Using Dynamic Simulation Software in Machine and Mechanism Design Classes

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ABSTRACT

The design and analysis of machines and mechanisms is an important area of study in any mechanical engineering curriculum. Teaching the concepts of kinematics and kinetics can be challenging, however, as the static nature of traditional teaching methods are not particularly well suited to developing an understanding of the physical dynamics of a mechanism. Until recently, dynamic simulation software was expensive and cumbersome to use, and so its role in undergraduate education was limited.

Over the past decade, many new software tools have become available for use in teaching machine and mechanism design courses. These tools, all of which can run on moderately-priced personal computers, include:

- 2-D and 3-D CAD packages with associative capabilities (the ability to rebuild a model in response to a dimension change),
- 2-D stand-alone dynamic analysis programs, and
- 3-D dynamic analysis programs that work with solid modeling software.

At Milwaukee School of Engineering, all of these tools are being used in a variety of undergraduate courses and also in high school outreach programs. The authors share some of their experiences in using these tools, and their observations on the effects on student learning. The courses include both mechanical engineering and mechanical engineering technology courses. Also discussed is a high school summer program in which students model a windshield-wiper mechanism with solid modeling software in an introduction to mechanical engineering experience.

The authors have found that well thought-out applications of these tools can bring dynamic systems to life and supplement the analytical methods that are traditionally taught in machine and mechanism design courses.

BACKGROUND

One of the challenges facing mechanical engineering (ME) and mechanical engineering technology (MET) programs today is the implementation of state-of-the-art software within the curriculum. The use of “modern tools” is a requirement of both the Engineering Accreditation Commission (EAC) and the Technology Accreditation Commission (TAC) of the Accreditation Board of Engineering and Technology, Inc. (ABET) [1,2]. Designing curricula and courses that utilize these modern tools without short-changing coverage of classical engineering theory can be a delicate balance. Consider the use of finite element analysis (FEA) software. In the 1970’s and early 1980’s, most courses in FEA courses were taught at the graduate level, with heavy emphasis on theory. Later in the 1980’s and into the 1990’s, FEA classes were added at the undergraduate level, as use of the tool became more widespread in industry. Because commercial FEA programs were complex to learn and use, it was difficult to combine significant theory with instruction in how to use a program. A typical engineering course might still focus predominately on theory, while an engineering technology course might be centered on the use of a commercial program, with a small amount of theory. Over the past five-ten years, FEA programs have become increasingly easy to use (and less expensive), allowing a convergence of sorts of the two types of courses. Ease-of use allows applications to be added to the theory-heavy courses, while the potential for misuse is an incentive to add more theoretical content to the application-based courses.

The use of dynamic simulation software may be similar to that of FEA software a few years ago. The software has become easier to use, especially when combined with solid modeling software. Industrial usage, which was once confined to large companies, is becoming more widespread. One important difference from FEA exists, however: The *theory* associated with dynamic simulations is largely covered in existing dynamics, mechanisms, and machine design courses in most ME and MET curricula. Therefore, modern tools can be integrated into existing courses in most cases. At Milwaukee School of Engineering (MSOE), modern tools for dynamic simulation have begun to be integrated into courses in both the ME and MET programs. In addition to tools that have been created specifically for dynamic analysis, we have included computer-aided design (CAD) software with features that are beneficial to performing mechanism analysis. The tools to be discussed can be categorized as:

- 2-D and 3-D CAD packages with associative capabilities (the ability to rebuild a model in response to a dimension change),

- 2-D stand-alone dynamic analysis programs, and
- 3-D dynamic analysis programs that work with solid modeling software.

2-D CAD

Most machine dynamic texts utilize graphical methods in addition to analytical methods to find the positions, velocities, and accelerations of links and points. At MSOE (and in most MET programs), MET students take a mechanisms class before calculus. The text for this course is *Machines and Mechanisms* by Myszka [3]. Graphical methods are a major part of this class, along with trigonometry-based analytical solutions. While 2-D CAD has long been a helpful tool for graphical analysis, newer CAD packages with associative capabilities have greatly enhanced the value of their use. Consider the position-analysis problem presented in Figure 1. Given the lengths of the links of a 4-bar linkage and the angular position of the driving length, students are to find the angles defining the positions of angles 3 and 4. This problem may be solved graphically by drawing the linkage to scale or analytically with trigonometry (which is not as straight-forward as it appears). However, the solution gives almost no insight into how the linkage works.

