

Learning Kinematics from Concept and Experience

Akihiko Kumagai and Mukasa E. Ssemakula
Division of Engineering Technology
Wayne State University
Detroit, MI 48202

Abstract

Study of kinematics and dynamics of machinery involves very challenging mathematics for engineering technology students who typically take this course at their junior level in a 4-year baccalaureate curriculum. Although mathematics is an essential tool for designing and analyzing mechanisms, this heavy burden in mathematics carries a risk of taking students' attention away from developing the important fundamental concepts of kinematics which are truly beneficial in their future practical technical work. This paper describes an attempt at WSU to develop an experimental kinematics and dynamics course such that students learn the subject from concept and experience. In this method, students are first challenged to solve kinematics problems through the computer simulation software Working Model without knowing the underlying mathematical tools. In this challenge, students will improve the simulation results through trial and error and their own approaches. In most cases, they will realize that the perfect solution has to be obtained from an approach they do not yet know. This challenge will provide them with the experience to develop a concept of each kinematics problem. Only after this challenge, will students be exposed to mathematical approaches to provide perfect solutions to challenge the problems. Finally, they will try another set of simulations using the mathematical approaches they mastered and verify the validity of the mathematical approaches.

I. Introduction

In a traditional kinematics course taught at a typical American university or college, students spend the majority of study time to master mathematical skills to solve miscellaneous kinematics problems. Mathematical skills represented by linear algebra and calculus are very challenging to many students who take kinematics courses in their junior year in a four-year BS curriculum. In addition to the material itself being intellectually demanding, it is frequently taught in a lecture format with little opportunity for active student participation or experimentation. Consequently, students often find it difficult to make the connection between the theoretical concepts covered in the lectures and the corresponding physical phenomena.

This paper describes the development of a course for kinematics and dynamics of machines, aimed at students pursuing BS degrees in Manufacturing and Mechanical Engineering Technology. The course is being developed under the auspices of the Greenfield Coalition (NSF supported project) at the Focus:HOPE Center for Advanced Technologies (CAT) in Detroit, Michigan. The course material is also used in the Kinematics of Machines course at Wayne State University. Most students attending those institutions are working students. They learn technical subjects most effectively and enthusiastically when they realize that those subjects have useful

and essential connection to applications in the manufacturing and design environment where they work. Based on this realization, this course is being developed so that students first observe a practical application associated with the technical subject which they are about to learn [3]. Next, students study the subject through a case study based on the application and then the results of the case study are extended to general theories of kinematics. This approach is quite different from that of traditional kinematics courses where general theories are taught first and then their applications considered.

This paper describes a learning approach so that students use computer simulations to build a conceptual understanding of kinematics and also to realize why mathematical tools are necessary to solve many kinematics problems. In this approach, students are challenged to solve kinematics problems before they learn mathematical tools and theories. They typically try to solve those problems through a trial-and-error approach using interactive features provided in simulations. After this struggle, they realize what technical issues they are facing (concept) and what skills they need to solve the problems. Based on this realization, they learn the mathematical tools and theories necessary to solve the problems. Finally, they perform another set of computer simulations to verify the effectiveness of the new tools they have learned.

II. Course Structure

This three-credit course is composed of the seven modules shown in Table 1. The first four modules are considered to be Part 1: Kinematics. The remaining modules (Modules 5 - 7) are considered to be Part 2: Dynamics. As kinematics is the basis for dynamics, it is essential for a candidate to have a full understanding of Part 1 contents before proceeding into Part 2.

Table 1: Modular structure of the kinematics course

Module No.	Title of Module	Major Topics Covered In Module
1	Basic Concepts of Kinematics	Basic terminology and concepts, Types of joints, Degrees of freedom, Types of mechanisms, Grashof criteria
2	Position, velocity and Acceleration Analysis of Mechanisms	Constructing kinematic models of mechanisms using vectors, Forward and inverse kinematic analysis of Telesis robot
3	Cam Design	Constructing SVAJ diagrams, Synthesizing cams using SVAJ diagrams
4	Gear Trains	Types of Gears, Calculating input-output speed ratios of simple and compound gear trains, Planetary gear systems
5	Dynamics	D'Alembert's principle, Calculation of joint forces and torques of the Telesis robot
6	Balancing	Single plane static and dynamic balancing, Two-plane static and dynamic balancing, balancing system for a 4-cylinder inline engine
7	Final Project	Features of Working Model, Creating planar mechanisms for simulation, Simulation of created mechanisms.

