Multibody dynamic modelling and analysis of roller coaster vehicles

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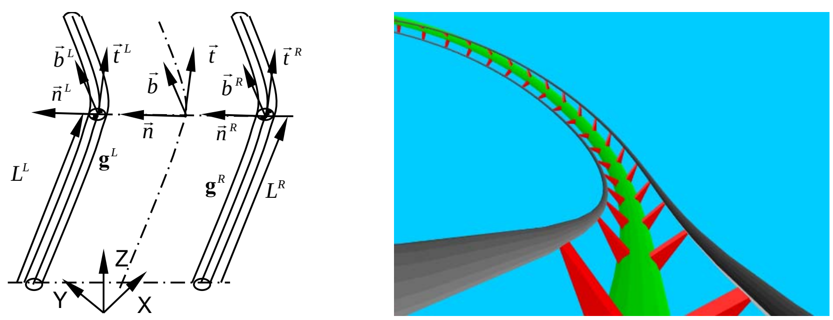
A roller coaster ride consists on a vehicle negotiating a track with a spatial geometry. During the ride, vehicle occupants withstand accelerations due to the car speed variation and track negotiation. The accelerations experienced by the human body must provide excitement without injury risks. The ingredients to model and perform the dynamic analysis of the roller coasters include the track geometry, vehicle-track interaction and vehicle suspensions. In this work a new path motion constraint is proposed to prescribe the motion of each wheelset of a vehicle along the rails, generated based on the roller coaster geometry. A multibody model to represent the roller coaster vehicle is developed together with a biomechanical model for the passenger. Finally, a realistic roller coaster is analyzed and a discussion on its dynamics and on passenger exposure to injury presented.

The most distinctive feature of a roller coaster is its spatial track composed of straight segments, loops or screw torsions, as that depicted in Fig. 1(b). The description of the track geometry is based on the definition of a spatial curve obtained by polynomial interpolation of a collection of nodes along the track centerline using the procedure proposed Pombo and Ambrosio [1]. The rail geometry is defined by sweeping two points in the osculating plane, separated by the track gauge, along the vector **n**, as in Fig. 1(a). By moving the Frenet frame along the curve the two points sweep two 'parallel' curves that are the centerlines of the rails. A new frame is associated to each of the rails centerline to define the rail cross-section geometry. The procedure is similar to that proposed by Pombo et al. [2] for the definition of the railway track geometry. The main difference is that no rail inclination is considered for the roller coaster rail, while for the railway rail a fixed rotation about the local **t** vector must be considered in each rail. The result of this procedure is the roller coaster track illustrated in Fig 1(b).

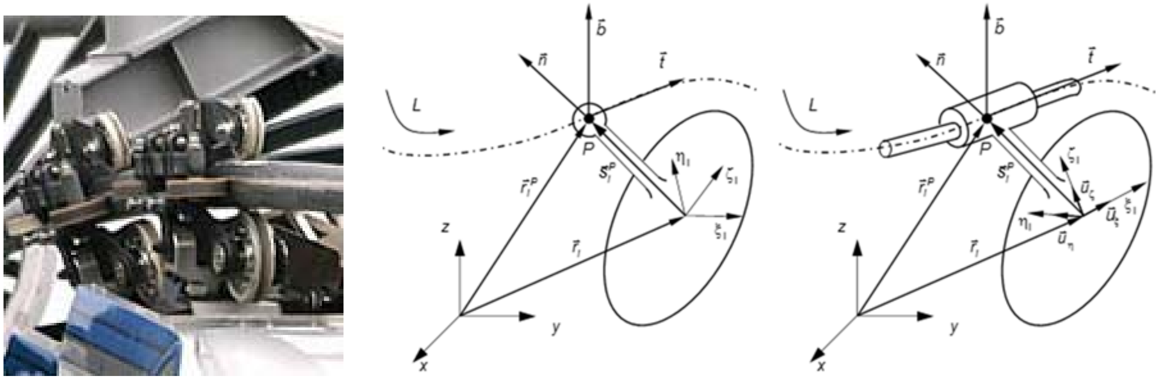


(a) (b)

Fig. 1: Spatial description of the roller coaster rails: (a) Frenet and rails moving frames: (b) Geometry of the rails for a roller coaster.

