AC 2003-1128: A FUN AND CHALLENGING ENGINEERING DYNAMICS PROJECT USING A LEGO CONSTRUCTION SET

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A Fun and Challenging Engineering Dynamics Project Using a Lego® Construction Set

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Abstract

This work seeks to integrate the theoretical development of a sophomore level course in engineering dynamics by incorporating a LEGO® fourbar mechanism project. The fourbar mechanism is constructed using the LEGO® TECHNIC Pneumatics Pack. Teams of two or three students learn how to model a physical dynamic system and apply the concepts introduced throughout the dynamics course to develop the kinematic and kinetic relationships for the linkage. The mathematical model is analyzed using a software package such as Mathcad®, TKSolver® or Matlab®. Once the mathematical model has been evaluated, students are asked to interpret and verify their results by working with the actual linkage. Using a hands-on project to teach dynamics allows students to build associations between analytical calculations, and what is being observed during the operation of the device. Using a LEGO® mechanism permits students to further develop an understanding of why assumptions are made, and when they are valid. This experience enables students to deal with problems that are more complex than classical textbook problems, thereby adding a new dimension to a traditional analytical course.

1. Introduction

A first course in engineering dynamics brings together basic Newtonian physics and various mathematical concepts including vector algebra, geometry, trigonometry, and calculus, all of which can be very difficult for a typical undergraduate student. Furthermore, dynamic behavior is often non-intuitive. Magill [1] suggests that dynamics is "one of the more difficult courses that engineering students encounter during their undergraduate study." A major reason for this difficulty is that dynamics has traditionally been taught without using a physical model. A conventional dynamics course requires students solve problems involving a particular state of motion for a particle or a rigid body at a given instant. Personal conversations by the authors with students reveal that students lack a complete understanding of the motion of a mechanism. Similar observations can be found in recent work [2,3].

In this paper, a real world problem is considered where assumptions have to be made, tested, and solutions verified. The kinematics and kinetics of a LEGO® mechanism are explored based on planar rigid body mechanics. Our educational goal is to provide students with a better physical understanding for and experience with the laws of dynamics by considering a practical project activity.

2. Format of the Dynamics Course Incorporating Project Activity

Dynamics (ES2503 Introduction to Dynamic Systems) at the Worcester Polytechnic Institute (WPI) is a seven-week sophomore level course that meets four class sessions per week for a total of twenty-eight class sessions (fifty minutes per session). The textbook by Hibbeler [4] is used and the topics covered in sequential order include kinematics of particles (chapter 12), planar kinematics of a rigid body (chapter 16), kinetics of a particle (sections 13.1-13.4), planar kinetics of a rigid body (chapter 17), work and energy (sections 14.1-14.6 & 18.1-18.5), and impulse and momentum (sections 15.1-15.4). The course grade is typically based on four exams (20% each), homework (20%) and a three-phase project that replaces the lowest grade of the first three exams. The project, which will be used for the first time to teach the course at WPI this spring, is the focus of this paper. Approximately 90% of each class consists of Mechanical Engineers and the remaining 10% are Civil, Electrical and Biomedical Engineers.

3. Project Goal and Phases

The goal of the project is to analyze the kinematics and kinetics of an inverted slider-crank fourbar linkage, to find the forces resulting at the pin joints and the pressure required in the actuating pneumatic cylinder to provide the corresponding motion. Two approaches may be employed to analyze a linkage, forward dynamics, and inverse dynamics. Forward dynamics problems are investigated with the forces known, and the position, velocity, and acceleration being the solution to the problem. Inverse dynamics problems start with known kinematics (velocity and acceleration), and seek to find the forces required to give the corresponding motion. In order to be consistent with the progression of the course as it is set up at Worcester Polytechnic Institute, inverse dynamics is employed in this project. The students learn to apply fundamental principles of dynamics to solve a real problem. Educationally speaking the students apply what they have learned in class and in homework to complete a practical project. The solutions are verified with experimentation and visualization.

