RIBBON OF CHAOS

Researchers develop a lab technique for snatching order out of chaos

By IVARS PETERSON

Initially standing upright like a stiff stalk of grass, a paper-thin metal ribbon begins to bend over. It bows low, then straightens. It bends again, this time making just a quick nod. Then it does a string of low bows, a few brief nods and another low bow, sometimes throwing in a wiggle or two. Wavering unpredictably, the ribbon's motion follows no apparent pattern.

Now a researcher adjusts the magnetic field in which the ribbon dances. In a few seconds, the ribbon's chaotic motion settles into a repeating pattern: first a deep bow, then a nod, then another deep bow, a nod and so on. Instead of abruptly and arbitrarily shifting from one type of motion to another, the ribbon endlessly repeats the same combination of moves.

This laboratory demonstration marks an unprecedented feat. For the first time, researchers have controlled the chaotic behavior of a real-world physical system simply by making small adjustments to one of the parameters governing the system's behavior. Physicists William L. Ditto, Steven N. Rauseo and Mark L. Spano of the Naval Surface Warfare Center in Silver Spring, Md., describe their achievement in the Dec. 24, 1990 PHYSICAL REVIEW LETTERS.

The first indication that such control might be attained surfaced in the March 12, 1990 PHYSICAL REVIEW LETTERS. In a theoretical paper, Edward Ott, Celso Grebogi and James A. Yorke of the University of Maryland in College Park introduced the notion that — just as small disturbances can radically alter a chaotic system's behavior — tiny adjustments can also stabilize its behavior.

The success of this strategy for controlling chaos hinges on the fact that the apparent randomness of a chaotic system is really only skin deep. Beneath this chaotic unpredictability hides an intricate but highly ordered structure — a complicated web of interwoven patterns of regular, or periodic, motion.

Normally, a chaotic system continually shifts from one pattern to another, creating an appearance of randomness. In controlling chaos, the idea is to lock the system into one particular type of repeating motion.

In their paper, Ott and his co-workers described their success in demonstrating the control of chaos in a numerical experiment on a computer. The Navy team has now matched this success in the laboratory.

"Far from being a numerical curiosity that requires experimentally unattainable precision, we believe this method can be widely implemented in a variety of systems, including chemical, biological, optical, electronic, and mechanical systems," Ditto, Rauseo and Spano write in their paper.

Their experimental equipment looks rudimentary. The key component—resembling a piece of stiff tinsel — consists of a metal strip 65 millimeters long, 3 millimeters wide and 25 micrometers thick, planted in a clamp that keeps it upright. Three pairs of electromagnetic coils the size of bicycle rims generate the magnetic fields surrounding the clamped ribbon.

But the metal ribbon, made from a specially prepared iron alloy, has a remarkable property: It changes its stiffness in accordance with the strength of an external magnetic field.

At first, the ribbon stands erect. Increasing the magnetic field along the ribbon's length causes the strip to soften, and the ribbon begins to droop under its own weight. Once the magnetic field reaches a certain value—only a few times larger than Earth's modest magnetic field — the ribbon abruptly begins to stiffen again, causing it to straighten.

Using a slowly oscillating magnetic field, the researchers can force the ribbon to droop and straighten in sync with the field. "It's like turning a dial and making the ribbon stiffer or softer, then letting gravity do the rest," Spano says.

However, increasing the forcing field's frequency or strength pushes the ribbon into a chaotic regime in which its motion becomes unpredictable. "It clearly exhibits the hallmark of a chaotic system—that is, getting continuously thrown from one periodic motion to another," Rauseo says.

He and his co-workers can construct a kind of map of this irregular motion by monitoring the ribbon's displacement at the end of each cycle of the oscillating magnetic field. If the ribbon repeats the same motion at regular intervals, then its position will be the same at the end of each cycle. The entire map then consists of a single point.

However, if its motion is irregular, then the ribbon's position will vary each time, and the map will show an array of scattered points, which happen to fall into a particular pattern (see cover). Such an array is known as a chaotic attractor. As the ribbon moves, a computer builds up an image, point by point, of the system's attractor.