The vehicle-track interaction representation for steel rail roller coasters, for which a generic set of wheels is shown in Fig. 2(a), the wheel-rail contact can be modelled by a set of contact pairs between cylinders or by a suitable path-following constraint, as shown in Fig. 2(b,c), proposed by Pombo and Ambrosio [2] and further generalized by Viegas [3]. The center of the three wheel set, is enforced to be always on a curve being some, or none, of its rotations with respect to the moving frame constrained. The complete formulation for each type of path-following constraints is derived and presented in this work.

The remaining parts of the model for the roller coaster, developed and presented in this work, are the vehicle and the biomechanical occupant model. The roller coaster vehicle model, shown in Fig. 4, is composed of a seating platform, articulated to the bogie frame by a secondary suspension, and four sets of three wheels linked to the bogie frame by a primary suspension system. The primary suspension mechanism ensures the proper running of



(a) (b) (c)

Fig. 2: Wheel rail interaction: (a) Sets of wheels of roller coasters: (b) Path following constraint by a point; (c) Path following constraint by a spatial cylindrical joint.

the wheelsets on the rails and controls misalignments that may condition the running of the vehicle along the track. The primary suspension mechanism includes spring-dampers that link the wheelsets to the vehicle frame and two types of constraint joints, prismatic and revolute, which are ensure that the wheelsets fit the rails. The secondary suspension is a passive tilting mechanism to reduce the non-compensated lateral accelerations, to which an occupant is exposed when the roller coaster vehicle is moving on a circular curve. The anthropometric model used has been proposed by Ambrósio and Silva[4], based on the early work by Laananen [5], representing the 50th percentile male. The biomechanical model, shown in Fig. 3, includes 16 rigid bodies, which represent independent anatomical segments, interconnected by 15 kinematic joints.

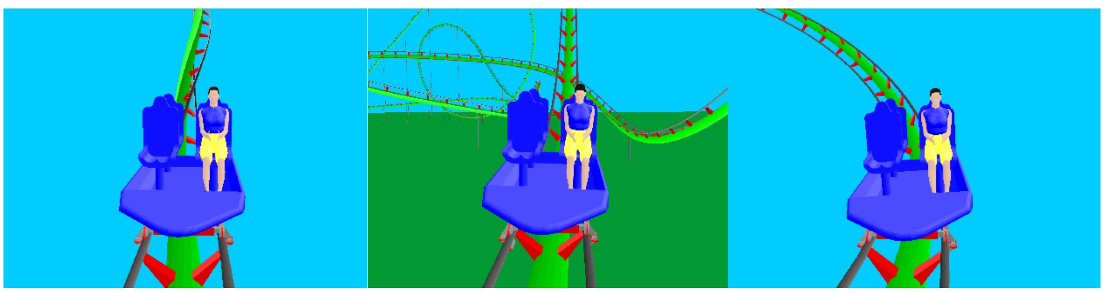


Fig. 3: Selected frames from the motion of a roller coaster vehicle with an occupant during a ride.

The roller coaster vehicle and biomechanical multibody model are simulated with the approaches proposed here. The track geometries used here include existing roller coasters and planned ones. The results obtained include not only the vehicle kinematics and joint reaction forces between the vehicle and track but also the relevant biomechanical dynamic responses to support the evaluation of human comfort and injury.

References

[1] J.Pombo and J. Ambrósio, “General Spatial Curve Joint for Rail Guided Vehicles: Kinematics and Dynamics”, *Multibody Systems Dynamics*, vol. 9, pp. 237-264, 2003.

[2] J.Pombo, J. Ambrósio and M. Silva, “A new wheel-rail contact model for railway dynamics”, *Vehicle System Dynamics*, vol. 45, no. 2, pp. 165-189, 2007.

[3] M. Viegas, *Development of Computational Models of Roller Coaster Vehicles and Occupants for Injury Analysis*. MSc Thesis: Instituto Superior Tecnico, University of Lisbon, Lisbon, Portugal, 2016.

[4] J. Ambrosio and M. Silva, “Structural and Biomechanics Crashworthiness Using Multi-Body Dynamics”, *Journal of Automobile Engineering*, vol. 218, no. D6, pp. 629-646, 2004.

[5] D.H. Laananen, *Computer simulation of an Aircraft Seat and Occupant (s) in a Crash Envi-ronment-Program SOM-LA/SOM-TA User Manual*. Report DOT/FAA/CT-90/4, U.S. Department of Transportation, Federal Aviation Administration Technical Center, Atlantic City Airport, New Jersey, New Jersey, 1991.