

---

# An example of the interaction between virtual and physical experiments in dynamics

H. P. Lee

*Associate Professor, Department of Mechanical Engineering, National University of Singapore; Deputy Divisional Director (Research), Institute of High Performance Computing, 1 Science Park Road #01-01 The Capricorn, Singapore Science Park II, Singapore 117528  
E-mail: hplee@ihpc.nus.edu.sg*

**Abstract** A web-based interactive virtual experiment on the subject of conservation of angular momentum is presented. Students can perform the virtual experiment anywhere via the web before executing the actual physical experiment in a laboratory. The virtual experiment is designed to incorporate factors and parameters that could be estimated or fixed arbitrarily, or to be varied based on the results of the physical experiment. Students will then have a better understanding of the limitations of a virtual experiment and how a physical experiment could help to refine the corresponding virtual experiment.

**Keywords** conservation of angular momentum; virtual experiment; web-based applications

## Introduction

Web-based presentation of products, experiments and courses are becoming very popular with the proliferation of personal computers and the popularity of web-based applications. The materials can be assessed at anytime from anywhere. In recent years, many instructors have put classes on the web that previously were given in a laboratory. A website of Johns Hopkins University [1] contains some of these virtual laboratories. Examples presented are on the subjects of diffusion processes, logic circuits, and robotic arm control, heat transfer in a duct and some other related topics. In a typical virtual lab, students can drill for hidden supplies of oil, program a robotic arm and design digital logic circuits.

It has been argued that, in this manner, students can be taught the engineering concepts without the high costs, time constraints and space limitations associated with physical laboratories. Although students may not get the full experience when using virtual equipment in a virtual laboratory, even if it is only 80% effective this must be considered against the cost, which may be only 10% of that of a physical laboratory.

One example of a virtual laboratory, CyclePad [2], relates to the teaching of thermodynamics. It enables students to construct and analyse a wide variety of thermodynamic cycles. Virtual laboratories have also been set up for teaching statistics [3] and mathematics [4]. The web-based presentation consists of case studies that include data from real experiments. Other features include the interactive computer simulations of important statistical concepts, detailed discussions and explanations of statistical issues related to case studies and simulations, and a set of statistical experiments that students can undertake to discover important statistical relation-

ships and principles. Of the large number of virtual experiments, many will be only for in-house use, and will not be widely known.

Virtual experiments can be carried out either as teaching aids on their own, without the need for doing any other physical experiment, or before actual physical experiments, or for comparison after performing physical experiments. Simulations can be carried out more rapidly in virtual experiments than additional physical experiments in a laboratory. Virtual and physical experiments can be designed to complement rather than replace one another.

In the present paper, a virtual experiment on the subject of conservation of angular momentum is presented. The virtual experiment is designed in such a way that the system parameters in the experimental set-up can be varied, based on the experimental results obtained from the corresponding physical experiments. Students will have a better understanding of the limitations of a theoretical model in describing an actual physical phenomenon and how a physical experiment can help to refine and improve a theoretical model. The time for performing the physical experiment could also be shortened because students will be experienced in performing the virtual experiment.

### The physical experiment

The experiment presented in this paper is related to the subject of rigid-body dynamics, which is usually taught as a first course in dynamics for undergraduate students in the Department of Mechanical Engineering at the National University of Singapore. The experiment is designed to elaborate the principle of the conservation of angular momentum for a specific rotational motion. The physical set-up consists of a Perspex rim with two crossed tracks mounted on a rotating shaft (Fig. 1). The rotation of the shaft is controlled by a motor via a pair of meshing gears. There is a steel ball on each side of the crossed tracks. The steel balls are first confined to their innermost position (at a radius of  $r_1$  from the axis of rotation) and retained at this position by spreader arms (Fig. 1), when the pair of gears is engaged (Fig. 2). The whole rim with the steel balls is then set into motion at a prescribed speed. The spreader arms are then released, with the simultaneous disengagement of the gears. The steel balls thereafter immediately move to the outermost position (at a radius of  $r_2$  from the axis of rotation) due to the action of centrifugal forces. As the moment of inertia of the steel balls about the rotating axis increases suddenly, there is a sudden decrease in the rotating speed of the system. The rotational speed is measured by a tachometer.