III. Learning Approach

The learning approach for each technical subject in this kinematics course consists of the following five major stages.

1. Observation of practical application

The course development was based on the premise that basic science and engineering principles are best understood by demonstrating their practical applications. Students will observe operations of machines through video clips, photos and in some cases see actual operations of machines at CAT of Focus:HOPE [3]. The aim here is not to teach technical tools of kinematics but to make students realize that a machine they see has a distinctive role in the context of its integrated environment such as a manufacturing line. At later stages of the learning process, this recognition should become a motivation factor to study the mathematics and science behind the mechanism operation.

2. Discovery simulations

Students use computer simulations and manipulate controllable parameters of a mechanism. Discussions among students and between students and an instructor are encouraged to describe the changes they observe by modifying those controllable variables. This is a discovery stage to make students think about relationship between parameters and outcomes to develop a concept of a given kinematics issue. Most of computer simulations in this course were developed using Working Model. Working Model is a very user friendly software package for designing and analyzing mechanisms and it has been often used in kinematics education [2,5].

3. Simulations with specified conditions

At this stage, students are asked some specific questions to help solve kinematics problems using computer simulations. Those questions are designed so that students are able to find out if the concept they developed in the previous stage was appropriate. Also some questions are provided so that students will become frustrated trying to find a right combination of input parameters to satisfy an output requirement by a mere trial-and-error type approach. Students realize that there should be a systematic way to solve a given problem.

4. Learning of technical tools

Students learn the mathematics and science based approach to solve the kinematics problem they struggled to solve in the simulations.

5. Verification simulations

Students verify effectiveness and validity of kinematics tools they learned in the previous stage through a new set of computer simulations.

IV. Examples of Instructional Materials

Example 1: Grashof criteria

The four-bar mechanism is a fundamental linkage mechanism and its applications are found in variety of mechanisms including fixture clamps [3] at Focus:HOPE CAT. Three different kinds of four-bar mechanisms, crank-rocker, double-rocker and double-crank can be generated depending on how the relative link lengths among four bars are set and which of four links are grounded. The crank can rotate continuously through 360° while the rocker can rotate only for a limited range of angle less than 360° . This technical issue called Grashof criteria [1] is covered in Module 1. The computer screen of a simulation to study Grashof criteria is shown in Fig. 1. Scroll bars are provided to change the link length of any of the four bars of the four-bar mechanism shown on the left part of the screen. The bottom link of the mechanism is grounded and motion of the mechanism can be generated by installing a motor at a pin joint (Point A or Point D).

At the stage of "Discovery simulations," each student tries to develop his or her own idea of how parameters provided by those scroll bars could affect the generation of different types of four-bar mechanisms. To give students some guidance for exploring their thought, a hint is provided besides each scroll bar. For example, the top scroll bar is labeled as "Crank Rocker Mechanism, Link 1 – Shortest, Motor – Link1." After some idea is developed, students are encouraged to exchange their findings using word processors and email bulletin boards. The instructor is also encouraged to participate in this discussion to provide appropriate guidance to students. As mentioned earlier, the aim at this stage is not necessarily to obtain a perfect answer or description but to encourage students to build a concept by deriving technical findings from their observations.

At the next stage of "Simulations with specified conditions," more specific directions will be provided to students to come up with technically more mature descriptions and answers. For example, to form a crank-rocker mechanism, the shortest link must be located adjacent to the grounded link. To fully understand this condition, students may be asked to answer a series of questions such as

- (1) Make Link 1 shortest, run the mechanism to see what type of mechanism resulted.
- (2) Make Link 2 shortest, run the mechanism to see what type of mechanism resulted.
- (3) Make Link 3 shortest, run the mechanism to see what type of mechanism resulted.
- (4) Make Link 4 shortest, run the mechanism to see what type of mechanism resulted.
- (5) Which cases generated a crank rocker mechanism?
- (6) From these results, where must the shortest link be placed relative to the grounded link?

Students should find out that only two cases (1) and (3) above result in the crank-rocker mechanism, and for these cases, the shortest link is adjacent to the grounded link. After these simulations, students study this subject through a kinematics textbook such as [1], to learn useful technical tools such as math equations. Authors believe that the experience from computer simulations will greatly help students to master the contents of those technical tools. After studying the textbook, students go back to the computer simulations again to verify the validity of those technical tools they learned.