To control the ribbon's motion, the researchers display the attractor on a computer screen and select a point that corresponds to a particular type of periodic motion. Then they wait until the ribbon's motion, as represented by successive dots on the computer screen, shows up near the point they've selected on the attractor. That close encounter triggers a simple computer program that calculates how much and in which direction to adjust the underlying, steady magnetic field to keep the ribbon trapped in the desired periodic motion.

Corralling the ribbon's motion is akin to balancing a ball on a saddle, Spano says. The ball won't roll off the saddle's raised front or back, but continual adjustments—in the case of the ribbon, a steady train of small magnetic nudges — are needed to kick it back into position as it begins rolling off at the sides.

By making slight adjustments approximately every second to the steady, vertical magnetic field acting on the ribbon, the researchers can maintain the ribbon's regular motion for as long as they want. As soon as they relinquish control, the ribbon resumes its chaotic dance. They can then reestablish control, bringing the ribbon back to the same periodic motion it had before, or, just as easily, putting it into a different type of regular motion.

"We don't avoid the chaos; we stay in the chaotic region," Ditto says. "We take advantage of the system's sensitive dependence on initial conditions."

The trick is to exploit the fact that a chaotic system already encompasses an infinite number of unstable, periodic motions, or orbits. That makes it possible to zero in on one particular type of motion, or periodic orbit, or to switch rapidly from one type of motion to another.

The theory developed by Ott, Grebogi and Yorke suggests that scientists could use this technique for controlling many different chaotic systems. "The method is very general and should be capable of yielding greatly improved performance in a wide variety of situations," they assert in their March report.

Surprisingly, researchers don't even need to know the mathematical equations describing the dynamical behavior of a particular system in order to make the control technique work. It's sufficient to observe the system long enough to map its chaotic attractor and to determine by experiment a few crucial quantities necessary for establishing control.

"You don't need to have a deep theoretical understanding of what's going on," Rauseo says.

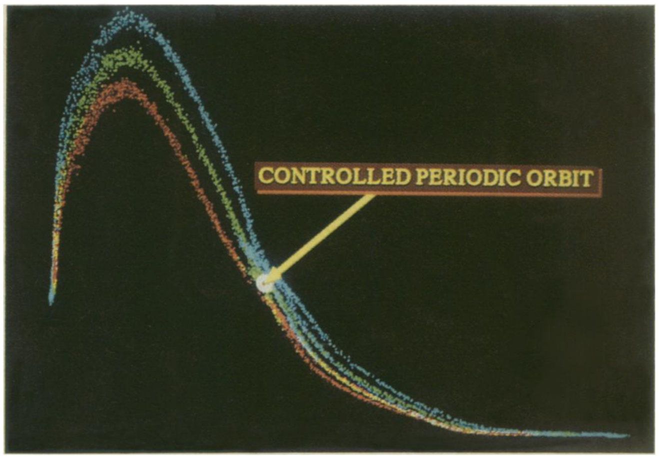
"All you need to know is, in effect, the shape of the saddle, and that you can get from observations of the system," Spano adds. "You don't need an equation."

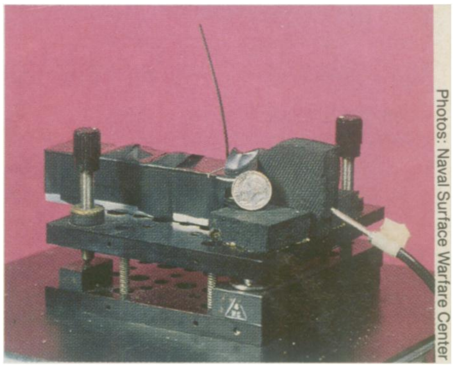
To simplify matters further, researchers need bother with only one control parameter. The Navy team, for example, could control the magnetic ribbon's motion by making small adjustments to the oscillating magnetic field's frequency or strength, to the steady magnetic field's strength, or even to the ambient temperature. They chose the parameter they could adjust most easily: the steady magnetic field.