In the physical experiment, students are asked to plot the angular speed,  $\omega_1$ , before the release of the spreader arms against the angular speed,  $\omega_2$ , immediately after the release of the spreader arms and disengagement of the motor. From the momentum–impulse equation:

$$(I_{b1} + I_s)\omega_1 + \text{external angular impulse} = (I_{b2} + I_s)\omega_2$$

The term  $I_{b1}$  is the moment of inertia of the four steel balls in the innermost position about the rotational axis. Similarly, the term  $I_{b2}$  is the moment of inertia of the

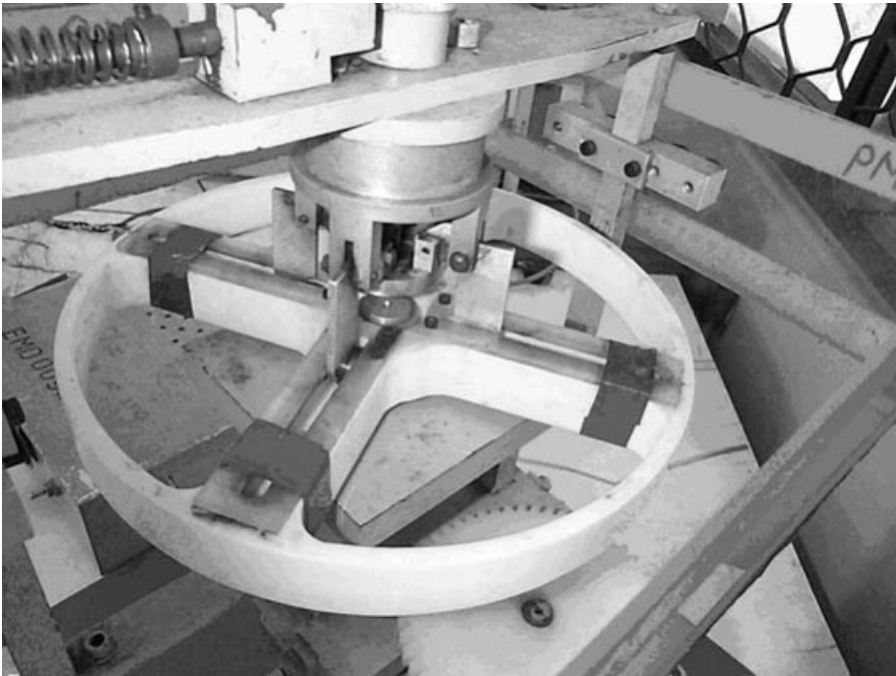


Fig. 1 The Perspex rim with the spreader arm retaining the four steel balls.

four steel balls in the outermost position, after the release of the spreader arms about the rotational axis. The term  $I_s$  is the moment of inertia of the remaining parts – the shaft, the spreader arms, the gear and the rim about the rotational axis. The external angular impulse can be expressed as  $M_{ave}(t_2 - t_1)$ . The term  $M_{ave}$  is the average external moment acting on the system,  $t_1$  is the time when the motor is disengaged and  $t_2$  is the time when the steel balls reach the outermost position. As the steel balls take a very short time to move from the innermost to the outermost position, the term  $t_2 - t_1$  is a very small quantity. As  $M_{ave}$  tends to be a finite quantity, the external angular impulse, which is a product of a finite quantity with a very small quantity, will tend to be negligible. It is a good approximation that:

$$(I_{b1} + I_s)\omega_1 = (I_{b2} + I_s)\omega_2$$

where:

$$I_{b1} = 4\left(\frac{2}{5}ma^2 + mr_1^2\right)$$

$$I_{b2} = 4\left(\frac{2}{5}ma^2 + mr_2^2\right)$$

The term  $a$  is the radius of the steel balls.

By plotting  $\omega_2$  against  $\omega_1$ , the slope of the straight line is equal to  $(I_{b1} + I_s)/(I_{b2} + I_s)$ . As  $I_{b1}$  and  $I_{b2}$  can be computed,  $I_s$  can then be estimated from the gradient of the

