Roller coaster train dynamics: the effect of the zero-car location

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Modern steel roller coasters that contain geometrically complex track elements, such as high-speed turns and inversions, have been manufactured only since the 1980's. During this relatively short history of the modern steel roller coaster, an endless variety of attractions has been developed by manufacturers and theme park operators. Besides the many different track lay-outs that have been realized, the variety in train designs has grown drastically.

The overall appreciation of roller coasters by the general public is primarily determined by the level of thrill and sensation of the ride hardware in combination with its storytelling and theme. However, in recent years, the experience of manufactures, theme park operators and roller coasters enthusiasts has indicated that also passenger comfort is an important determining factor in a roller coaster's success. Unbalanced lateral forces, i.e. the dynamic forces passengers experience in their sideways direction, are a primary source of discomfort, as they contribute to the unpleasant feeling of "shakiness" that is experienced on high-speed roller coasters. Hence, for a comfortable ride experience, it is essential to minimize the lateral forces exerted on the passengers. To this end, the lateral inclination of the roller coaster track, also referred to as banking, is designed such that it minimizes the lateral forces in turns. With an accurate predication of the train's velocity, each track section can be banked such that the average lateral force is close to zero at all times.

However, in practice there will be a certain amount of play between the roller coaster train and track. Trains with a fixed wheel suspension also need this play in order to be able to make it through turns geometrically. Unfortunately, the presence of this play will allow the roller coaster trains to vibrate or rattle continuously, mainly in the lateral direction. Over the years, roller coaster manufactures have developed a large number of different train configurations in order to cope with this lateral play. There are important differences in the way coaches are connected together to form a train. Also, the way the chassis, main axle and wheel suspension assembly are connected together within one coach varies from design to design. For example, nowadays almost all manufacturers equip their roller coaster trains with a wheel suspension system that uses pretension to ensure contact between the wheel and the track at all times. Yet, no scientific publications can be found that discuss the influence of roller coaster train configurations on the ride dynamics in general and the lateral vibrations in particular.

In this work, the influence of the zero-car location on the lateral train dynamics is investigated. Typically, each coach of a roller coaster train has a single main axle, either at the front or rear of the coach. This means that at one end of the train, an additional axle is required to support the final coach. This final axle is referred to as the zero-car. Figure 1 indicates the zero-car of a four coach train. Both front-running and rear-running zero-cars are used in practice. Based on stability considerations, it is likely that there is a difference in the dynamic behavior between both train configurations. Although the trains' lateral motion is constrained by the track, it is expected that a difference can be found in the way the trains have a natural tendency to vibrate or rattle. This difference is investigated in multibody dynamics simulations and in experiments of scale models. Both the simulations and experiments are performed with the same train, travelling in both directions, thereby in fact changing the location of the zero-car from the front to the rear.

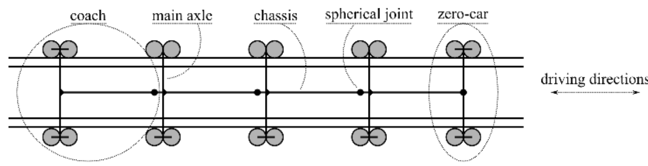

Fig. 1: Schematic top view of a roller coaster train with four coaches, connected to a zero-car

The multibody dynamics simulations use the floating frame of reference formulation for describing the dynamics. All bodies are considered to be rigid. Kinematic constraints between the bodies are enforced using Lagrange multipliers. A contact model is implemented for the contact between the wheels and the track. A small amount of play between the wheels and track is taken into consideration. The experimental setup is constructed from a large amount of commercially available plastic toy construction parts. A roller coaster train of four coaches is constructed that has the same degrees-of-freedom as the numerical multibody model. An accelerometer is attached to each of the four coaches to measure the lateral vibrations of the train.

In an attempt to isolate the effect of the train configuration from as many other effects as possible, the dynamic behavior on a straight horizontal track is investigated first. In the numerical simulations, the track is modeled to be perfectly straight, yet the train is given a small lateral velocity as initial excitation. In the experiment, initial position uncertainty and construction tolerances are sufficient to cause a lateral excitation. Both the simulations and experiments shown lateral vibrations indeed. However, no significant difference could be found between front-running and rear-running zero-car trains. It is therefore concluded that this difference in train configuration is not pronounced on straight tracks.

In a second study, the multibody simulations are performed on several track geometries that contains multiple horizontal turns. Comparing experiments are not made for practical reasons. In this numerical study, only some track geometries showed a significant difference between both train configurations. In these cases, it seems to be slightly favorable to have a rear-running zero-car. This is concluded by comparing the root-mean-square value of the lateral accelerations of the total simulation time. However, in all simulations performed, it was found that for the lateral vibrations in the coach connected to the zero-car were up to 20% lower for a rear-running zero car. In other words: in case of a rear-running zero-car, the lateral vibrations of the coached connected to the zero-car are significantly lower, whereas no pronounced difference is observed in the lateral vibrations of other coaches. Based on the performed simulations in this work, a rear-running zero-car would be the preferable train configuration. In the full paper and corresponding presentation, detailed results of the simulations and experiments will be presented and explained.