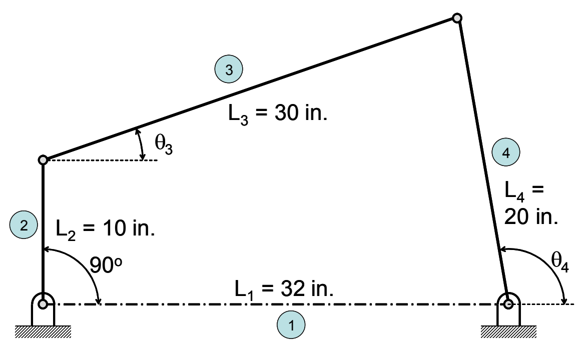

Figure 1 Typical Position-Analysis Problem

If associative 2-D CAD is used, then the problem can be expanded very easily. The problem statement might be extended to read:

> The 4-bar linkage shown here is connected to a motor that drives link 2.
>
> a. Examine the range of possible motions. Is link 2 a crank or a rocker?
> b. Graphically find the range of possible values for θ_4.
> c. Graphically find θ_3 and θ_4 when θ_2 equals 90 degrees, as shown, and verify your answer analytically.

A SolidWorks drawing of the linkage is shown in Figure 2. In addition to the dimensions shown, the linkage is further defining by fixing one of the points of Link 1. Link 1 is displayed in black, indicating that its position is completely fixed. The other links are shown in blue, indicating that they are underdefined and free to move.

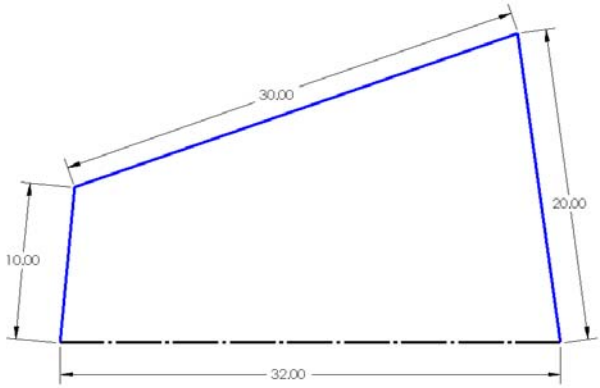

Figure 2 SolidWorks Drawing of Linkage

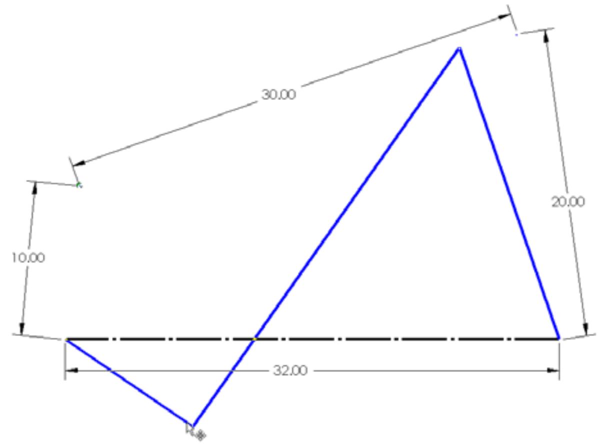

Figure 3 Finding Range of Motion of Link 2

The allowable motion of the linkage can be explored by simply clicking on and dragging one of the links or joints, as shown in Figure 3. Students can easily determine that link 2 is a crank, with a full 360 degrees of motion, while link 4 is a rocker, oscillating between two limiting positions.

These two limiting positions can easily be determined by dragging link 2 and observing the motion of link 4. In Figure 4, one of the limiting positions is shown. Note that the dimensions defining the angular positions of links 2, 3, and 4 are specified as *driving dimensions*, so that they do not define the position of the linkage, but simply reflect the values of these dimensions as link 2 is dragged to a new position. In addition to determining the values of the limiting positions, the students can see that these positions exist when links 2 and 3 are collinear.

