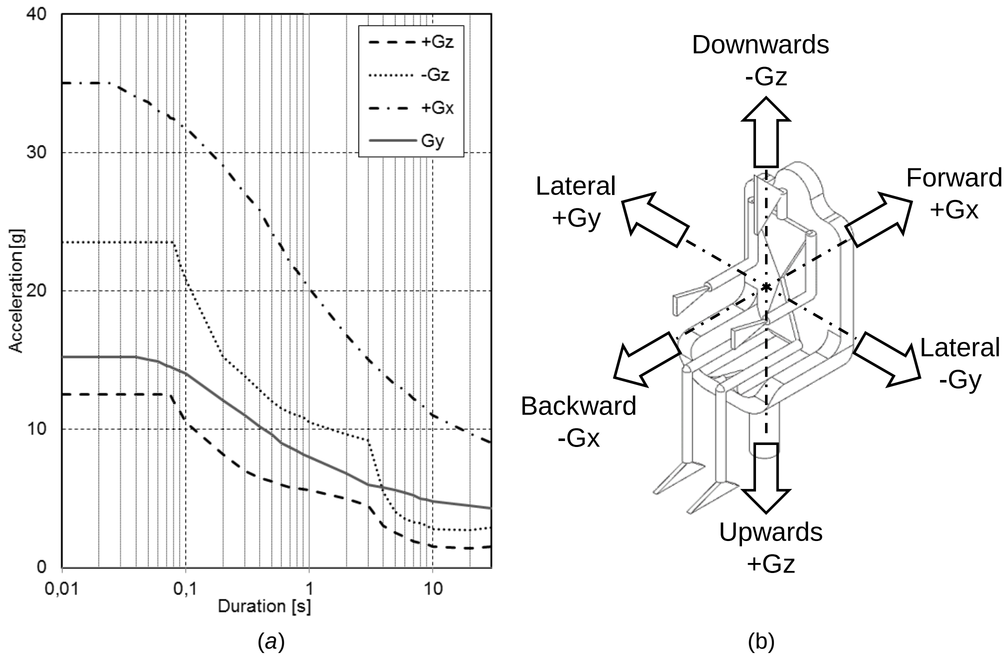

Figure 3.2: (a) Thresholds of human tolerance to g-forces, with respect to duration [4, 5]; (b) Nomenclature for acceleration components.

4 Application the Analysis of Roller Coaster Rides

The tracks geometry are obtain in the site https://nolimits-exchange.com/, which is a forum to exchange roller coaster tracks with the purpose to be used in the roller coaster game simulator *No Limits 2 – Roller Coaster Simulation.*

The comparison between the human tolerance to g-forces in forward +Gx direction and the magnitudes of g-forces measured for several time durations on the roller coaster passenger can be seen in Figure 4.1. It can be seen that the g-forces acting on the passenger in the forward +Gx direction are far below the tolerance to this direction, thus suggesting a safe ride.

In the lateral Gy g-force graph, presented in Figure 4.1, it can be seen that for the time duration $\Delta t = 0.01s$, the g-force acting on the roller coaster passenger is the highest. This probably happens due the peaks of accelerations, which has a value of acceleration way above the rest. For the complete time durations, the g-forces measured present healthy values, below the human tolerance. These results suggest that the geometry of the track about the point at which the response is closer to the threshold can be revised for a safer ride.

In the upwards and downwards g-force directions, Figure 4.1, there are no values above the human tolerance. In the upwards +Gz direction there two values of g-force that approach more the limit, in the first two time intervals measured. The downwards –Gz direction the tolerance, the time intervals presents a good response, with results below the human tolerance. As can be seen in the graphs from Figure 4.1, the values of g-forces never exceed the human tolerance, which suggests that there is no G-force induced loss of consciousness (GLOC), or blackout, caused by the vertical direction g-forces.