The project is done in groups of two or three students, typically two, and is divided into the following three phases:

- Phase 1: Preliminary Analysis (20%)
- Phase 2: Kinematics (40%)
- Phase 3: Kinetics (40%)

where the grading breakdown for each phase is shown. The project assignments and solutions for each phase can be obtained from the authors upon request via e-mail. Phase 1 is given out the first day of class, Phase 2 at the beginning of the third week of class, and finally Phase 3 at the beginning of the fifth week of class. A new phase is distributed after each phase has been handed in. The students receive the solution to the completed phase so they can figure out if and where any mistakes were made and so everyone in the course will start a new phase without any compounding mistakes.

The fourbar mechanism to be analyzed is constructed using the LEGO® TECHNIC Pneumatics Pack 5218 kit [5], and can be seen in Figure 1. The kit shown allows for the construction of many different mechanisms, however several are too advanced for an introductory dynamics course. The more advanced mechanisms could be used for teaching higher-level courses such as kinematics and dynamics of machinery. The mechanism that will be the focus of this project can be found on page 53 of the LEGO® TECHNIC 5218 kit instruction manual. The fourbar linkage that is considered in this project can be seen outlined in Figure 1. A small hand pump is used to pressurize a small air tank which acts as a reservoir. A pneumatic cylinder using low pressure air drives the mechanism. A manual valve directs pressurized air to either side of the piston within the pneumatic cylinder. Low pressure air is supplied from the reservoir to the cylinder thereby applying a force to the piston causing the pneumatic cylinder to expand and rotate the attached boom with angular velocity and angular acceleration.

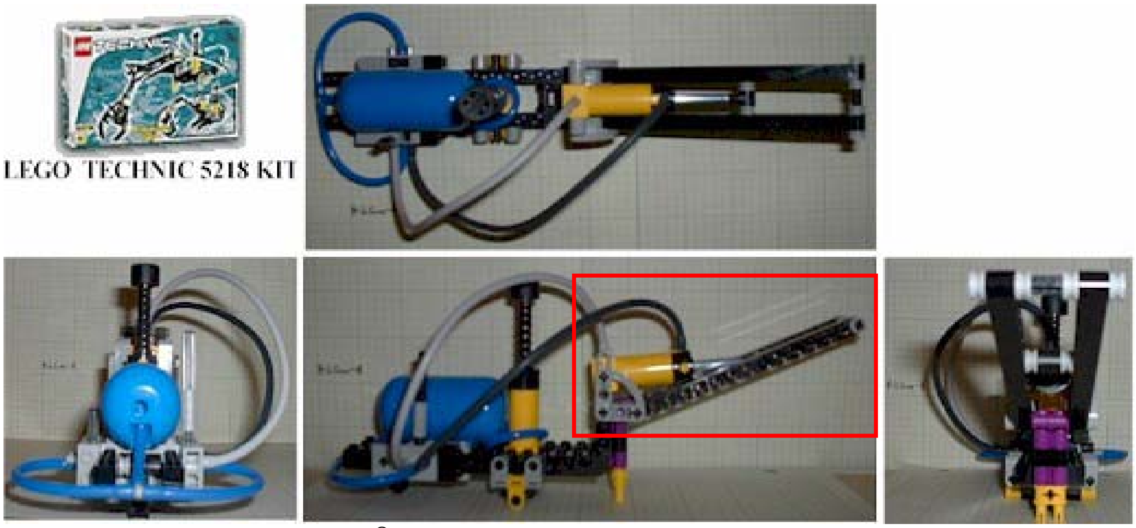


Figure 1. LEGO® TECHNIC Pneumatics Pack Mechanism [5].

Each project phase handout is organized into a number of tasks, some with subtasks. The problem is structured such that sophomore level students approach the assignment in an organized manner therby making the project easier for the professor to grade. References for dynamics principles required to complete a particular task are provided in the project handout [4,6]. Tables are provided for students to fill in the required information with calculated and/or experimentally established quantities (i.e., mass, acceleration, and force). Certain tasks require students to construct sketches that complement their solutions in order to provide a complete understanding for the information requested (i.e., labeled sketches of links with dimensioned mass centers, kinematic diagrams, etc.).