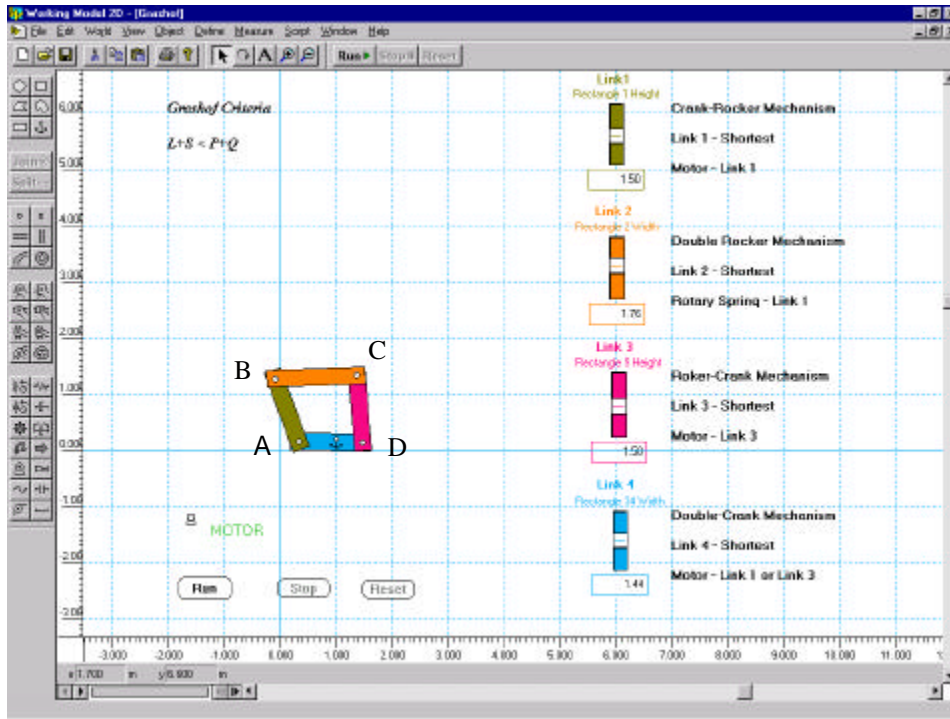


Fig. 1 Grashof Criteria Simulation.

Example 2: Forward and inverse kinematics of a two-link robot

Today the robot is widely used in manufacturing automation and it is a good practical example of a mechanism to study the relationship between the input and output motions. In Module 2 of this kinematics course, students learn forward kinematics and inverse kinematics of a simple two-link robot called "Telesis Robot" used in a manufacturing operation at Focus:HOPE CAT.

At the stage of "Discovery simulations," students try to manipulate the two input joint displacements (angular displacements of links 1 and 2 measured from the line parallel to the x axis into the counter-clockwise direction) for a given output condition using the computer simulation shown in Fig. 2. Students will be asked to position the end-effector to each of three points A, B or C shown on the computer screen. This is a practice to discover the relationship between input and output motions.

At the next stage of "Simulations with specified conditions," students are asked to generate the outer and inner boundaries of the workspace of the robot. These boundaries are generated by two circles; one generated by rotating Link 1 for one complete cycle after setting the relative angle between two links to zero, and the other generated by the same manner except setting the relative angle between two links to 180° . The reachable points are contained in the workspace just created. They will also realize that it is difficult to discover the correct set of input joint displacement values to perfectly position the end-effector to a given reachable point. This experience tells them that they need some systematic method, which they do not know yet (inverse kinematics), to accomplish this positioning task. These computer simulations will