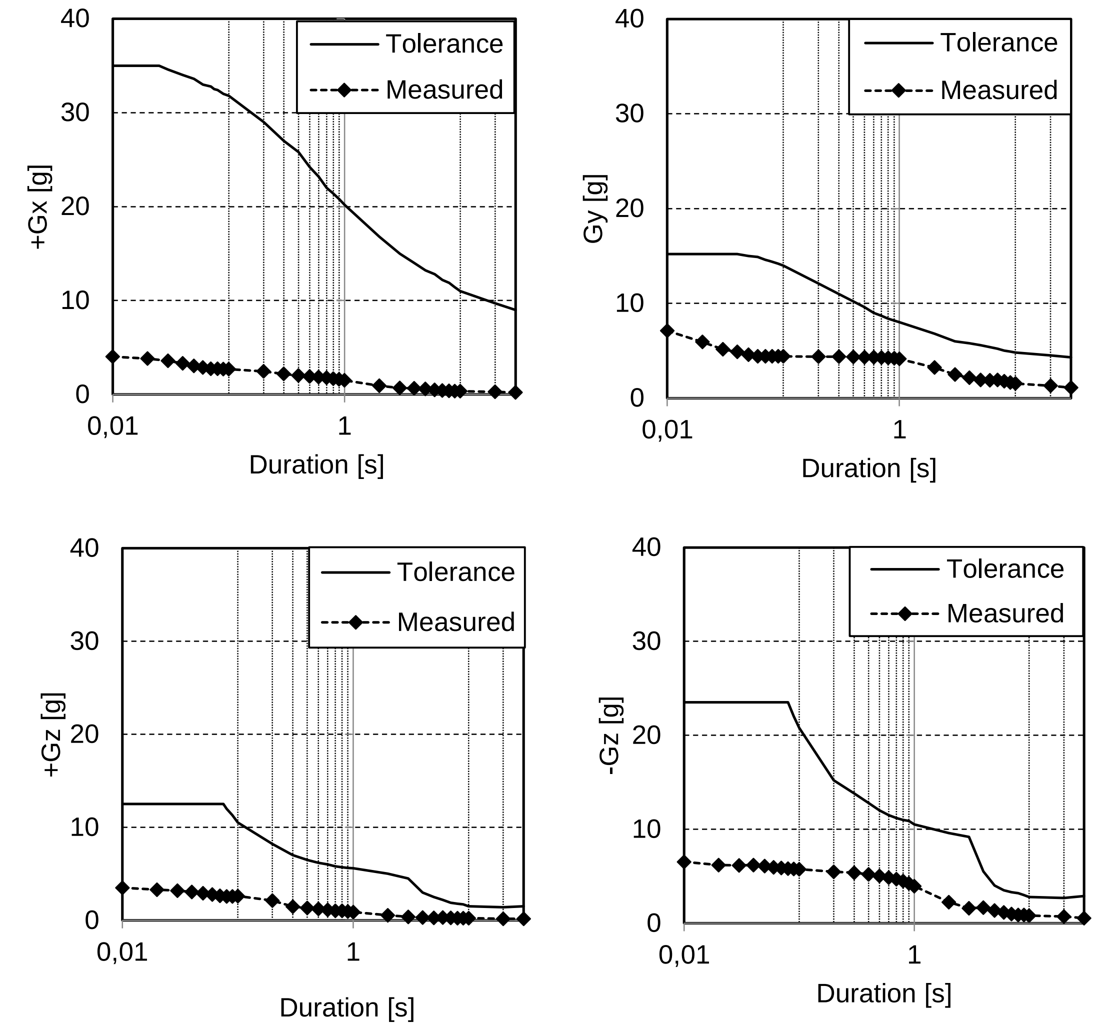

Figure 4.1: G-force acting on passenger for the Looping Star

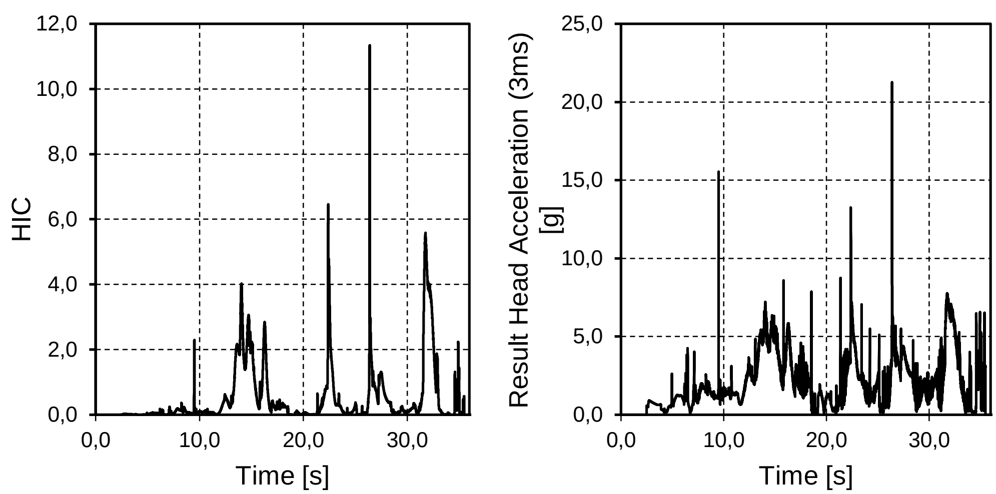

Figure 4.2: HIC and Result Head Acceleration (3ms) for the Looping Star

The human response to accelerations is also evaluated using the Head Injury Criteria (HIC) and the Result Head Acceleration (3ms). In Figure 4.2, it can be seen the evolution of the HIC over time, during the roller coaster simulation, which produces a maximum value of 11.34. The maximum value appears around the 26 s, and it is far from being a concern, according to the AIS code.

For the Head Acceleration, shown in Figure 4.2, the same behavior is observed as the maximum value is clearly below the 80g threshold. The maximum acceleration measured in a time interval of 3 ms is 21.27g, also around the 26s. In any case, the peaks observed for the head acceleration criteria provide indications on which region of the roller coaster track can be improved for human protection against its exposure to harmful accelerations.

5 Conclusion and Future Work

A roller coaster vehicle model based on a multibody methodology was developed. The multibody model uses a new prescribed path kinematic constraint, developed in this work, necessary to improve the roller coaster analysis. The vehicle model developed has four wheelsets being prescribed independently around the roller coaster track, and it is able to control track misalignments, to ensure the fit of the wheelsets in the rails, to allow separation between wheelsets and to compensate track irregularities or gauge variations. It was also implemented a passive tilting mechanism, in order to compensate the effects of lateral accelerations, felt by the passengers as an uncomfortable sensation. A biomechanical model of the roller coaster passenger is restrained to the seat, in order to represent the natural resistance of a roller coaster occupant, and to obtain reliable measures of the human exposure to roller coaster induced g-forces.

Two different roller coaster tracks were analysed, and both present g-forces far below the human tolerance thresholds. The injury criterions analysed are also extremely low, proving that roller coaster riding is associated with a very low injury risk, and resulting head motion fall within the range of normal activities and far below human tolerance thresholds for normal individuals.