4. Project Equipment Required

When deciding on a LEGO® project for the course the authors wanted to minimize cost and ensure that the equipment could be easily found at the university or at a local store. Furthermore, the authors wanted to limit the complexity of the mechanism since th LEGO® kit permits various configurations. The following equipment is needed to carry out this project:

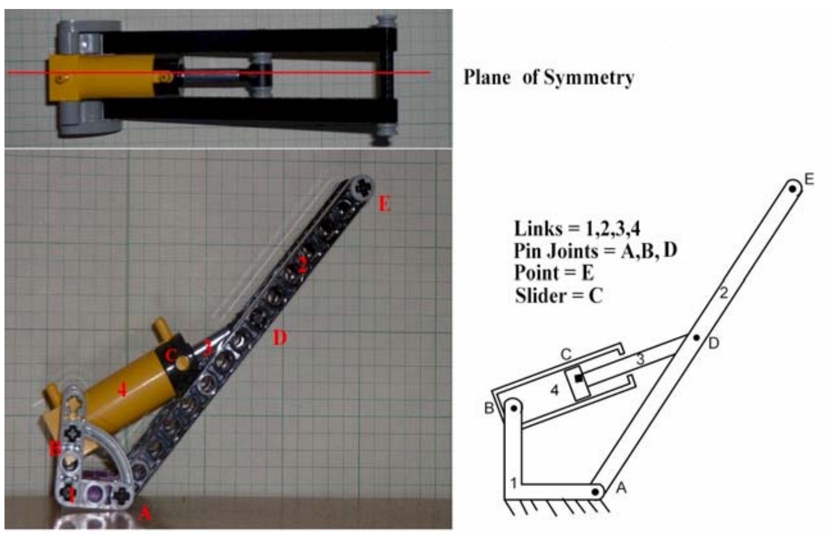
- *LEGO® TECHNIC Pneumatics Pack (# 5218) [5].* Cost is approximately twenty dollars.
- *Engineering Dynamics Textbook.* Any book can be used, however, the authors refer to Hibbeler [4] and Beer and Johnston [6].
- *Ruler.* With a millimeter scale at least 150mm long.
- *Scale.* Or mass balance with a 1/10 gram accuracy.

At WPI the students are required to purchase the above equipment, however, one could have the equipment available outside of class.

5. Phase 1: Preliminary Analysis

The goal of Phase 1 is to familiarize the students with the LEGO® mechanism, its function and some of the concepts that will be used to solve the problem in Phases 2 and 3. Concepts such as geometry, mass, mass center, mass moment of inertia, and engineering idealization are considered in this phase. Students are provided with Figure 2, where Figure 2A shows the real three-dimensional (3-D) mechanism to be analyzed. The mechanism may at first look complicated to students, therefore they are shown the two-dimensional (2-D) idealized sketch in Figure 2B and are instructed on the assumptions associated with the idealization. Phase 1 is divided into one qualitative and six quantitative tasks. Though the Phase 1 results will be used in Phases 2 and 3, tasks that involve elementary calculations are dealt with in Phase 1 to evenly distribute the project workload over the seven-week term. This project requires that students find dimensions and mass properties experimentally, and then use their results in subsequent calculations therefore making the project a more complete learning experience. Traditionally, this information is given in the textbook problem description.

The students are asked to qualitatively describe the kinematics of the mechanism by studying the actual LEGO® device (i.e., motion visualization). They are asked to sketch the mechanism in various displaced positions in order to examine what happens to the other links when the piston moves. Furthermore, the physical understanding developed from Phase 1 will be used to interpret the numerical results of Phase 2. All too often students hastily start performing calculations without developing a physical understanding for the problem. Phase 1 forces students to think about the qualitative aspects of the project before any dynamics calculations are necessary. Though students are required to calculate certain properties of the device, emphasis is placed on qualitative work and physical comprehension. This phase is very important to Phases 2 and 3 that follow, especially when students try to understand and interpret their numerical results. The graduate student author appreciated the ability to physically operate the mechanism for it provided a better understanding of the problem.



a. Real 3-D Mechanism — b. Idealized 2-D Mechanism

Figure 2. Real (LEGO®) and Idealized Fourbar Linkage.