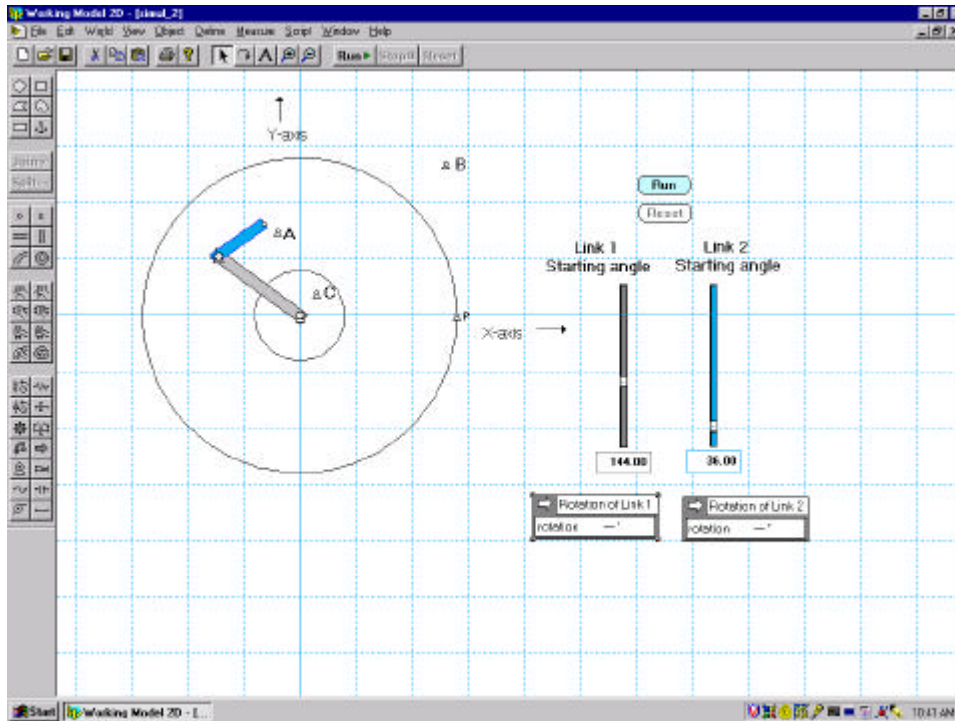


Fig. 2 Point Reach Trial Simulation of a Two-Link Robot.

prepare students to study the mathematical analysis of kinematics of robots as they now know the need for it.

After students learn the mathematical tools needed to analyze forward and inverse kinematics of the two-link robot [4], they work on additional simulations to verify the effectiveness of the kinematics tools they learned. Fig. 3 shows a screen of a computer simulation to position the end-effector point of the robot to any desired target point (Point 1 in the figure). Students can change this target point by mouse dragging or scroll bar operations. When it is positioned within the workspace, the simulation prompts the user to select one of two branch configurations to reach the target point. After reaching the point by one branch configuration, students can try the other branch configuration to reach the same target point. If the target point is located outside of the workspace, the simulation pops up a message to indicate that the point is in fact out of reach. When this happens, students may try to reach the point again by changing the link lengths. Students can also look into the code running the program. The code was developed using the mathematical equations studied in this course. Therefore, students will be able to see how those mathematical equations play roles in running this simulation.

The inverse kinematics equations studied in this course are further extended to control the robot in simulating PTP (Point to Point) and CP (Continuous Path) operation. Fig. 4 shows a computer screen of this simulation. In this simulation, the end-effector point of the robot first moves by PTP operation from its home position to a specified point (call this point Point A). Then it moves along a straight line constrained by Point A and another specified point (call this point Point B) by CP operation. Finally it returns by PT operation from Pint B to the home position. Students