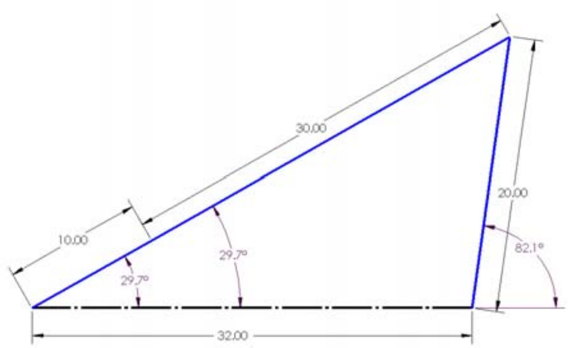

Figure 4 Finding Limiting Position of Link 4

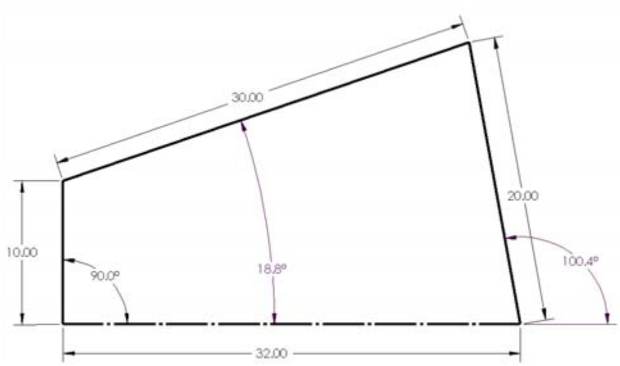

Figure 5 Linkage with θ_2 Defined

The last part of the problem is solved by changing the dimension defining θ_2 to a *driving* dimension, as shown in Figure 5. Although the linkage is now fully defined, any of the driving dimensions (any of the lengths or the angle θ_2) may be changed by double-clicking its value and entering a new value. For example, students might be asked to explore the possible motions of the linkage if the length of link 3 is changed from 30 inches to 20 inches. Link 2 becomes a rocker, and the toggle positions can be found by dragging link 2 to its limiting positions.
In addition to position analysis, 2-D CAD is valuable in velocity analysis when the instant center method is used. 2-D CAD can also be used for vector mathematics in velocity and acceleration analysis, but the authors have found this use of CAD to be not particularly helpful. We have attempted to use CAD only where it can aid in the understanding of analytical solutions.

In summary, we have found that associative 2-D CAD is quite useful in an introductory mechanisms course. Among the primary positive features of this tool are:

1. Drawings are quick and easy to create and modify. Links are simulated with lines, just as they are in kinematic diagrams.
2. The associative nature of the tool allows the motion to be "simulated" and multiple solutions found from a single model.
3. The nomenclature used – driving, driven, fixed – parallels that used in kinematics texts and aids in a more thorough understanding of the terms.

3-D CAD

The use of 3-D CAD allows students to more clearly see the relationship between a kinematic diagram and an actual mechanism. Also, visualization of the mechanism's motion can aid in the understanding of analytical solution. Consider the mechanism illustrated in Figure 6. A typical problem might involve the calculation of the velocity and acceleration of the joint between