"We kind of expected this might be a very difficult thing to do," Ditto says. "It was actually remarkably easy for us to implement."

Random disturbances persist, springing from an array of environmental factors such as temperature fluctuations and errors in the measurements necessary for characterizing the system's attractor and saddle. But so long as this "noise" remains small, a controlled system, kept in line by a constant stream of nudges, stays under control. "You can achieve control even in the face of noise and imperfect measurements," Grebogi says.

In the past, most scientists and engineers considered a chaotic system's extreme sensitivity to initial conditions as something to be avoided. To ensure that, say, a chemical reaction or a bridge would function reliably and predictably, they tried to design systems that shunned chaos. Both the Navy and Maryland groups now argue that chaos may offer a great advantage, allowing system designers greater flexibility and making possible systems that adapt more quickly to changing needs.





To confine the chaotic oscillations of a magnetoelastic ribbon (bottom) to a single type of repeating motion, as depicted on the system's chaotic attractor (right), researchers make small adjustments to the steady magnetic field acting vertically on the ribbon.

Photos: Naval Surface Warfare Center

"This characteristic is often regarded as an annoyance, yet it provides us with an extremely useful capability without a counterpart in nonchaotic systems," contend Troy Shinbrot, Ott, Grebogi and Yorke in a new paper in which they outline a shortcut for achieving control of a chaotic system. That paper accompanies the Navy report in the Dec. 24 PHYSICAL REVIEW LETTERS.

"In particular, the future state of a chaotic system can be substantially altered by a tiny perturbation," the Maryland researchers write. "If we can accurately sense the state of the system and intelligently perturb it, this presents us with the possibility of rapidly directing the system to a desired state."

It's like using a feather instead of a sledgehammer to achieve a certain result, Spano says.

The Navy team considers its magnetic ribbon not only a fascinating vehicle for vividly demonstrating the intricacies of chaotic dynamics but also a candidate for a "smart" material – one that automatically responds to changes in its environment by changing its properties to achieve a desired result (SN: 3/10/90, p.152). "We would like to exploit the chaotic behavior of the ribbon instead of avoiding it," says Ditto. "We want to make a device that can adapt to the real world. That's where we're headed."

The Navy is interested in using smart materials, such as magnetoelastic ribbons, for designing quieter submarines, controlling vibrations, detecting motion, and improving tracking and pointing devices.

As a potential peaceful application, Grebogi envisions a hypothetical set of chemicals that, when mixed in different concentrations, reacts to produce dyes of different colors. Chemical engineers might design a factory for producing various dyes by building separate chemical reactors, one for each color. But by introducing and controlling chaos, they could get away with building a single reactor. If they adjusted the ingredient concentrations so that the system's products would shift chaotically from one color to another, then a simple control scheme involving tiny adjustments in the concentration of one ingredient would suffice to stabilize the reaction so that it produced only one color. The same control system would also allow them to shift dye production rapidly from one color to another.

"Thus, when designing a system intended for multiple uses, purposely building chaotic dynamics into the system may allow for the desired flexibility," Ott, Grebogi and Yorke suggest.

A conventional heart pacemaker, for example, supplies a steady beat, whereas a person's heart varies its pace depending on his or her exertions. A pacemaker patterned on a chaotic phenomenon might make such rapid adjustments to the heartbeat when needed, Ditto says.

Indeed, the recent success in controlling chaos raises the issue of how common this control mechanism may be in biological systems. For example, controlled chaos may play a role in the human ability to quickly produce strings of different speech sounds.

"Such multipurpose flexibility is essential to higher life forms, and we, therefore, speculate that chaos may be a necessary ingredient in their regulation by the brain," Ott, Grebogi and Yorke say.

"We think biological systems use chaos, and the richness in chaotic behavior, to change [their] behavior on the fly," Ditto says. "We've provided some of the first evidence that this type of mechanism is possible." ☐