Teaching Multibody Dynamics to Freshman Students using a Design Project: The Race Party Challenge

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Abstract

This work presents the use of the Race Party pedagogical project to teach multibody dynamics to first-year engineering students. The Race Party challenge consists of a minicar competition, in which students, organized in groups of five, must design, develop, and build a dragster-type minicar powered by a standard helical spring. The main goal is to travel five meters on a smooth, horizontal surface as quickly as possible [1]. Each group of students receives a basic kit of components, shown in Fig. 1a, which must be utilized in the Race Party challenge. Figures 1b and 1c show, respectively, an example of a student-built car without its body and a minicar during competition.



(a) (b) (c)

Figure 1: **(a)** Basic kit of components provided to each team of students; **(b)** Example of a minicar developed by students; **(c)** Track used during the Race Party competition at the end of semester.

The main objective of this study is to present a simple, practical, and comprehensive approach for teaching the dynamics of mechanical systems to first-year engineering students. For this purpose, the dragster car challenge is utilized as a hands-on application in which students must design, model, and analyze the dynamic performance of a minicar propelled by a tension helical spring. The dragster car challenge engages students in a fairly complete project, as it incorporates several key topics related to teaching multibody dynamics, including the development of free-body diagrams, the application of Newton's laws of motion, the solution of equations of motion, and the identification of dominant and secondary variables affecting the minicar's dynamic performance. It must be noticed that aspects related to machining, assembling and building physical prototypes of the minicar are not the focus of this study.

The formulation proposed in this work to model and simulate the dynamics of mechanisms can be summarized in the following steps [2]:

(i) ***Discretization of the system***. The first step of the proposed approach deals with the modeling process of the system under analysis with an appropriate level of detail, keeping in mind the aim and purpose of the problem to be solved. The mathematical model should be kept as simple as possible without compromising the primary objectives of the analysis or the accuracy of the results.

(ii) ***Selection of coordinates***. In this step, the type of coordinates used to define the position and orientation of the bodies in the system must be selected. Among the various coordinate types commonly used in multibody dynamics, this study adopts absolute coordinates. In this formulation, the pose of each body is defined by the x and y coordinates of its center of mass, along with a rotational coordinate, θ, representing the body's orientation.

(iii) ***Drawing free-body diagrams***. The third step involves constructing the free-body diagrams for all the components of the system, which provide a clear and straightforward representation of the forces acting on each body. Accordingly, a separate free-body diagram must be drawn for all the bodies, or parts, of the multibody system.

(iv) ***Formulation of the equations of motion***. Based on the free-body diagrams constructed in the previous step, the Newton-Euler equations of motion are formulated. For planar systems, Newton's second law states that the sum of the applied forces equals the mass times the linear acceleration. Similarly, Euler's equation states that the sum of the applied moments about the center of mass equals the mass moment of inertia at the center of mass times the angular acceleration.

(v) ***Establishment of the kinematic constraints***. This step involves developing the kinematic relations associated with the system's constraints, specifically those imposed by the revolute joints and the wheel–ground interaction.

(vi) ***Assembly and resolution of the equations of motion and kinematic constraints***. In this step, the equations of motion are combined with the kinematic constraint equations and solved numerically. It should be noted that kinematic constraints are typically formulated at the position level and therefore cannot be directly incorporated into the equations of motion, which are expressed at the acceleration level. Consequently, the constraint equations must be differentiated twice with respect to time. Combining the equations of motion with the differentiated constraint equations yields a system of differential–algebraic equations, which can be written in matrix form as [3]

$$\begin{bmatrix} \mathbf{M} & \boldsymbol{\Phi}_{\mathbf{q}}^{\mathrm{T}} \\ \boldsymbol{\Phi}_{\mathbf{q}} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{q}} \\ \boldsymbol{\lambda} \end{Bmatrix} = \begin{Bmatrix} \mathbf{g} \\ \boldsymbol{\gamma} \end{Bmatrix} \tag{1}$$

where $\mathbf{M}$ is the system's mass matrix, $\boldsymbol{\Phi}_{\mathbf{q}}$ represents the Jacobian matrix of the constraint equations, $\ddot{\mathbf{q}}$ denotes the vector containing the system accelerations, $\boldsymbol{\lambda}$ is the Lagrange multipliers vector that includes the joint reaction forces, $\mathbf{g}$ is the generalized vector of applied forces, and $\boldsymbol{\gamma}$ denotes the right-hand side vector of the acceleration equations [4].

(vii) ***Visualization of the outcomes.*** The final step involves the verification and visualization of the results, which can be presented as tables, plots, or animations. This step is crucial for evaluating the accuracy and effectiveness of the developed model, as it enables the physical interpretation of the data obtained from the analysis.

The key aspects discussed in this study include several topics related to dynamics analysis, such as the construction of free-body diagrams and the application of Newton's second law of motion [1]. Additionally, the formulation and solution of the resulting equations of motion for the minicar have been central issues addressed in this work. Following this, the implementation of computational codes based on the proposed approach has also been analyzed, including considerations of the power source and dissipative effects. This enables the investigation of how the main variables and parameters influence the minicar's performance. Overall, the project has presented a significant challenge and has proven highly successful for both the students and the instructors [5]. The methodology presented can also be applied to analyze and discuss a variety of mechanical systems, including different types of machines and mechanisms. Moreover, the use of commercial software as an alternative for modeling and analyzing complex systems is considered within the scope of the present study, particularly in applications to industrial problems.

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