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Student Experiment on Coriolis Force

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A simple experiment is described in which measurements may be made of the trajectory of a of a particle moving under the influence of the Coriolis force; these measurements in turn provide experimental verification of certain elementary features of the motion.

INTRODUCTION

If recent textbooks[1–3] are indicative of the material presented at the freshman–sophomore level, the concept of Coriolis force is introduced now at an early stage in many physics programs. In spite of the confusion that often follows the presentation of this concept, the author knows of no elementary experiment which permits the student to make measurements of the trajectory of a particle moving under the influence of the Coriolis force. Demonstration apparatus qualitatively showing the nature of the Coriolis force has been described.[4,5] Expect for these brief articles, nothing has been found that would serve adequately as an elementary investigation of this phenomenon.

The basic ideas underlying the experiment can be understood by referring to Fig. 1(a). A ball of mass m is moving with constant speed v in the channel AB which is fixed with respect to the xy-coordinate system. Beneath the channel is a turntable rotating with constant angular velocity $\boldsymbol{\omega}$ about the point 0. Relative to an observer situated on the turntable, the ball experiences a force given by[6]:

$$\mathbf{F} = -2m(\boldsymbol{\omega}\times\mathbf{v}_1) - m[\boldsymbol{\omega}\times(\boldsymbol{\omega}\times\mathbf{r})], \qquad (1)$$

where $\mathbf{r}$ is the radius vector from 0 to the position of the ball and $\mathbf{v}_1$ is the velocity of the ball relative to the observer on the turntable. The resulting trajectory is a spiral and is shown in Fig. 1(b). Near the point 0, the velocity $\mathbf{v}_1$ approaches $\mathbf{v}$, the velocity of the particle in the inertial frame of reference, so that the equation of motion at 0 can be written:

$$2m\omega v = mv^2/R, \qquad (2)$$

where R is the radius of curvature of the trajectory at the point 0. Solving Eq. (2) for R yields the relation:

$$R = v/2\omega \qquad (3)$$

The apparatus described in this article is designed so that R, v, and ω can be measured, and thus permit Eq. (3) to be verified.

It is obvious that Eq. (3) can be derived equally well by an observer in the inertial frame solely on the basis of kinematics, so that the prediction of the trajectory can be viewed as a mathematical exercise. This fact serves to emphasize the kinematical nature of the Coriolis force and to demonstrate that a kinematical problem in the inertial frame can be viewed as one in dynamics in the rotating frame. The correspondence between kinematics in one frame and dynamics in another should help to remove

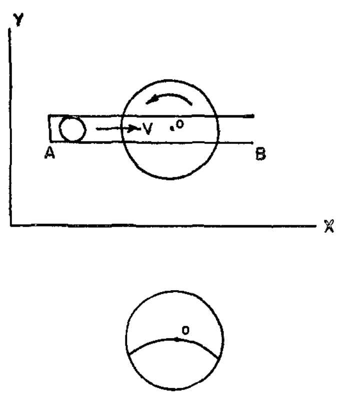

Fig. 1(a) Ball of mass m is moving with constant velocity through the stationary channel AB above a turntable rotating about the the point 0. (b). Trajectory of the ball as seen by an observer rotating with the turntable.

[1] F. W. Sears, *Introduction to Mechanics. Heat and Sound* (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1958).
[2] U. Ingard and W. L. Kraushaar, *Introduction to Mechanics, Matter and Waves* (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1960).
[3] R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics* (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1963).
[4] A. A. Klebba and H. Stommel, Am. J. Phys. **19**, 247 (1951).
[5] A. G. Rouse, Am. J. Phys. **27**, 429 (1959).
[6] D. E. Christie, *Vector Mechanics* (McGraw-Hill Book Company, Inc., New York, 1964).

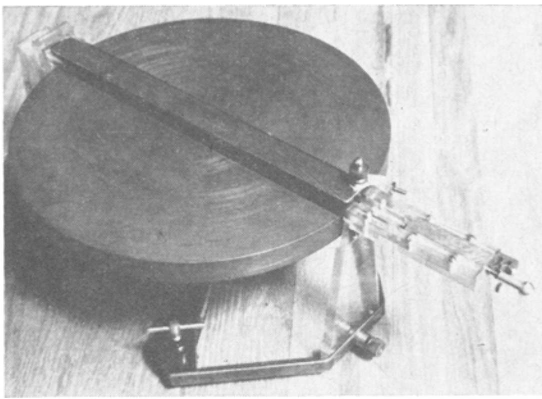

FIG. 2. Photograph of the launcher, lucite channel, and turntable.

the aura of mystery that often shrouds the concept of Coriolis force.

I. EXPERIMENT AND EQUIPMENT

Most of the equipment required for this experiment is available commercially; the modifications and additions required are modest and well within the scope of any department that has access to a machine shop. The major pieces of equipment are the turntable and tripod base, both of which are available commercially.[7]

The major addition consisted of a lucite channel situated $\frac{1}{16}$ in. above the table and a spring-loaded plunger which launched a $\frac{5}{16}$-in. steel ball into the channel; the launcher and channel were constructed as a single unit. The roof of the channel was made of $\frac{1}{16}$-in. steel plate. The launcher and channel were supported by a vertical sheet of $\frac{1}{4}$-in. lucite which in turn was supported at its base by a section of angle iron attached to two of the legs on the tripod base. A photograph of the turntable, channel, and launcher is shown in Fig. 2.

