Calming Bad Vibes

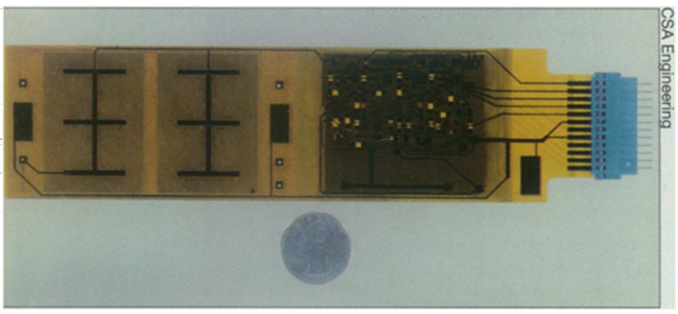
From microscopes to skyscrapers, smart structures help control vibration

By SID PERKINS

Thanks to the transistor, computers are no longer basement-sized behemoths pursuing only the most arcane of tasks. Now, they sit atop desks or even fit in briefcases. Shrunk onto a few electronic chips, they can constantly adjust the fuel injection in cars and even nag the driver who forgets to buckle a seat belt or leaves a door ajar.

More than ever before, engineers are using the brain power of computers in combination with new classes of exotic materials to create what they call "smart structures," or objects that can sense their environment, process the information, and then react appropriately. Designers are beginning to bestow upon bridges, buildings, and even sporting goods the same limited degree of self-awareness and perhaps intelligence currently given to cars and aircraft.

Smart structures have many potential applications, but almost all of them involve controlling undesirable vibrations of various sizes, from annoying sound waves to building sway. Many engineers see smart structures as the wave—or, perhaps more appropriately, the antiwave—of the future.


CSA Engineering

This type of unit, which combines sensors and piezoelectric materials, makes smart structures possible. Computers can monitor the flexing of the unit through the electric connector and can transmit signals that cause the piezoelectric materials to resist movement and minimize vibration.

Vibrations are inescapable. Some may be pleasing—the soft strum of a guitar, the gentle swing of a hammock, the soothing sound of a mother's voice—but many vibrations cause problems. Consider bridges and tall buildings that sway excessively in a stiff gust of wind or a moderate earthquake, floors that flex or shimmy as people walk across them, and noisy aircraft cabins and whirring home appliances.

Structural engineers use several methods to minimize unwanted vibrations, says B.F. Spencer Jr., professor of civil engineering at the University of Notre Dame (Ind.). They place buildings on large rubber pads to isolate them from ground vibrations and use large shock absorbers inside structures to calm movements more quickly. Often, aerospace engineers must add material to stiffen aircraft wings.

These techniques have their downside, however, Spencer says. They typically add weight, and they work only for certain frequencies of vibrations. To help overcome these limitations, designers are increasingly turning to smart materials with controllable properties.

Piezoelectric materials, for example, change shape when an electric current passes through them and generate electric signals when they flex. These materials are therefore doubly useful for controlling small vibrations. Incorporated into a machine, piezoelectric components can monitor its flexing; stimulated by an electric signal, they can apply forces that initiate or resist movement.

In effect, these materials become the smart structure's nerve endings and muscles, while the computer control becomes its brain.

Smart materials can reduce the weight of structures by allowing designers to incorporate extra stiffness without adding bulk. The weight-saving potential of smart materials drove their initial development for applications in space, where every ounce counts, says Mark S. Whorton, an aerospace engineer at NASA's Marshall Space Flight Center in Huntsville, Ala. "As a general rule of thumb, it takes about $10,000 to put a pound of payload into orbit," he explains.

The appeal of smart structures has spread from its aerospace roots to a variety of arenas. Possible applications range from controlling vibrations in microscopes to reducing the sway in bridges.

Researchers at CSA Engineering in Palo Alto, Calif., and their colleagues are trying to commercialize several products developed in their laboratories, says Eric H. Anderson, an engineer at the company. One of the innovations is a programmable device that integrates sensors, piezoelectric components, and electronic circuitry into a single unit.

According to Anderson, this technology has reduced the noise in aircraft cabins by cutting down on vibration in the walls, which are typically made up of many large panels of thin, unstiffened metal. The same technique could, in theory, tame the noise from washing machines, clothes dryers, and refrigerators, he adds.

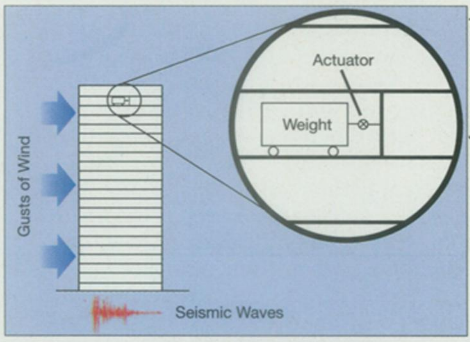
CSA researchers have also developed what they call an "active shock absorber" that fits into the legs of a table or workbench to reduce vibrations caused by nearby footsteps or other floor movements. A computer underneath the work surface monitors sensors in the table legs and sends signals to the shock absorbers. The system reduces the tabletop vibrations to less than one-millionth of an inch—a standard necessary for the manufacture or inspection of semiconductor wafers, Anderson says.

