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Roller Coaster Dynamics at Purdue University

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Abstract

Inspired by a handful of passionate students, in the fall of 2009, the School of Mechanical Engineering at Purdue University offered a new course entitled Roller Coaster Dynamics. Little did the instructors of the course (the co-authors of this paper) know, but that course and the many variants that followed would have a marked impact on students and instructors alike, prepping scores of civil and mechanical engineering students for careers in the themed entertainment and amusement attraction industry and opening up new avenues for technical exploration in the areas of nonlinear and multi-body dynamics. This paper adopts a balanced narrative and technical format, not only highlighting the development, subsequent evolution, and impact of Roller Coaster Dynamics at Purdue University, but also providing a brief technical overview of the many focus areas of the course. The paper also highlights recent advancements associated with the course, including the design and implementation of a virtual reality based roller coaster design-build-test exercise; the formation of Theme Park Engineering and Design (TPED) at Purdue; and a forthcoming research paper series that aims to provide a more holistic design and analysis framework for two- and three-dimensional roller coaster designs.

Keywords: Roller Coasters; Dynamics; Design.

1. Introduction

Despite the fact that the academic study of dynamics – the relationship between forces and motion – pre-dates Aristotle, and that modern undergraduate curriculum in the area of Newtonian mechanics has remained largely unchanged for more than a century, over the past two decades large numbers of engineering educators have actively modified their pedagogical approach in this core curricular area, both to increase learning efficacy and to adapt to changing student interests, experiences, demographics, and technological competency. In recent years, these changes are perhaps best exemplified by both the widespread adoption of project-based learning (PBL) and alternate active, blended, and collaborative (ABC) pedagogical practices [see, for example, Rhoads, 2014]. At Purdue University, for example, a team of researchers and practitioners (including the authors) developed, adopted, and disseminated (to both other classes and universities) a curricular framework commonly called Freeform, which leverages hybrid lecture notes/textbooks, an online course portal with discussion forums, an extensive multimedia library, and a large number of group activities, to provide students with a holistic educational experience that caters to a wide range of learning styles [Rhoads, 2014].

Though Freeform has received considerable attention, both in the popular press and from the engineering education research community, due to its documented ability to markedly reduce the rate at which students receive failing (D,
F, or withdraw) grades in a key undergraduate course, the future success of the ecosystem was far from certain when it was launched in 2008 [Rhoads, 2014; DeBoer, 2016]. In fact, the authors of this work actually “hedged their bets” at that time and simultaneously initiated a lower-profile educational effort – namely the development of a new course entitled Roller Coaster Dynamics (RCD), which was designed to teach advanced dynamics concepts to undergraduate students using an application-first approach and project-based learning in hopes of facilitating deep student engagement. This paper seeks to provide a practitioner-oriented overview of RCD by highlighting its unusual origins, delineating the current course content, describing the various activities and projects utilized in the course, and concluding with a discussion of the various unexpected outcomes of the course over its near decade-long history. The authors hope that others will find inspiration herein and perhaps a means to further engage undergraduate students at their own academic institutions.

2. A Brief Narrative History of Roller Coaster Dynamics at Purdue University

As noted above, the School of Mechanical Engineering at Purdue University made a concerted effort in 2008 to modernize its core mechanics curriculum through the creation of Freeform. At the time, a key and novel component of this educational ecosystem was an online discussion forum (blog), which facilitated asynchronous student-to-student and student-to-instructor interaction. While the majority of communication on the site focused on routine correspondence related to the various lecture materials and homework assignments associated with the course, the instructors frequently encouraged their students to identify physical systems in their daily lives that exemplified “dynamics in action”. In the spring of 2009, the latter took an unexpected turn when a sophomore-level student began posting snapshots of various roller coasters that he had created in NoLimits design software [NoLimits, 2011], along with a handful of long and detailed dynamics questions related to 3D kinematics and kinetics. At first, these posts appeared to be aligned with others posted by passionate students with the topic capturing the attention of the class for a single period. However, as the posts continued, it became apparent that something was quite different – additional students started to share their personal experiences and comment, leveraging a combination of intuition, basic mathematics, and physics to discuss dynamics content that was as complex, if not more so, than the topics discussed in Purdue University’s graduate level courses in the field.