The objective of this work was to present a tool to be used to assess potential injury risks by riding roller coasters. So, this work was not focused in the precise modelling of any existing roller coaster. The source of the roller coaster track geometries used is not the most reliable, so, obtaining reliable and accurate track geometries or even a tool to build them can be a future development

It is necessary time to tune and calibrate the suspension systems of the roller coaster vehicle and to make it adjusted to the roller coaster track. By using optimization tools the best characteristics for the springs and dampers of the suspension systems, for each particular roller coaster track can be identified, thus leading to better rides.

The method to restrain the biomechanical model of the roller coaster passenger implemented here lack the physical significance associated to the roller coaster vehicle restraints and human muscle bracing. It is necessary to develop a model of contact between the biomechanical model and the seat, and to develop realistic models for the vehicle over the head restraints. Also the use of different percentile dummies, in different positions of the vehicle are required to represent the diversity of the roller coaster users. The simulations presented in this work, only involved one biomechanical model and one vehicle, which is not what happens in reality. So, it is also important to develop the analysis with a train of roller coaster vehicles, linked between them, having several of its seats occupied by diverse biomechanical models.

In this work, it was used a kinematic constraint to simulate the interaction between the wheels and the track. In order to perceive track irregularities and induced vibrations, a model of contact between the wheels and the rails can be devised. Such model would allow considering conditions as the wear of the wheels and rails, or even flexible tracks.

With these and other approaches, this work proves to have the necessary tools for model validation, to assess several types of injury in the human body. With access to experimental data, this task must be accomplished by comparing the computational response of the roller coaster models to the experimental measurements of real roller coasters. Not being complete, from this point of view this work provides all the basic tools for a comprehensive analysis of roller coaster rides.

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