The plate on the roof of the channel was connected to the high-voltage terminal of a synchronous spark timer, also available commermercially[7]; the ground terminal was connected to the turntable. The sparking caused by the moving ball left a visible trace on a sheet of Teledeltos paper cemented to the turntable; a sample trace is shown in Fig. 3.

A second modification was introduced by drilling a $\frac{1}{8}$-in. hole through the axis of the turntable and tripod base to accommodate a piece of piano wire which could be raised by a simple lever arrangement to puncture the paper cemented to the turntable. This puncture located the point 0, and thus served as a convenient reference in measuring the angular velocity of rotation. Since sufficient variation in the angular velocity could be provided by spinning the turntable by hand, the necessity of a driving mechanism was eliminated.

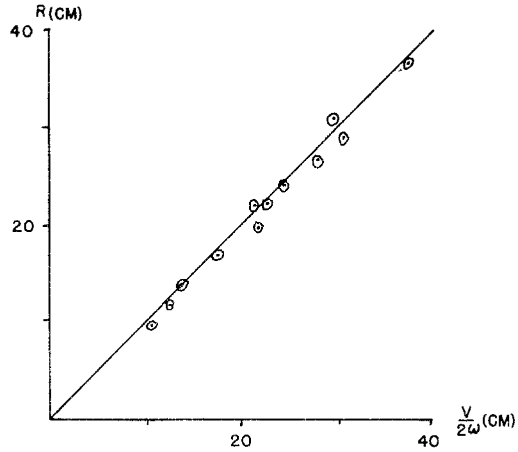

FIG. 4. Graph of the radius of curvature R as a function of $v/2\omega$. The solid line represents Eq. (3); the circles represent experimental points.

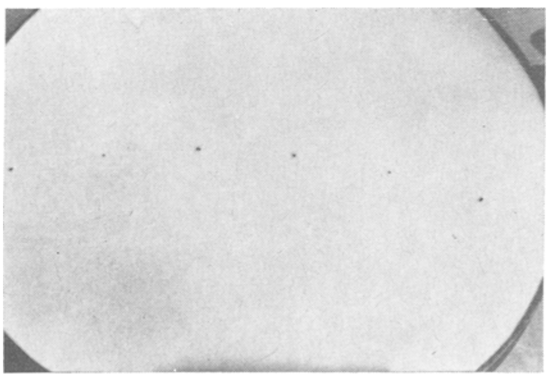

FIG. 3. Photograph of the trajectory of the ball which has crossed the turntable.

II. RESULTS

It is evident that all three variables in the motion, R, v, and ω can be measured from a trace of the type shown in Fig. 3. Since the laboratory time required to obtain one trace is approxi-

[7] Central Scientific Company, 1700 Irving Park, Chicago 13, Ill.

mately 1 min, one lab group can obtain 10–15 traces in a very short period of time. This has the obvious advantage of enabling three or four groups to use the same piece of apparatus and to avoid the necessity of duplication of equipment.

Figure 4 shows the results of a set of sample traces taken with this apparatus. The agreement between the experimental points and the solid curve representing Eq. (3) is reasonably good. The values of R and $v/2\omega$ in the range shown can be measured with a ppe of $\pm 10\%$. The size of the turntable sets the upper limit on the range for which reasonably precise values of R can be taken while friction sets the lower limit by causing the speed of the ball to change appreciably within the neighborhood of 0.

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Do-It-Yourself Knudsen Gauge

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A Knudsen Gauge, suitable to be designed and built by sophomores, is described. This experiment gives an example of a theory (molecular transport of momentum) which has an easily seen breakdown, namely the finite size of molecules. The students verify the idea of molecular momentum transport and then use the deviations of the experimental results at high pressures from their simple theory to give them a measurement of molecular collision cross sections.

We all know that the usual blackbox laboratory bears no relationship to the way work is carried out in a real laboratory. However, a black box lab does expose the students to a series of new phenomena and is an efficient method of exposing them to a large number of these phenomena. You might now ask the question: is this what you want to accomplish in a lab course? A vital ingredient is missing from this sort of lab. When the students have finished being exposed, they have little more idea of how to examine a new situation than when they started the course.

We tried a different approach in the first term of the sophomore experimental course. The students are given two projects to complete in the first term. These projects are based on physics that a sophomore can understand—basically mechanics concepts (i.e., damped harmonic oscillator, Hooke's law, torque). The catch is that they must design and build the apparatus from scratch. The design work includes all the calculations that go into the experiment. The necessary technology (which depends only on knowledge) is given by the instructors as a series of possible choices of materials at each step in the design. The students base their design calculation on these materials. As an aside, this process seems to bother some students because they find no unique design possible. They continually ask for the "right" answer in the beginning, and it is only after having completed a project that they realize how meaningless this question is.

With this background one of these projects, the Knudsen gauge, can be examined. This project was chosen because a simple theory of its behavior in a region can be developed. A natural limit to this theory can be seen and used to measure the effect (molecular cross section) that causes the theory to break down. The Kundsen gauge is basically a device for measuring the momentum flux carried by hot molecules. It consists of a hot body at a temperature $T_1°$ placed in front of one side of a vane at temperature $T_0°$ strung on a torsion fiber. (See Fig. 1.) The molecules that come from the hot body carry more momentum than the molecules that are at temperature T_0. The vane is pushed away from

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