Recognizing a potential, albeit unusual, opportunity, the authors talked with key student stakeholders to assess interest levels and decided to try an educational experiment that leveraged ABC pedagogical practices, but did so in a very narrow fashion – they created an elective course on Roller Coaster Dynamics. From the onset, the aim of the course was to convey advanced dynamics concepts in an application-first format, paying little attention to conventional topical orders or difficulty levels, and instead letting the complexities of roller coaster design guide the curriculum. To this end, the initial course curriculum was built from a variety of resources, ranging from the physics education literature [Alberghi, 2007; Bagge, 2002; Muller, 2010; Nordmark, 2010; Pendrill, 2005a; Pendrill, 2005b; Pendrill, 2008; Pendrill, 2012; Pendrill, 2013; Pombo, 2007] and the short, yet deeply insightful, scientific papers of Clark [Clark, 1988; Clark 1989a; Clark, 1989b], to interviews with professionals in the field and research literature related to tracked vehicle dynamics (particularly railroad engineering) [see, for example, Pombo, 2003]. The result was a class geared towards the passionate few not afraid to tackle advanced engineering mathematics in a practical context, which now lives on nearly a decade after its conception.

3. An Overview of the Course Curriculum

From its inception, Roller Coaster Dynamics was designed as a dynamics course whose content was driven by the specific needs of creating tools for the students to design roller coaster tracks. The pre-requisite barriers for students enrolling in this course were purposely set low in order to include a broad spectrum of interested prospective students. A working knowledge of calculus and physics from the first-year engineering curriculum was expected, along with process skills from an introductory third-semester vector mechanics course. Although the analysis that goes along with the RCD course is primarily dynamic in nature, the sophomore-level dynamics course was not included in the pre-requisite listing for the course. The instructors felt that the dynamics background needed for the roller coaster designs was low enough in level that they could provide this instruction in class as design ideas were introduced; the fourth-semester students not having a dynamics background could learn the essentials in class and also learn from the upper-level engineering students who would also be attracted to the course.
The first offering of the RCD course during the fall 2009 semester had an enrollment of 24 engineering students, ranging from fourth-semester students up through upper classmen near graduation, demographics that were anticipated by the instructors. The course was offered for a single credit, making it somewhat of a novelty course, and not being particularly relevant to satisfying credit requirements for graduation. Since the class met one time per week for the fifteen-week semester, the instructors chose to limit the range of course topics to introductory concepts in dynamics and roller coaster dynamics specific material found in the publications of Pendrill and Clark referenced earlier. This material included the g-force analysis of planar vertical loops and air-time hills, along with some of the simpler 3D track components, such as corkscrews and banked turns. Particular emphasis in the course was placed on using the set of path-oriented design equations [Pendrill, 2005b], which consist of three differential equations employing prescribed track curvature (shape) information to produce planar track coordinates. Students worked in groups writing computer algorithms in Matlab suitable for numerically integrating these equations for their first design project in the course, that of a planar coaster track made up of loops and hills. The course concluded with students moving on to the design of roller coaster tracks in three dimensions, here employing the use of the NoLimits design software [NoLimits, 2011]. The NoLimits software application allows for the incorporation of elaborate design features in 3D tracks without the need of the user to deal with the mathematics of the design implementation. Again, the students worked in groups for their final course design project, where emphasis was placed not only on the technical issues, but also the aesthetics and commercialization of their amusement park roller coaster ride.

The instructors considered this first offering of the course to be an overwhelming success. The intended goal of driving the learning and the reinforcement of fundamental dynamics principles was met. The students were successful in demonstrating their ability to apply path-based kinematics principles to design fun and safe roller coaster tracks. Working in teams, the lower classmen in the course clearly benefitted from the interaction with the upper classmen in developing these skills. The class showed a remarkably high level of esprit de corps throughout the semester. Some additional unexpected outcomes from that semester’s course offering are highlighted in the following sections of this paper.

In spite of this initial success, the instructors felt that the course was still somewhat limited in what could be accomplished with the curriculum. Since the pre-requisite level for the course had been purposely set low, the instructors were limited in how far that they could go in the dynamic analysis. Special cases of simplified models did not go very far in helping the students interpret the results of their 3D NoLimits design projects. Both the breadth and depth of the course material needed to be expanded. To this end, in subsequent semesters, several changes were made in the curriculum of the RCD course. Analysis and design issues beyond the simplified planar particle motion needed to be considered. The level of the course material needed to be raised to allow the course to be more relevant in satisfying degree requirements. And, more class periods were needed to allow for three course credits, the standard for most courses taken by the engineering students.