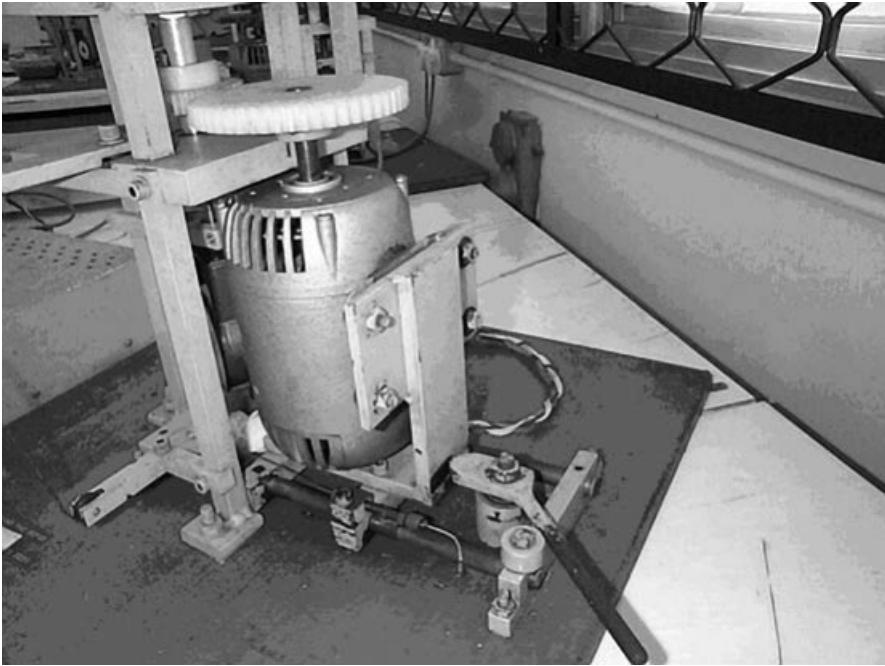


Fig. 2 Motor with the pair of gears engaged.

straight line. The intercept of the line is an indication of the experimental error as well as the contribution from the external angular impulse, which has been assumed to be negligible.

Details of the write-up for the experiment can be found in the paper by Lee and Sabbir Ahmed [5].

### The virtual experiment

For the virtual experiment,  $I_s$  is first given an estimated value. It is also initially assumed that there is no external angular impulse acting on the system, such that  $M_{ave}(t_2 - t_1)$  is equal to zero.  $I_s$  could be updated using the results obtained from carrying out the physical experiment.  $M_{ave}(t_2 - t_1)$  could also be estimated from the results obtained from the physical experiment. The virtual experiment can then be repeated with the undated data. The theoretical model for the virtual experiment is thereby refined.

The output screen at the beginning of the virtual experiment is shown in Fig. 3. The rim with the steel balls is rotating at a speed of 300rpm. The range of rotating speeds for the physical experiment is from 300 to 1000rpm and the virtual experiment is also confined to this range. However, the rotation is presented at 1/100 of the actual speed so that the students can see and 'feel' the rotation on the screen.

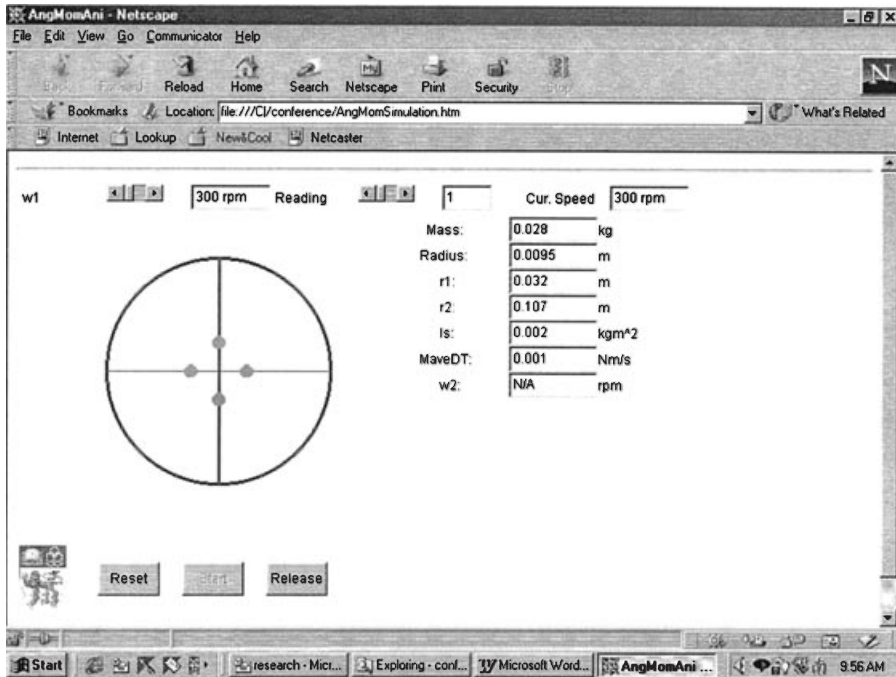


Fig. 3 The output screen at the beginning of the virtual experiment.

The actual speeds would be too fast for the students to see the changes in rotational speed on the screen. The values for all the other parameters, such as the mass of each steel ball,  $r_1$ ,  $r_2$ ,  $I_{b1}$ ,  $I_{b2}$ ,  $I_s$  and  $M_{ave}(t_2 - t_1)$  are also indicated on the screen. These parameters could be changed either arbitrarily or based on the results from the corresponding physical experiments.