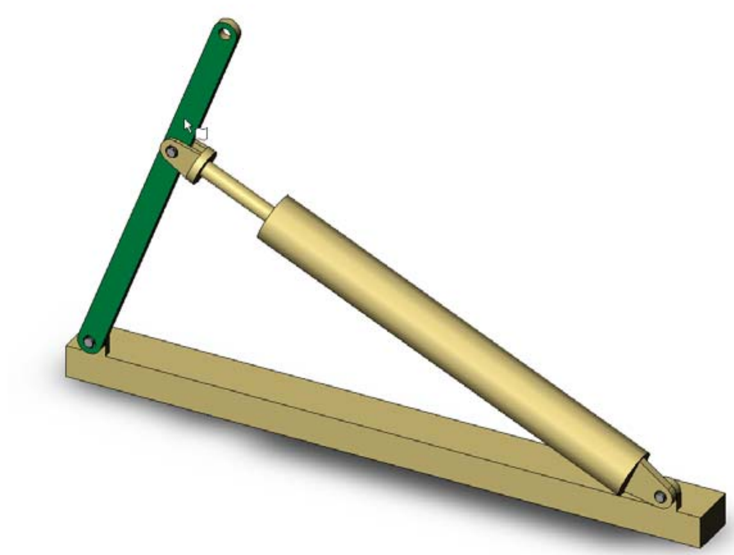

Figure 6 3-D CAD Model of Cylinder Mechanism

the cylinder rod and the pivoting link, given that the rod is extending from the cylinder at a constant rate. An error that students often make is to assume that the rate of the rod's extension is equal to the magnitude of the velocity of the joint. In the SolidWorks model shown in Figure 6, the motion of the assembly can be simulated by dragging the pivoting link. Students can see that the cylinder and rod rotate during the motion, so the rotation must be considered in the velocity calculation. In the mechanisms course in the MET program at MSOE, 3-D CAD is currently used only by the instructor as a teaching aid, as 3-D CAD is not a prerequisite of the course. Even though the basics of SolidWorks are quite easy to learn, we have not concluded that including 3-D CAD as an element of the course is worth the time commitment. Students may become too focused on the process of building and assembling the model rather that the analysis of the motion. Therefore, we currently include motion analysis with 3-D CAD as an element of only a solid modeling course later in the curriculum (although as discussed later, we are considering expanding the use of 3-D CAD by providing component part files to the students and allowing them to assemble the parts and perform motion analysis).

We have used 3-D CAD in a summer introduction to engineering program with high school students. Students quickly grasp the basics of the SolidWorks software, and we attempt to relate the program activities to the design process. Beginning with SW 2003, the software now includes a simulation feature that does not require additional add-in products. This simulation is limited to a qualitative analysis – velocities and accelerations are not calculated – but its simplicity makes it especially useful for the high school program. Students are given the component models for the windshield wiper assembly shown in Figure 7. After assembling the components, a rotary motor can be applied to the crank link, and the resulting motion is displayed on the screen. Students can visualize how an input motion (constant velocity rotation) can be modified through a mechanism to produce the desired output (the oscillation of the wiper blades). It should be noted that the built-in simulation feature of SolidWorks allows fairly complex mechanisms to be modeled. Consider the Geneva wheel mechanism shown in Figure 8. This model is difficult to simulate with dynamic analysis software because of the

Figure 7 Wiper Assembly Model

intermittent contact surfaces that must be defined. In SolidWorks, the simulation is easy, as the software recognizes and simulates the part contacts automatically. The resulting simulation is a valuable aid in the visualization of the workings of the Geneva wheel mechanism.

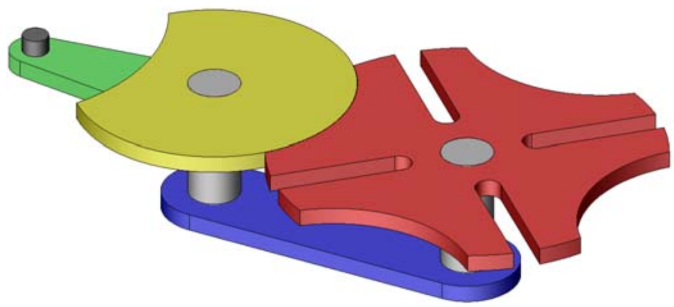

Figure 8 Geneva Wheel Mechanism Model

2-D Dynamic Analysis Software

The incorporation of 2-D Dynamic Modeling tools in the mechanism analysis and design courses of the ME program at MSOE has helped students more quickly engage the concepts being studied. Working Model (Student Edition) is a 2-D dynamic modeling tool that is presently being utilized at MSOE. It comes packaged with the text adopted for these courses, *Design of Machinery,* by Norton [4], giving the students easy access for their modeling.

Time constraints of the course do not allow covering exactly how the modeling software works. Rather, an explanation that merges the students' knowledge of basic mechanics with their recent experiences in numerical modeling prepares them to avoid many of the problems that can arise with this type of modeling software. After working through a brief tutorial on the software, the students find building and analyzing models to be intuitive and quickly begin modeling with Working Model.

At MSOE, 2-D dynamic modeling is incorporated early in the mechanisms courses to help the students verify their hand calculated analyses of basic mechanisms. They assemble limited models in Working Model to gain insight on the behavior of the mechanism. After working through their hand calculations they verify their results by comparing them to their model. As the students progress through the courses, the mechanisms become more complicated. By the end of their experience, the students are using simplified sketches and hand calculations at discrete positions to verify that their complicated computer models are behaving correctly.