After several revisions in the course over the past few offerings, the course now stands as a three-credit offering that can be taken as a technical elective, with the credit hours contributing to the minimum of twelve credit hours for technical electives in the program. The course also qualifies for the newly-created set of “restricted electives” required for graduation by the School of Mechanical Engineering at Purdue University. Such qualifications allow the course to become more mainstream within the mechanical engineering program, and increases the interest of the students. The pre-requisites for the course have been raised to include the fourth-semester dynamics course and a course in differential equations. A listing of the topics included in the current offering of this course is presented in Table 1. A few topics from the first course offering in 2009 remain: for example, Topics 1, 2, and 8 on history, on the planar analysis of loops and hills, and on the simplified 3D components. Topics 4, 5 and 10, which are related to course projects and experiments, will be described in more detail in the following section of this paper. The remaining topics in the current curriculum have resulted from the instructors’ efforts in developing new material, much of which has not previously been seen in the roller coaster dynamics literature. Manuscripts on these topics are currently being prepared by the authors for submission as a series of publications in physics education journals. These topics are summarized in the following.

Transition segments (Topic 3) play a critical role in the design of roller coaster tracks. The connections between track elements, such as loops and hills, govern the comfort and safety of track designs. Several roller coaster dynamics publications have discussed how inattention to continuity of curvature in the design of track component transitions can lead to high levels of “jerk” being felt by the roller coaster passengers. The new RCD course
described here has followed the lead of these prior works via the introduction of methods to reduce the jerk at points of transition through the use of the path-based design differential equations. The instructors here added onto the knowledge base related to this topic through an analysis of how jerk at the track level produces unsafe, force-aft whiplash acceleration in the passengers. Incorporation of these results allows the students to quantify the effects of jerk and produce transition curve designs that maintain safety and comfort in the ride.

At the early stages of coaster track designs, energy losses due to friction and air resistance are typically neglected since the effects of these are minimal on the instantaneous track performance. Over the long range on the track, such effects become important in producing limitations on a track design. Energy losses (Topic 6) are dealt with directly in the track designs of this course. The loss-generating terms are built into the path-based design equations, and become part of the standard design process. Discussions of the general results from the inclusion of friction/rolling resistance and air resistance become part of the conversation of the course, with conclusions being drawn on how each type of energy loss manifests itself in the ride performance.

Another simplification typically assumed at the early stages of track designs is the treatment of a coaster train as a single cart, or even simpler, as a point mass. In this course, the modeling of coaster trains (Topic 7) is brought into the design arena at the early stages. Previous publications [see, for example, Alberghi, 2007] provide qualitative interpretations of the differences between the dynamics of single carts versus the dynamics of multi-cart trains. In this course, considerable effort is directed to quantifying these differences. Tools are developed for the straightforward inclusion of multi-body influences into the track design equations discussed previously.

A signature component of this course is the inclusion of the general 3D analysis and design of roller coaster tracks (Topic 9). In planar analysis and design, the students learn that the performance of a roller coaster track is dictated by the single shape characteristic of “curvature”; the curvature of the track multiplied by the square of the cart speed produces the centripetal component of acceleration (the “g-forces”). Students in this course, and in the pre-requisite dynamics course, learn to inspect planar sections of tracks to gain an intuitive understanding of the g-forces produced. The complications of a three-dimensional track are intimidating to the students at first inspection when they shift focus from 2D to 3D track components. In the RCD course described here, the students learn that in three dimensions, the track is characterized completely by not only its curvature, but also by its “torsion”, an out-of-plane measure of the track shape. The set of track design differential equations are modified by the additional shape parameter. Through active learning exercises in class, the students gain intuition on the influence of both curvature and torsion on track shape and track performance. These insights aid them in their work in designing for performance and for safety against high levels of jerk, and provide a means of interpreting the complicated track shapes produced in the NoLimits design software in their final design project.

In summary, the instructors feel that the curriculum of this course has led their students through meaningful design experiences that address the complicated dynamics involved in roller coasters. These topics serve well in bringing life to the study of dynamics and for training the students for future work.

4. Assignments, Experiments, and Projects

As highlighted in the previous section, the RCD curriculum has evolved tremendously since the initial course offering in 2009; this is true of the various assignments, experiments, and projects in the course as well. Today, active learning methods are employed in approximately half of the class periods. Typically, students work in small groups, designing and/or analyzing various track elements or transition features through the use of mathematics and geometric drawing. The assignments are designed to encourage creativity and thoughtfulness, and frequently require the students to draw on their own personal experiences with well-known rides.

Complementing these in-class activities are a small number of structured experiments aimed at exploring the validity of the mathematical design tools emphasized in class. These rather-simplistic experiments leverage flexible rubber tracks, small spherical “carts”, and timing gates to explore: (i) the work/energy relationship; (ii) the source of various physical constraints in the design of loops and hills; and (iii) the role of energy dissipation in a “real” coaster design. Students are asked to complete pre-lab activities, design their test tracks during the laboratory, and interpret their experimentally-determined results within the context of brief reports. While most of these activities could be
easily completed by an advanced high school student, the experiments have a marked positive effect on the students’ confidence in the mathematical design tools being learned, and thus they remain a key portion of the class.