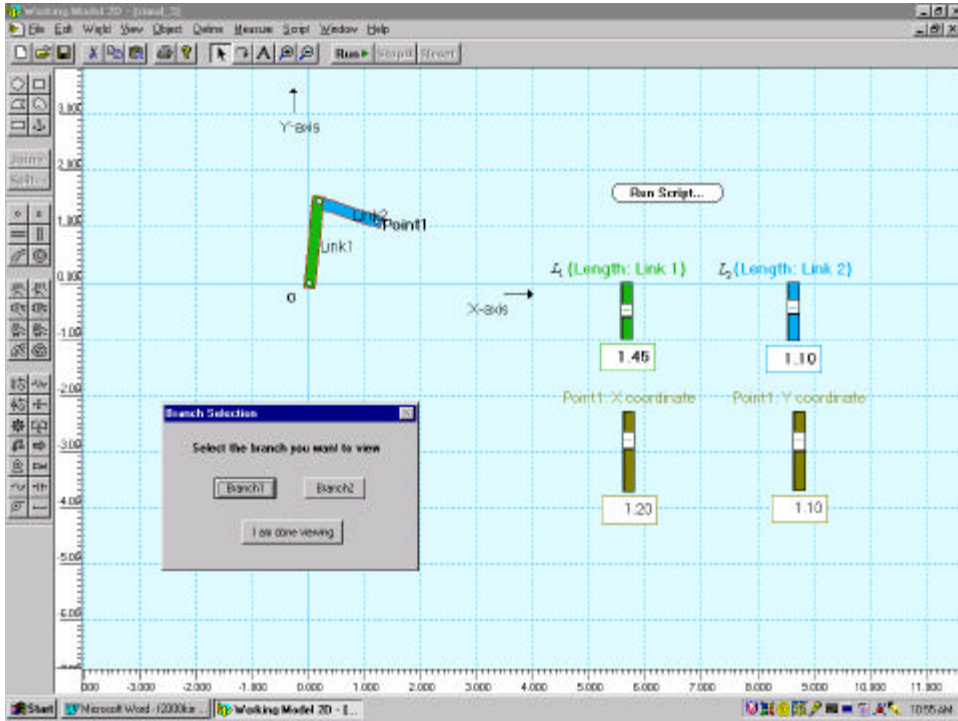


Fig. 3 Inverse Kinematics Computer Simulation.

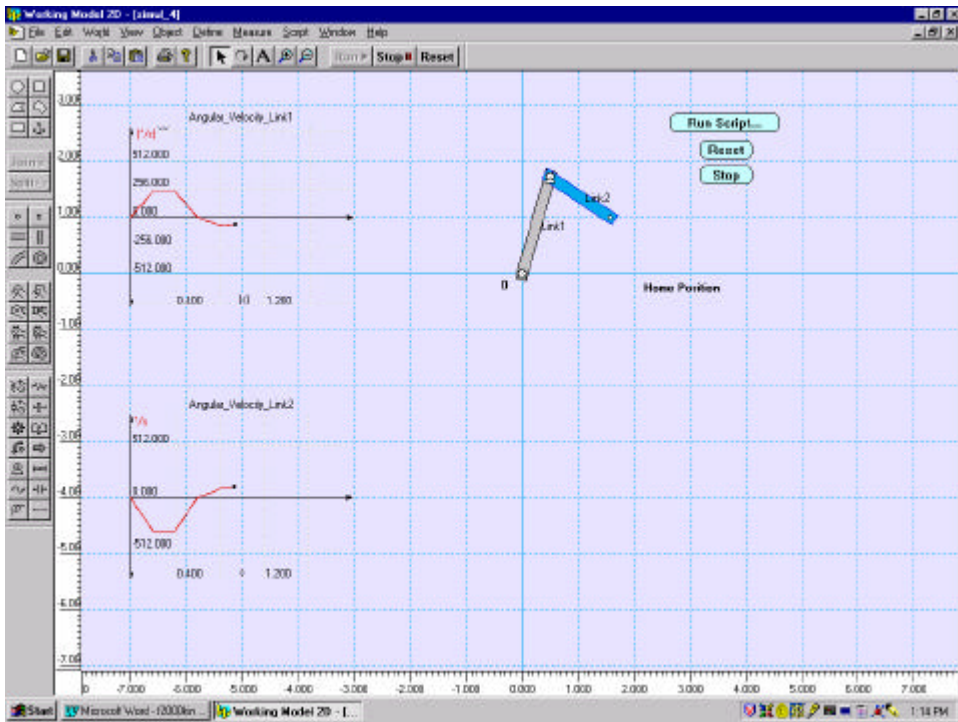


Fig. 4 PTP - CP Simulation.

can manipulate the locations of points A and B through dialog boxes provided by this simulation. They learn how to appropriately construct smooth joint velocity movement using the trapezoidal velocity profile for the PTP motion. In PTP motion, students calculate the joint displacements to reach Point A from the home position using the inverse kinematics formulas. Then they will construct trapezoidal velocity profiles for both joints knowing that the area of the trapezoid is equal to the joint displacement. For the CP motion, students realize that the joint velocities are constrained by the output trajectory (straight line) given.

Example 3: Balancing of a rotational disk

Static and dynamic balancing of rotational machinery is an important technical subject especially in the Detroit area where our university is located and where the automotive industry prospers.