6. Phase 2: Kinematic Analysis

The goal of Phase 2 is to study in detail the planar rigid body motion of the inverted slider-crank LEGO® fourbar linkage. Students use the vector equations for general plane motion to mathematically describe the kinematics of each link. The equations are then used to define the kinematics of the complete fourbar mechanism given a velocity ($\bar{v}_c$) and acceleration ($\bar{a}_c$) of the piston. Point C is a point on the piston as shown in Figure 3. Phase 2 is divided into three tasks wherein students must examine the mechanism's position, velocity, and acceleration (including the acceleration of each link's mass center). Students are required to complete the calculations, and to sketch kinematic diagrams of the links relating the numerical solutions to the qualitative kinematic study done in Phase 1.

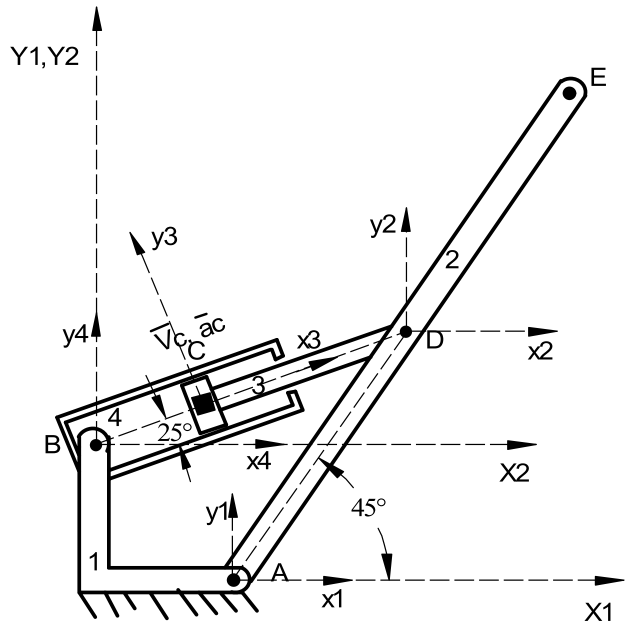


Figure 3. Given Instantaneous Configuration of the Fourbar Mechanism.

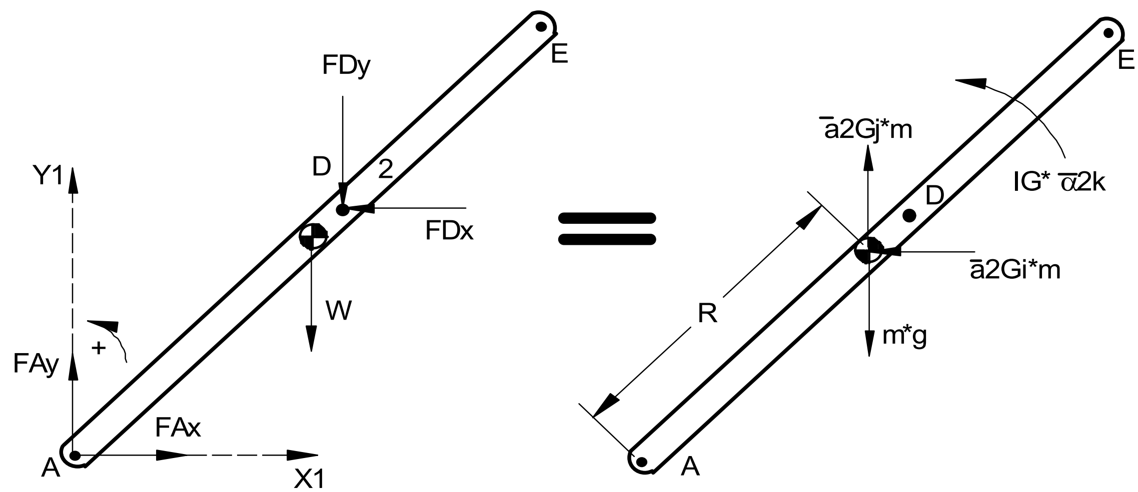
The use of both global and local right-handed coordinate systems, as shown in Figure 3, is strongly emphasized. The authors have found that students struggle with the kinematic equations when coordinate systems are not drawn. Therefore, the use of coordinate systems is required throughout the project and the course. Using position vectors students describe the mechanism's position and geometry. The students then use the vector equations for general plane motion to describe the mechanism's velocity and acceleration (including the accelerations of each link's mass center). The system of linear algebraic equations are implemented in Mathcad®, TKSolver® or Matlab® and numerically solved for the particular instant in time. Given the power of today's software the authors considered completing the analysis using equations, which are functions in time. However, to limit the problem's complexity and be consistent with introductory engineering dynamics textbooks the authors believe it was best to investigate one particular instant in time.