Researchers at Sandia National Laboratories in Albuquerque took a slightly different approach to removing the jiggle in semiconductor manufacturing equipment. They needed to control vibration in the platform that holds the silicon wafer underneath the photolithography head, which projects ultraviolet light onto the wafer to etch the circuitry.

"Any degree of vibration causes blur, which means you can't etch extremely small circuit features," says Jim Redmond, an engineer at Sandia. The challenge is magnified even further, he says, because the platform must move and stop abruptly as the same pattern is etched repeatedly onto the wafer. After each sudden stop, the platform must settle and stop vibrating before a new portion of the silicon wafer can be exposed to the ultraviolet light.

By embedding three small strips of smart material in the platform, the Sandia researchers reduced the magnitude of its vibrations from 240 nanometers to 4 nm and cut the platform's settling time after each movement from 15 milliseconds to 9 ms, Redmond says.

Tackling the same problem on a much larger scale, researchers at the University of Miami can alleviate the symptoms of shaky floor syndrome by attacking the source of the problem—the floor itself. Civil engineer Linda M. Hanagan developed a way to use an electromagnetic shaker to damp floor vibrations.



By using a computer-controlled actuator to push back and forth on a large movable weight, engineers can help cut down on the amount of building sway caused by wind and seismic waves.

In Hanagan's system, the shaker, which is mounted underneath the floor, consists of a 74-kg frame and a 30-kg movable mass and is smaller than a two-drawer filing cabinet. A personal computer takes readings from a nearby sensor 2,000 times each second. Whenever the floor moves, the computer sends signals that drive the movable mass back and forth to compensate for the vibration.

The researchers have tested the system in two offices and a university chemistry laboratory. In all three cases, the system reduced the problem vibrations to less than a quarter of their previous magnitude, says Hanagan.

Using computer feedback to control large structures is a daunting task. In bridges and buildings, each girder or I-beam can weigh a ton or more, and vibrations can arise from powerful forces such as gusts of wind and earthquakes.

Pushing and pulling on the building with powerful actuators may therefore not be the most effective way to control unwanted vibrations in tall buildings, says Spencer. Shifting masses back and forth to change the building's response to outside influences is often a better approach.

In Nanjing, China, engineers are working on a newly constructed 341-meter tower that has a problem with wind-induced vibrations in one of its observation decks. They plan to turn the tower into a smart structure next year by installing a device called a hybrid mass damper, a combination of a large weight and actuators to move it back and forth. A 60-ton, ring-shaped weight will be mounted on bearings around the tower's waistline. When a sensor detects vibrations, three actuators will push and pull against the massive weight to cut down on the tower's overall movement.

Japanese engineers leapt to embrace smart structures during a skyscraper construction boom that began about 10 years ago, Spencer says. Today, 20 hotels and office towers in Japan, 14 of them more than 26 stories tall, use hybrid mass dampers. The Yokohama Landmark Tower, the tallest building in Japan, uses two such dampers, each weighing 170 tons, to cut down on building sway.

"The Japanese are not ahead of us on research, but they've zoomed ahead of us in the implementation of this technology because they see its tremendous potential," Spencer says.

Smart dampers, which are essentially controllable versions of large shock absorbers, represent another effective way to counter large forces in massive structures, says Spencer. One type of smart damper contains a magnetorheological fluid, a material that can undergo considerable and almost immediate changes in its viscosity when subjected to a magnetic field.

These fluids can be transformed from the consistency of water to that of a thick pudding in a matter of milliseconds, Spencer says. Prototype dampers filled with the fluids can generate reactive forces of up to 20 tons with as little as 50 watts of power, which a modest battery can supply.

A sensor inside K2's Smart Shock monitors the position and the movement of the piston, and microelectronics control the flow of fluid through the shock to adjust the stiffness of the ride.

Smart structures have enjoyed widespread use in university, corporate, and government research labs for the last decade, but they are only slowly making their way into commercial applications, says Anderson. At an American Society for Mechanical Engineering conference last week, he identified a few of the obstacles—the complicated nature of the technology, its formerly high price, and a dearth of successes outside the lab environment.

In one commercial arena, smart structures have succeeded in hurdling these barriers, following a path blazed by another aerospace product: graphite-epoxy composites. Composite materials once languished in the labs, but they captured widespread attention when sporting goods manufacturers used them to make tennis rackets and golf clubs.

Today, the same industry has fastened onto smart structures for its latest innovation. K2 Corp. in Vashon, Wash., produces smart skis that use a piezoelectric ceramic plate mounted just in front of the ski binding. The plate's flexing generates electricity, which powers a circuit that helps control troublesome vibrations and keeps the edge of the ski in contact with the snow. One model, introduced less than 2 years ago, quickly became the hottest-selling ski in the United States, and K2 shipped well over 10,000 units last year, says marketing manager Andy Luhn.

Researchers at Active Control eXperts in Cambridge, Mass., are the people who put the "smarts" in K2's smart skis—with technology they originally developed to control large vibrations in fighter aircraft, says engineer Brian Degon. They then used the same materials to develop a smart shock absorber, powered by a 9-volt battery, that can make more than 900 adjustments per second in the stiffness of a mountain bike's suspension and thus smooth the ride.

With the recent surge of research and a number of successes both in the laboratory and in the field, smart structures are poised to solve a variety of problems, on small to grand scales. The infiltration of smart structures into mainstream design may come only slowly, Spencer says, but he has no doubt that it will come. □