At the discovery stage, students try to discover the effect of concentrated masses attached to a rotational disk to unbalance behavior through a simulation as shown in Fig. 5. The simulation allows students to change the location of the attached masses, the value of each mass, and the speed of the motor. When the simulation is run, the x and y components of the shaking force at the rotational axis of the motor are displayed on the graph shown on the upper left part of the computer screen.

At the next stage of simulations, students are asked to observe the behavior of the shaking force by changing one parameter at a time. Here students should notice that the shaking force changes proportionally to some input parameters but non-proportionally to some other parameters. For example, students should notice that the shaking forces are proportional to the square of the input motor speed.

After learning mathematical equations to calculate the location and value of a counter mass to achieve the static and dynamic balancing of the rotational disk, students try another set of simulations to verify the effectiveness of the equations they learned. The computer screen of the simulations for this purpose is shown in Fig. 6. The rotational disk shown in Fig. 6 is initially unbalanced (Invisible masses are attached to the disk). Students first confirm that the disk is unbalanced by running it and observing the x component of the shaking force. The location and mass value of the counter mass (See Fig. 6) is calculated by using the equations learned with the phase angle and peak value of the shaking force obtained from the force graph. The example of the graph shown in Fig. 6 indicated that the resultant shaking force is nearly zero after the counter mass is attached to the rotational disk in this manner.

V. Conclusions

A learning approach using computer simulations to help students develop an understanding of kinematics concepts and theoretical tools has been described. Digitized videos, animations and simulations enable the student to visualize concepts in multiple ways. Additionally, interactive features of computer simulations help the student to explore the course content more thoroughly. The course material described in this paper has been used for the past two semesters in the undergraduate Engineering Technology curriculum at WSU. Simulation performances and test scores from those students have been extremely encouraging to confirm

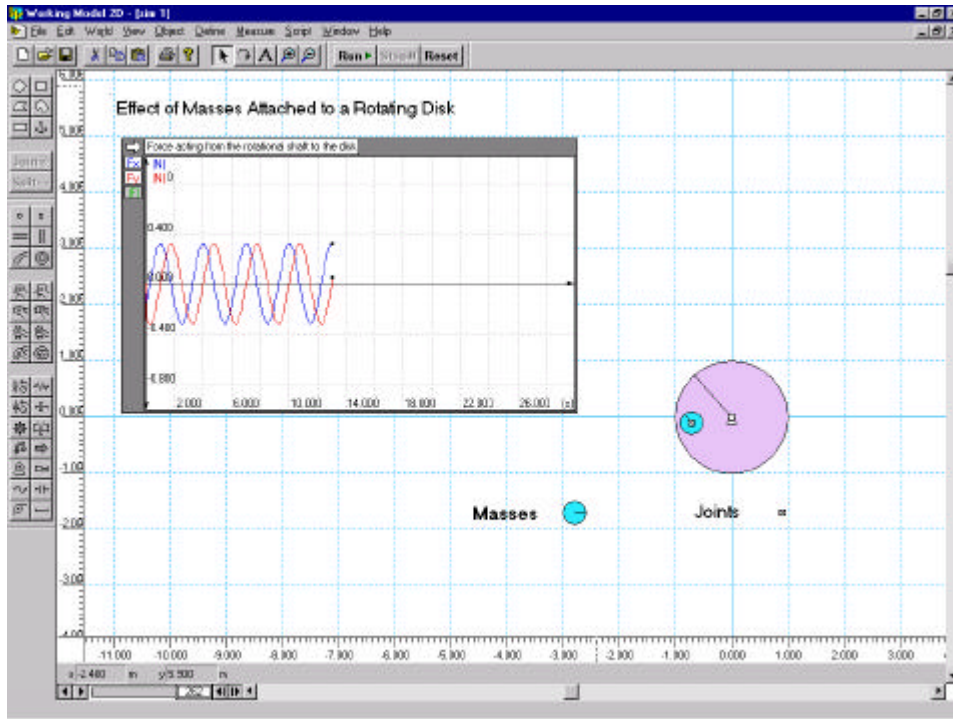


Fig. 5 Simulation for Effect of Masses Attached to a Rotational Disk.

