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THE MERCER ONLINE INTERACTIVE CHAOTIC PENDULUM

By Matt Marone

AT MERCER UNIVERSITY, WE HAVE DEVELOPED AN ONLINE INTERACTIVE CHAOTIC PENDULUM (HTTP://PENDULUM.MERCER.EDU). THIS PENDULUM IS UNIQUE IN THAT IT IS NOT A COMPUTER SIMULATION BUT AN ACTUAL DEVICE THAT YOU CAN remotely control through the Internet. Our objective is threefold. We are attempting to provide an educational resource for chaos, demonstrate a new technology, and experiment with a new method of laboratory education.

Figure 1 shows the pendulum control panel. As students vary the driving frequency, they can watch the pendulum's motion switch from simple periodic motion to chaotic motion. The control software incorporates several mathematical analysis functions so that students can view the pendulum data in different ways. Students can conduct experiments using the pendulum, download their data, and conduct their own mathematical analysis.

Hardware

Randall Peters, the chair of Mercer University's Physics Department, designed the chaotic pendulum. TEL-Atomic (www.telatomic.com) markets a commercial version called the Multipurpose Chaotic Pendulum. (Details of the TEL-Atomic chaotic pendulum, as well as pendulums from several other companies, appear elsewhere.[1]) We modified the commercial version to produce our online interactive version.

A necessary condition for chaotic motion is that the bob can freely swing over the top. The bob is driven by an induction motor, with the pendulum arm connected directly to the motor armature. An induction motor has little friction and is easily reversed by altering the phase of the drive coils. A square-wave drive signal (the black square wave in Figure 1) periodically reverses the motor's rotational direction.

An eddy current sensor captures the velocity data. An aluminum disk connected to the motor shaft rotates between two rare-earth magnets mounted on a small cantilever. This rotation produces eddy currents, and the cantilever bends. A symmetric differential capacitance sensor monitors the cantilever's deflection. Because the eddy currents are velocity dependent, the deflection indicates the velocity.

We obtain position data by integrating the velocity signal, using a simple op-amp (LF 356) integrator circuit. Op-amp integrators use a capacitor for feedback and are prone to saturation. At DC (zero frequency), the capacitor blocks the feedback and the output wanders off to saturation. A common way around this problem is to make a "leaky" integrator, which places a high resistance across the capacitor.[2] However, this "hardware" integration produces an artifact in the phase space data. For periodic motion, the phase space plot should be a circle. The integrator circuit causes a slight phase shift, so the velocity and position signals are not exactly 90 degrees out of phase. Thus, the phase space plot appears elliptical.

Software

To perform remote control and data acquisition, we use National Instruments' (www.ni.com) LabVIEW, a graphical programming language for constructing *virtual instruments*. Instead of writing lines of code, programmers connect a series of icons with "wires" that direct the data flow among the icons. LabVIEW has an add-on Internet Developers Toolkit, which enables remote control through common gateway interface VIs. These are essentially subroutines that allow data transmission from the client's Web browser to a LabVIEW program.

LabVIEW programs consist of a front panel and a diagram. The front panel contains all the controls, while the diagram contains the code that executes the program. Users of the chaotic pendulum see an image of the front panel that is updated periodically. To provide front panel animation, we employ the server push technique. Web browsers that support server push will show an animated page; those that do not support it will show a static image that the user must manually refresh. The front panel is image mapped, with a particular shape defin-

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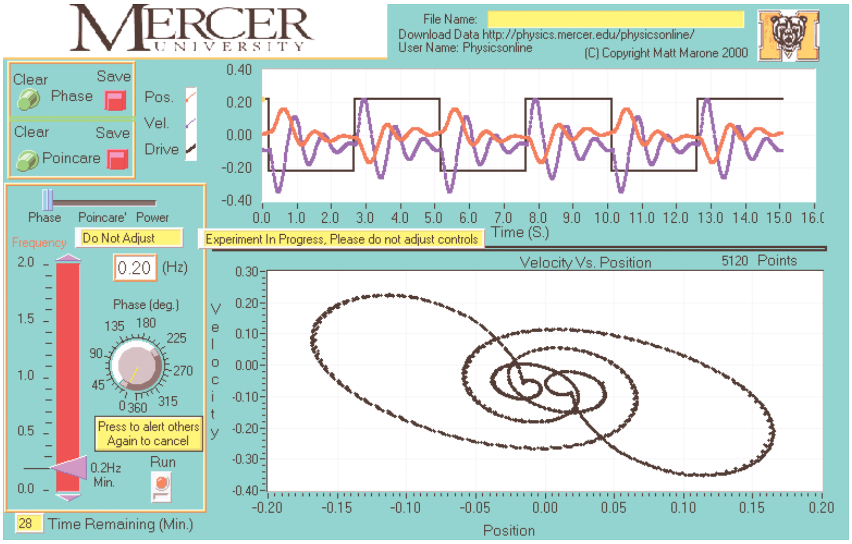

File Name:
Download Data http://physics.mercer.edu/physicsonline/
User Name: Physicsonline
(C) Copyright Matt Marone 2000
Do Not Adjust
Experiment In Progress, Please do not adjust controls
0.20 (Hz)
Press to alert others
Again to cancel
28 Time Remaining (Min.)