Figure 9 shows an example of a mechanism modeled in Working Model. It is part of a student solution to an assigned mechanism design problem. The problem was to connect a pair of barn doors so that they would open together when the right hand door was pulled. One of the requirements of the design involved an analysis to demonstrate that the hand force needed to open the doors would not exceed the force a person constrained to a wheelchair might be expected to exert on the door. Among other parameters, their analysis had to include modeling the friction at the hinges of the doors. Working Model's motor constraints were effectively applied in this student solution to simulate the friction. Results of the hand force for this linkage can be seen in Figure 10.

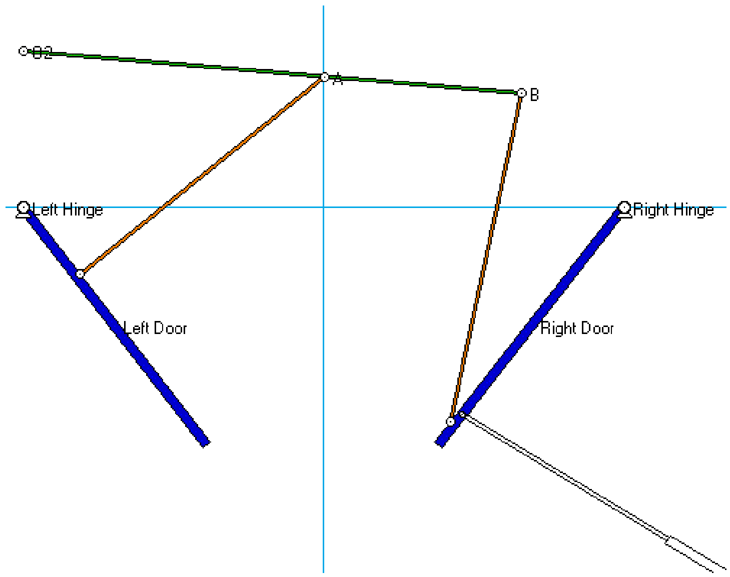

Figure 9 Barn Door Mechanism Example

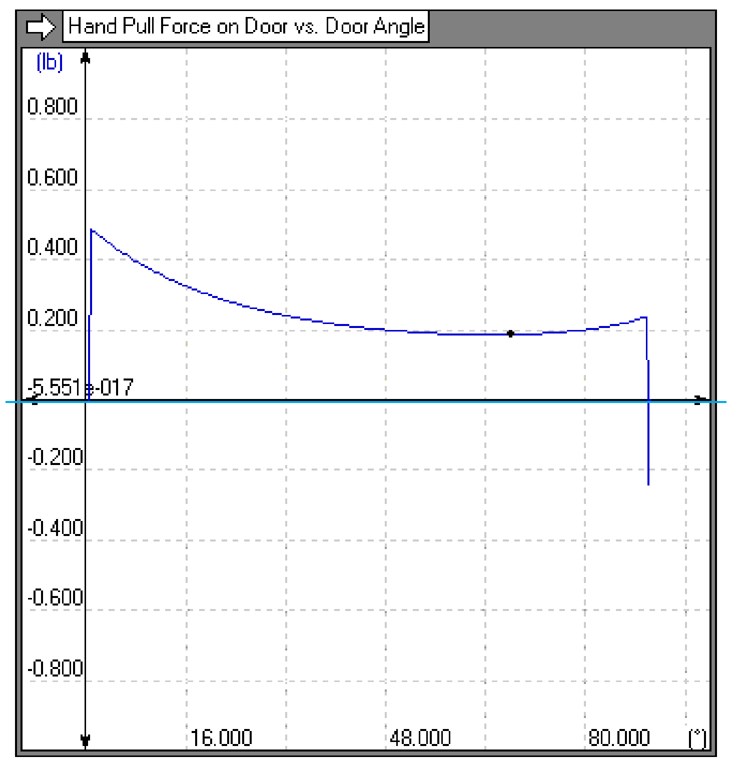

Figure 10 Hand Force From Barn Door Example

The adoption of the 2-D modeling tool has not been at the exclusion of other classic methods used in mechanism design. To help emphasize the fact that many mechanisms are assembled in overlapping planes, there are still assignments that require the students to construct cardboard models of their linkages and demonstrate how they move. In addition, it is emphasized to the students that computer models alone do not form a complete solution. The model's form and results must correlate with hand calculated solutions to verify performance. Since the incorporation of the 2-D dynamic modeling software in ME programs mechanism courses, the students have been able to better explore alternative designs and gain a better experience with the analysis and design of mechanisms.