The release of the spreader arms is simulated by hitting the release button. When this button is hit, there is a sudden decrease in rotational speed. The output screen is shown in Fig. 4. The new speed is shown on the screen as about 222rpm. Moreover, the steel balls move from the innermost position to the outermost position. There is a visible slow-down in the rotation of the rim and the steel balls. The virtual experiment can be found on the author's website [6].

The applet is designed to perform 15 sets of experiments for obtaining 15 sets of values for  $\omega_2$  and  $\omega_1$ . This is designed to be compatible with the actual physical experiment, for which the students are also asked to collect at least 15 sets of values.

The parameters such as  $I_s$  and  $M_{ave}(t_2 - t_1)$  in the virtual laboratory can be changed based on the results from the physical experiments. The students will then have a better understanding of how a physical experiment can help to refine a virtual experiment. In this example, the values of  $M_{ave}(t_2 - t_1)$  and  $I_s$  can be estimated from the physical experiment, as they are difficult to derive theoretically. With the digital pictures of the experiment and the virtual lab, the student will be familiar with the actual

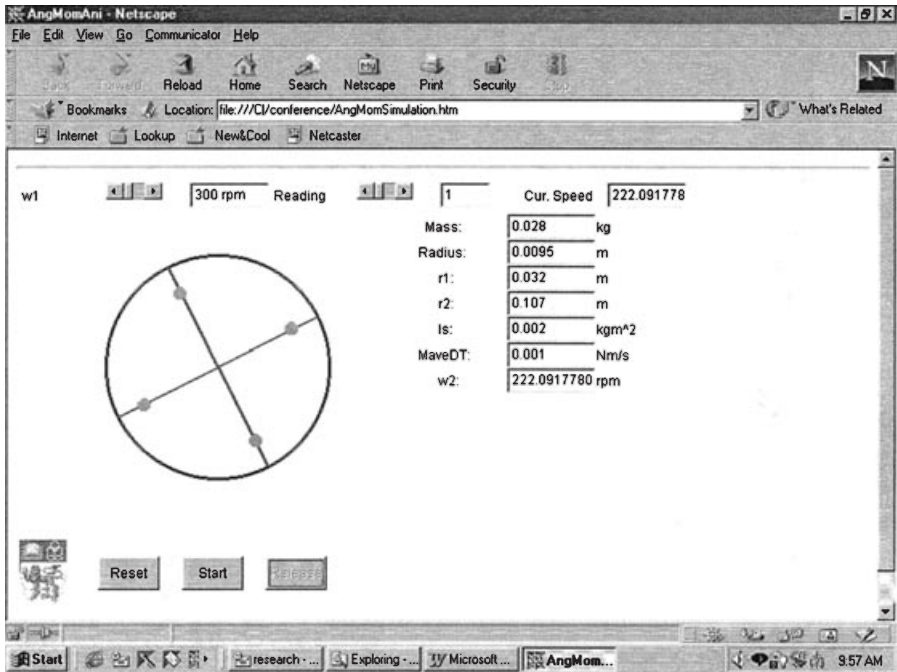


Fig. 4 The output screen after the release of the spreader arms.

physical set-up and experimental procedure before performing the actual experiment. This will enable students to perform the actual physical experiment in a shorter time and enable a better understanding of the principles.

## Conclusion

A virtual experiment elaborating the principle for the conservation of angular momentum has been presented in this paper. The corresponding physical experiment is also described for getting a better understanding of the virtual experiment. The paper also describes how the theoretical model of the virtual experiment could be refined and improved with the results obtained from the physical experiment. The present work is an extension of an earlier work by Lee and Sabbir Ahmed [5] on an interactive web-based manual for laboratory classes in dynamics.

## Acknowledgement

The author wishes to thank Sabbir Ahmed for performing the Java programming of this virtual experiment. All the links in the references were active during the preparation of this manuscript.

## References

- [1] <http://www.jhu.edu/virtlab/virtlab.html>
- [2] <http://www.qrg.ils.nwu.edu/projects/NSF/Cyclepad/cyclepad.htm>
- [3] [http://www.ruf.rice.edu/~psyc/news/Rice\\_Virtual\\_Lab\\_in\\_Statist.html](http://www.ruf.rice.edu/~psyc/news/Rice_Virtual_Lab_in_Statist.html)
- [4] <http://www.indiana.edu/~ucspubs/ucstimes/1996/t137/>
- [5] H. P. Lee and K. Sabbir Ahmed, 'Interactive web-based manual for laboratory classes in dynamics', *IJMEE*, **28** (2000), 213–220.
- [6] <http://137.132.147.80/angmom>