Figure 1. The control panel for the Mercer online interactive chaotic pendulum. The pendulum drive frequency is set to 0.2 Hz, and the "Press to alert others" function is activated.

ing each control. When the user clicks within a region that is mapped to a control, information is transmitted to the server and in turn to the data acquisition program.

The data acquisition program runs independently of the Web interface; users interact with it through the interface. As Figure 1 shows, the software graphs velocity, position, and motor drive data as a function of time. This represents raw data that can then be analyzed or plotted in various ways. Users can view the data as phase space plots, Poincaré maps, or power spectra. Each of these representations is a common mathematical method for analyzing chaotic systems. Descriptions of the control functions appear on the operating instructions Web page (http://physics.mercer.edu/pendulum); I summarize them here.

Frequency

Users can vary the drive frequency from 0.2 Hz to 2.0 Hz in 0.1-Hz increments.

Phase, Poincaré, Power

With this control, users select the type of displayed graph. The phase space plot is a graph of the velocity as a function of position. For a periodic system, this is a closed, elliptical curve (which, as I mentioned earlier, should actually be a circle). In a chaotic state, the curve will not be closed and subsequent cycles will not overlap. Figure 2a shows a phase space plot for a period three limit cycle (the inset shows a Poincaré map). Figure 2b shows a phase space plot indicating chaotic behavior.

A Poincaré map is also a plot of velocity as a function of position, but using only one pair of velocity–position coordinates. The map scales the graph according to the information that the phase space plot generates. So, users must first select the phase space plot before they select the Poincaré map. The phase space is "strobed" so that

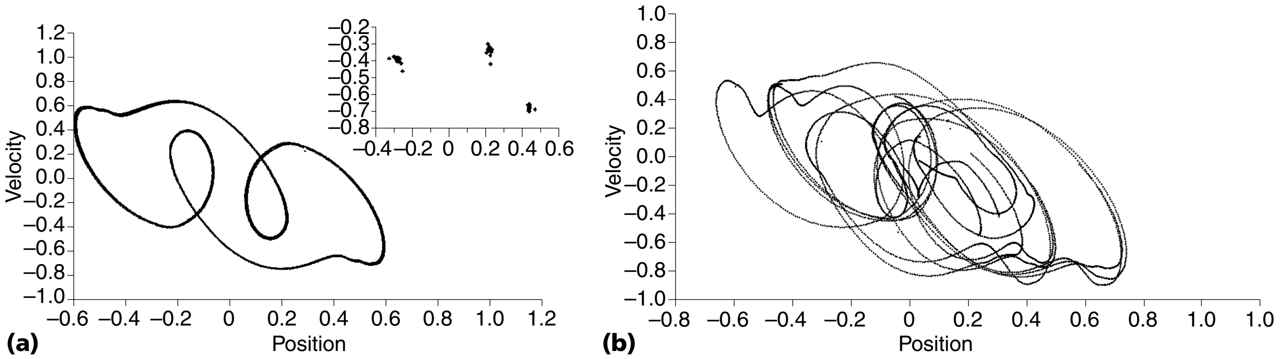

Figure 2. Phase space plots: (a) A period three limit cycle with 0.9-Hz drive frequency. The inset shows a Poincaré map for this motion with the phase set to 0°; the three groups of dots indicate the period three limit cycle. (b) Chaotic motion with 0.8-Hz frequency.

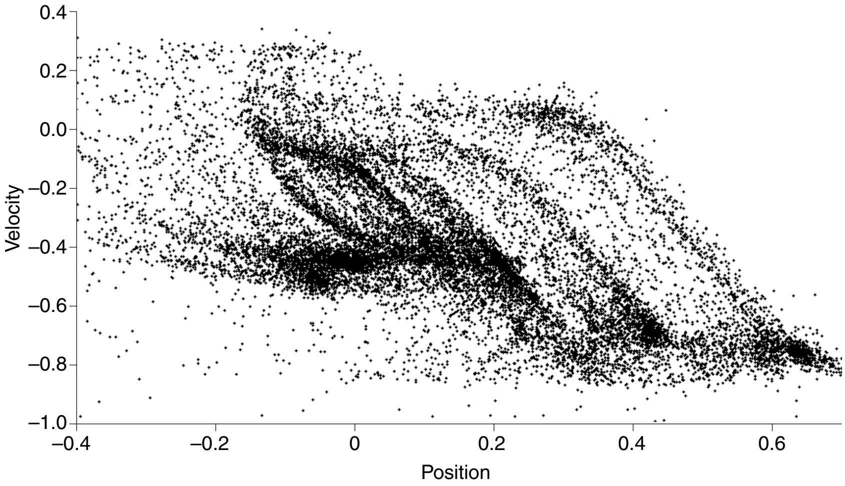

Figure 3. A Poincaré map for chaotic motion at 0.8 Hz with phase set to 0°. The map contains over 16,000 points.

the velocity–position values are determined at a fixed time after the first positive slope of the drive cycle.