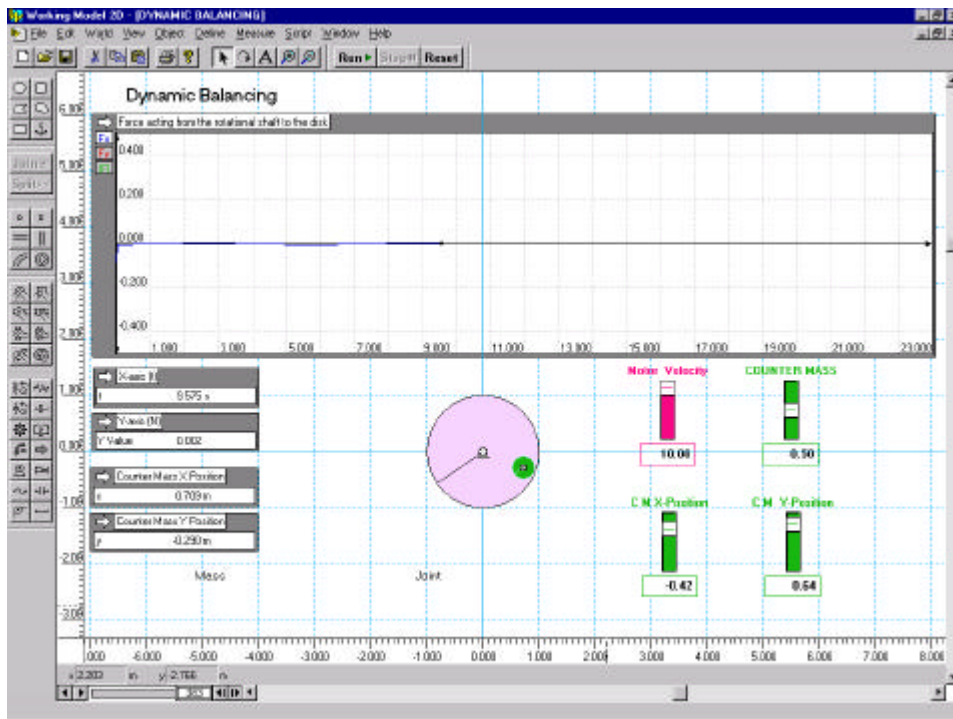


Fig. 6 Dynamic Balancing Simulation

that this course material is suitable for a wide variety of students who seek careers in design and manufacturing fields to understand important concepts in the kinematics and dynamics of machines.

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Bibliography

1. Erdman, A. and Sandor, G., *Mechanism Design: Analysis and Synthesis*, 3rd Ed., Prentice Hall, 1997
2. Jong I.C., Onggowijaya, S.N., "Animation Programming with QuickBASIC to aid the Teaching of Kinematics," Proceedings of 1998 ASEE Annual Conference, Seattle, WA, June 28 - July 1, 1998, Session 1668.
3. Kumagai, A. and Ssemakula, E., "Kinematics for Manufacturing Engineering Technologists," Proceeding of 1999 ASEE Annual Conference, Charlotte, NC, June 20- 23, 1999, Session 1463.
4. Kumagai, A. and Ssemakula, E., "Learning Kinematics for Robots Without Using Transformation Matrices: A Computer-Based Approach," to appear in Proceedings of Flexible Automation and Intelligent Manufacturing Conference, College Park, MD, June 26-28, 2000
5. Morrison, D., Neff, G., and Zahraee, M., "Aircraft Landing Gear Simulation and Analysis," Proceedings of 1998 ASEE Annual Conference, Seattle, WA, June 28 - July 1, 1998, Session 1620.

AKIHIKO KUMAGAI is an Assistant Professor of Engineering Technology at Wayne State University, Detroit, MI. He earned his B.S. and M.S. in Mechanical Engineering from the University of Florida in 1983 and 1985 respectively, and his Ph.D. in Mechanical Engineering from University of Wisconsin-Milwaukee in 1993. His current teaching and research interests include manufacturing, kinematics, dynamics, robotics and controls. Prior to joining WSU, he worked for Motorola and United Technologies Automotive to pursue various Manufacturing and Automation related projects.

MUKASA E. SSEMAKULA graduated from the University of Manchester Institute of Science and Technology, England, with a Ph.D. in Mechanical Engineering in 1984. He joined Wayne State University in 1993 as an Associate Professor of Engineering Technology. His has research interests and has published widely in the areas of Manufacturing Systems and Computer Aided Instruction. He teaches in the areas of manufacturing, robotics, mechanics, and engineering mathematics.