3-D Dynamic Analysis Software

Motion analysis software is a powerful addition to many popular solid modeling software packages. At MSOE, COSMOS/Motion is available to students as an add-in to the SolidWorks software (the SolidWorks Education Edition includes COSMOS/Works finite element analysis, FloWorks fluid flow analysis, and COSMOS/Motion). Once students learn how to assemble parts in SolidWorks, setting up and running the motion analysis is intuitive. In fact, the mating commands used in SolidWorks are automatically converted into the corresponding joints in the COSMOS model. Motion can be specified for any of the joints, and velocities and accelerations are calculated. Figure 11 shows plots of the acceleration components for the cylinder rod-to-pivoting link joint of the cylinder mechanism shown. This type of motion simulation allows verification of results calculated by the students with hand calculation methods. Force analysis can also be performed, with the inertial properties of the members included. So far, the use of this software at MSOE has been restricted to a required solid modeling class in the MET program and for demos by instructors in other classes. This limited use has been due mostly to logistical reasons, as the software has only been installed in one laboratory. We plan to make greater use of this tool in the coming year, with the software available over the MSOE network. SolidWorks experience is not a necessary prerequisite for use of the motion analysis if the component part files are provided to the students. The students can be taught how to assemble the parts and prescribe motion in a one-hour session.

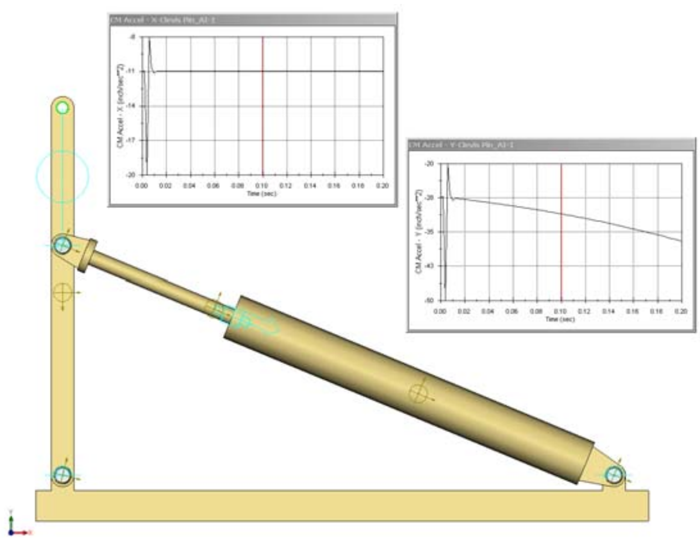

Figure 11 COSMOS/Motion Model of Cylinder Mechanism

Conclusions

As CAD and dynamic analysis software has become more powerful, more affordable, and easier to use, its potential for use in dynamics and mechanism and machine design courses has risen. Well-planned usage of these tools can be an effective supplement to the textbook methods and problems.

Several barriers prevent more widespread usage. The first is instructor familiarity and acceptance. Although the tools discussed are all easy to learn, preparation of lectures and assignments utilizing them adds to an instructor's workload. Also, each instructor needs to weigh the relative effectiveness of each tool to his/her class, and to adjust the time devoted to each topic accordingly. Another factor is simply the time required to teach students to use each tool. One solution to this problem would be to choose specific tools and integrate them fully into the curriculum, so that students are exposed to the tools repeatedly. This fully-integrated approach limits the flexibility of each instructor to integrate new tools when appropriate. This approach also "locks in" the use of these specific tools and makes curriculum changes more cumbersome. With the volatility of the software market, having the flexibility to quickly drop and add software tools is desirable. Therefore, at MSOE, we have avoided such tight integration of software tools into the curriculum.

So far, our observations on the effects of using these tools on student learning have been qualitative. Student comments are positive, but no attempts have been made to date to conduct controlled evaluations of student learning.

References

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