When a user selects the Poincaré map, a thin orange cursor appears on the graph of the square wave drive. The cursor indicates the velocity–position pair that will be plotted (see the section "Phase"). When the system is periodic, velocity at a particular position should simply repeat itself (within experimental uncertainty). In this case, a black dot will appear on the screen. In the case of a limit cycle, several dots might appear, indicating the limit cycle's frequency.

The inset of Figure 2a shows a Poincaré map of a period three limit cycle, with three groups of dots. Experimental resolution and reproducibility determine the spread of points in a group. In a chaotic system, the velocity–position data points might not overlap; this situation produces a more complex shape. Figure 3 shows a Poincaré map of the pendulum oscillating chaotically. In a random system, many different velocity–position pairs are possible. Given enough time, the graph will be a solid mass of black dots. For a chaotic system, however, some velocity–position pairs never occur, and blank areas appear on the graph. Although the order in which the points are plotted is unpredictable, users can clearly observe which pairs are not possible. This graph's characteristic shape gives rise to what is known as an *attractor*. A Poincaré map requires thousands of data points and can take a long time to produce.

Selecting the Power option displays a power spectrum derived from a Fourier transform of the velocity data. For a periodic system, only the drive frequency appears. A common precursor to chaos is the development of subharmonics in the spectrum. Chaotic systems often contain a broad spectrum of frequencies, although multiharmonic spectra are possible in systems that have many degrees of freedom and are not chaotic.

Phase

Changing this control will produce different Poincaré maps. Users can vary the time at which the phase space is strobed. The phase angle is measured with respect to the positive slope of the square wave drive signal. With the control set to 0°, the cursor will fall on the positive-slope edge of the first square wave. A setting of 180° would correspond to the middle of the square wave.

Press to alert others

This control is a virtual "Do Not Disturb" sign. Because this is a real experiment, only one user at a time should be in control. When activated, this control signals other users that an experiment is in progress and requests that they not adjust the controls. The warning will flash for 30 minutes or until the current user presses the button again. The remaining time appears near the bottom of the screen. After 30 minutes, the display turns off automatically.

However, this control does not lock out other users. At present, we have not set up a system to prevent control by multiple users. We could set up the system so that only one user from a particular IP address or with a password controls the pendulum. Other users would only be able to observe. We have not yet received any reports from users indicating that the lack of lockout is a problem.

Clear, Save, and File Name

The Clear button erases the data displayed on either the phase space plot or the Poincaré map. Users may also save the data they acquired during an experiment as an Excel spreadsheet. Phase space plots can contain a maximum of 5,120 data points. Once an experiment has acquired more than 5,120 data points, the oldest data points are eliminated one at a time. Poincaré maps can have an unlimited number of points. The points' physical size will automatically decrease once their number exceeds 1,000.

This helps reveal structure in the Poincaré map.

When the user presses a Save button, the program generates a file name in this format: [Graph type-Ph/Po][frequency] [month]-[day] [hour] [min.] [sec.].xls. For example, Ph0,2Hz 01-10 14 46 39.xls indicates a phase space plot with a drive frequency of 0.2 Hz saved on 10 January at 14:46:39. A frequency of 0.2 Hz is expressed as "0,2Hz" because periods are used for file extensions. A graph type of "Po" indicates a Poincaré map.

Users can retrieve saved data from the download site, ftp://physicsonline@pendulum.mercer.edu. A folder on that site contains movies of the actual pendulum. Users can download prerecorded movies of the pendulum showing periodic and chaotic behavior. An MPEG player is necessary for viewing the movies. Live video is not practical because the transfer rate is usually too slow to display chaotic motion's sudden stops and reversals.

National Instruments has recently released a new LabVIEW remote panel tool that allows any Web browser to control a program without the need for image-mapped controls. This new feature requires the user to download a runtime engine, which enables control similar to a native LabVIEW environment. I intend to experiment with this new method of control in the future.

While the chaotic pendulum is an instructional resource in its own right, it also serves as a prototype. We are developing an online laboratory that will contain other experiments. Users will be able to request time for exclusive control and conduct experiments as part of a class. Experiments in thermodynamics, optics, and modern physics are under development. Instructors will be able to download materials such as procedures, laboratory data sheets, video clips, and discussion topics. We intend to make these experiments available to high schools and other education institutions.

References

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2. P. Horowitz and W. Hill, *The Art of Electronics*, 2nd ed., Cambridge Univ. Press, Cambridge, UK, 1989, pp. 222–223.

Matt Marone is an assistant professor of physics at Mercer University. His technical interests are experimental physics, computer interfacing, and data acquisition. He also enjoys teaching experimental physics, solid-state physics, and solid-state device physics. He is attempting to develop a remote laboratory and to determine if high school students can learn through remote experimentation. He received his BS in physics from the Rochester Institute of Technology and his MS and PhD in physics from Clemson University. Contact him at Mercer Univ., Dept. of Physics, 1400 Coleman Ave., Macon, GA 31207; marone_mj@mercer.edu.

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