Having the actual LEGO® device available to the students reveals aspects of the mechanism's kinematics not possible with a typical textbook problem. For example, if a group of students has calculated a clockwise rotation, and can physically observe the LEGO® mechanism operating counterclockwise, then they will know there is a mistake in their calculations. The student co-author found this capability invaluable for understanding and checking the numerical solutions.

7. Phase 3: Kinetic Analysis

The goal of Phase 3 is for students to investigate the kinetics of the inverted slider-crank LEGO® fourbar linkage to determine the forces acting at the pin joints and the pressure required in the air cylinder to give the resultant motion (Inverse Dynamics). Students apply the force-mass-acceleration method to analyze the mechanism. Phase 3 is divided into four tasks where students must draw free-body diagrams, draw kinetic diagrams (based on summing moments at and off the mass center), and solve the equations of motion. An additional task is included where students investigate gravitational effects. For example they are required to neglect the gravity component (g) in Figure 4B and compare their results to the case when it is included. The educational objective of this phase is to learn how to conduct a full dynamic analysis of a linkage.

Students are required to first construct the free-body and kinetic diagrams of each link. These diagrams serve two purposes. First, they reinforce an understanding of the terms in the equations of motion. Secondly, they define the right-handed coordinate systems, the notation for the unknowns, and show the known magnitudes and directions. Furthermore, the kinetic diagram focuses attention on the kinematics required to describe the inertia vector. Students are also required to use the method of equating the free-body diagram (Figure 4A) and the kinetic diagram (Figure 4B) to derive the equations of motion [4,6]. This analogy, as shown in Figure 4, has proven useful as another learning tool in understanding the terms in the equations of motion. A software tool such as Mathcad®, TKSolver® or Matlab® is again used to solve the system of linear algebraic equations.



A. Free-body Diagram b. Kinetic Diagram

Figure 4. Free-body Diagram Equal to Kinetic Diagram Analogy.

The students are once again required to verify their numerical results. While it may be difficult to relate the components of force at the pin joints, students should obtain a sense that an order of magnitude solution can be approximated. Additionally, an order of magnitude solution is helpful when verifying the pressure required in the air cylinder. For example, if calculated pressure values are on the order of kilopascals (or negative values) then they should be suspicious of the numerical results and revisit their calculations. An activity where the pressure could be experimentally measured by the students could be employed to verify the calculations. As a final verification task, students are asked to draw the kinetic diagrams and reapply the moment equations at a point off the mass center (typically a pin joint) of each link. This is done in order to verify the solution obtained when applying the moment equation at the center of mass.

8. Conclusion

The LEGO® TECHNIC mechanism enhances the learning of dynamics by providing students with the ability to use a physical device to solve, visualize and verify results for a particular problem. The theory and practical applications are brought together in a manner not available in homework problems and exams. Using a hands-on project to teach dynamics allows students to build associations between analytical calculations and physical observations during the operation of the mechanism. A real device further develops an understanding of why assumptions are made, and when such assuptions are valid. This experience enables students to deal with problems that are more complex than classical textbook problems. The student co-author developing the project found the physical mechanism to be particularly useful for interpreting the numerical results. If students are suspicious of their results they can go to the real device, operate it, and reason as to whether or not the solutions make sense. The authors believe that the project will bring excitement to the introductory dynamics course and renew the student's interest in the subject and engineering in general. Anyone who is interested in obtaining the student assignments and solutions can contact any of the authors through e-mail.

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