Table 1. A summary of topics covered in the current course curriculum and the approximate number of 75 minute lectures for which the topic is discussed.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Approximate Number of 75 Minute Lectures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. History of Rollercoasters and Associated Background</td>
<td>1</td>
</tr>
<tr>
<td>2. Planar Analysis of Loops and Hills</td>
<td>4</td>
</tr>
<tr>
<td>3. Transition Curves for Planar Tracks</td>
<td>3</td>
</tr>
<tr>
<td>4. Project 1: Design of a Planar Roller Coaster</td>
<td>2</td>
</tr>
<tr>
<td>5. Experiments with Planar Roller Coasters</td>
<td>3</td>
</tr>
<tr>
<td>6. Energy Losses on Planar Tracks</td>
<td>2</td>
</tr>
<tr>
<td>7. Modeling of Roller Coaster Trains</td>
<td>3</td>
</tr>
<tr>
<td>8. 3D Roller Coaster Elements: Banks, Corkscrews, Rolls and Inversions</td>
<td>3</td>
</tr>
<tr>
<td>9. Design and Analysis of 3D Roller Coaster Tracks</td>
<td>3</td>
</tr>
<tr>
<td>10. Project 2: Design of a Complete Roller Coaster in NoLimits 2</td>
<td>6</td>
</tr>
</tbody>
</table>

Perhaps the most distinguishing feature of the class is its two design projects, briefly alluded to in the preceding section. In the first, students are asked to design, and subsequently analyze, a planar roller coaster, inclusive of various loops and hills, along with all of the requisite transition elements using their own Matlab code. Through this exercise the students quickly learn to appreciate that designing elements, such as loops and hills, is often the easier part of track design, with the proverbial “devil being in the details” (in this case, the devil being the smooth transitions) to produce safe track designs. The second project, a true cornerstone of the course, is an extended design project leveraging NoLimits design software [NoLimits, 2011] (see Figure 1). Since the onset of the course, this project has served as a creative outlet, letting the students leverage their enhanced design knowledge to create physically-realistic creations and pairing them with the concepts of aesthetic design, theming, and marketing. In recent years, this project has been expanded, requiring students to include more advanced 3D analyses of specific elements within their design and formally present their designs to a panel of peers and subject matter experts. In the most recent incarnations of the class, various students, instructors, and visitors have been able to assess these projects in virtual reality, through the use of an Oculus Rift system, which is now fully integrated with the NoLimits software.
5. Unexpected Outcomes

After nearly a decade, RCD continues to be a strong success, with both instructor observations and student-submitted course instructor evaluations indicating that the students enjoy learning new, advanced dynamics concepts in the application-first format. It should be noted that while the more recent increases in technical depth have slightly tempered the class’ broad appeal, those who enroll in the course still demonstrate high levels of passion and engagement.

While the aforementioned outcomes are often the best an instructor can ask for, the numerous unexpected outcomes of the course are perhaps the most noteworthy. First, the course has seemingly served as a talent magnet. Of the first cohort of 24 students, nearly 80% eventually attended engineering graduate school, conducting research in the areas of design or dynamics, or alternatively entered the themed entertainment industry. For example, the student who made the initial discussion forum posts has recently completed his Ph.D. and is now a recognized expert in experimental dynamics. Second, the course has garnered considerable popular press, drawing interest ranging from National Public Radio (NPR) and the BigTen Network, to numerous popular and trade publications. Third, the course inspired its own student organization at Purdue, Theme Park Engineering and Design (TPED), which has grown to far surpass the course in both scale (there are typically in excess of 100 members in a given academic semester) and impact (the organization routinely assists with ride openings, park staffing, job placement, etc.). And finally, as alluded to above, the course’s curriculum has spawned a forthcoming series of journal papers, which have allowed the authors of this paper to have a little extra fun!

6. Conclusion

The development and implementation of the Freeform curriculum structure has led to new, modern thinking by the mechanics faculty in the School of Mechanical Engineering at Purdue University on instructional styles. This has led to a modified instructional culture where active learning and project-based learning methods are replacing the more structured lecture-based instruction. The philosophy of the Roller Coaster Dynamics course described herein is a natural outgrowth of the Freeform philosophy; students excel in learning new skills and engineering fundamentals through the direct application of these ideas to problem-based projects. The projects inspire a high level of ownership by the students during this learning process. Students acquire skills that can be directly applied in numerous fields after graduation. This roller coaster course is only a single example of such an instructional plan; inspired by the success of the course, the RCD instructors are currently working on ideas for courses in other areas of application in engineering that they hope to offer in the near future.
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