# Mecha...what?

*Following the lead of Japan and Europe, the United States is making headway in an engineering discipline few have heard of—mechatronics*

The world of engineering is like an archipelago whose inhabitants are familiar with their own islands but have only a distant view of the others and little communication with them. A comparable near-isolation impedes the productivity of engineers, whether their field is electrical and electronics, mechanical, chemical, civil, or industrial. Yet modern manufacturing systems, as well as the planes, cars, computers, and myriad other complex products of their making, depend on the harmonious blending of many different technologies.

Japan recognized that need over 20 years ago. Japanese engineers called it mechatronics, the way of designing subsystems of electromechanical products to ensure optimum system performance. The name was coined by Ko Kikuchi, now president of Yaskawa Electric Co., Chiyoda-Ku, Tokyo.

Recently, a technical committee on mechatronics was formed by the International Federation for the Theory of Machines and Mechanism, in Prague, Czech Republic. One of the new committee's first tasks was to adopt the following definition for the term: "Mechatronics is the synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes."

**TEAM PLAYER.** Mechatronics fits well with another discipline that has received a great deal more attention in the past few years: concurrent engineering. But the two approach the job of improving operating efficiency and system performance from different points of view.

In concurrent engineering, the groups that make up the project team develop parts of a system in tandem, working separately but sharing the overall results of their group efforts. For instance, the electronics engineering group will typically concentrate on problems unique to its discipline, such as ensuring the functionality of a chip using electronic design automation tools, while mechanical engineers work out packaging or read-head control problems using mechanical simulators. Although the engineering groups may share their results, each works with a less-than-perfect understanding of how its design decisions affect decisions of its counterparts in other disciplines.

The widespread availability of simulation tools such as Spice for electrical engineers and Catia for mechanical engineers has provided a solid basis for the use of simulation in concurrent engineering. By adding mechatronic tools to a concurrent engineering environment, each group can simulate how the various technologies that go into a system will interact, so that the overall system can be tuned for the best performance. These tools also help teams focus on system design issues rather than just those specific to their portion of the system implementation.

One of the earliest and most widely used commercial mechatronics tools is Saber, a mixed-technology simulator. Developed by Analogy Inc., Beaverton, Ore., Saber performs system simulations using component models written in Mast, a proprietary analog hardware description language (AHDL).

An engineer who is well versed in a technology uses an AHDL to write a software model that describes the behavior of a component mathematically [Fig. 1]. If the AHDL permits, the model can be built up incrementally, with more behavioral attributes added as needed to improve the precision of the simulation. These behavioral models can be stored in libraries and passed on to others for reuse. Working with Saber user groups over the last few years, Analogy has accumulated a library of electronic, mechanical, and other models, and this past June, the company began offering a custom modeling service.

To see how well a particular component performs in the system, engineers use Analogy's library models, custom models, or models they write themselves, working on a computer as they usually do with design automation tools. That is, they use graphical representations of the models to create schematics, and the schematic becomes the input to the simulator. The simulator uses the schematic to see which models it needs and how they are interconnected.

Some simulators not only demonstrate the way components perform, but also determine which components have the most impact on design performance (sensitivity analysis) and whether any component or group of components is operating near or beyond acceptable limits (dynamic stress analyses).

**MECHATRONICS IN ACTION.** The design of an electronic braking system for automobiles shows the benefits of a mechatronic approach. In this system, which consists of mechanical, hydraulic, and electronic subsystems, many of the components cross disciplines: the electric motor is both electrical and mechanical, and the valves are both mechanical and hydraulic.

```
template solenoid p m pos1 pos2 =
r, lmax, lcoef, kstop, kspg,  len_spg, cwind

     electrical p, m

     translational_pos pos1, pos2

     var i           i
     val v           v
     val l           lx
     val pos_m       gap
     val f           flux
     val frc_N       f_mag
     val frc_N       f_stop
     val frc_N       f_spg

values     {

           v = v(p) - v(m)

           gap = pos_m(pos1) - pos_m(pos2)

           f_spg = kspg*(len_spg - gap)

           if (gap >= 0) {
                     lx = lmax/(1 + lcoef*gap)
                     f_stop = 0
                     }
           else {
                     lx = lmax
                     f_stop = kstop*(-gap)
                     }

           flux = lx * i

           f_mag = (-0.5*lcoef/lmax)*(flux**2)
           }

equations {
           i(p->m)+= i + d_by_dt(cwind*v)
           i: v = d_by_dt(flux) + i*r
           frc_N(pos1->pos2) += f_mag + f_stop + f_spg
           }
```

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Even when a component relies on only a single discipline and can be easily modeled and simulated by other means, a mechatronic simulation will show how its operation may be affected by the full system.

Figure 2 is a braking-system schematic that could be applied in such a simulation. Commonly used electronic, mechanical, and hydraulic symbols represent the software models the simulator will employ. In the braking system represented, a battery-powered dc motor runs a pump to pressurize the hydraulic system. The midpoint of the braking pressure is set by a check valve in series with a solenoid-controlled two-way valve, and a damping orifice provides pressure feedback on the valve's spool as an internal control mechanism.

In addition to this simple, inner feedback loop, an outer feedback loop uses an electronic pressure sensor to set the pressure level. In this second loop, the armature of the solenoid controls the valve spool, to which it is rigidly connected. The output of the electronic sensor is a voltage proportional to the actual hydraulic pressure in the line. This voltage is fed to a difference, or error, amplifier, where it is compared with a reference voltage ($V_{ref}$). The reference voltage is either derived from the force exerted on the brake pedal or generated by a wheel-speed control processor.

The position of the solenoid armature is controlled by the difference between the two voltages, amplified by a dual-transistor drive circuit. Thus the sensor gives direct feedback on the state of the hydraulic pressure, which can therefore be directly controlled.

Pressure is applied to the brake assembly through a brake line consisting of a rigid line and a short flexible hose. The brake assembly itself is modeled as a brake cylinder with spring return attached to a load mass and a mechanical travel limit; the latter simulates contact and compliance between the brake shoe and the rotor. A sinusoidally varying source simulates the instantaneous, transverse displacement of the rotor, enabling the system to mimic the effects of rotor wobble on brake pressure regulation.

The models used in this schematic include all primary and many secondary effects. For instance, the models for both hydraulic lines include such primary effects as fluid momentum effects, as well as secondary effects like laminar and turbulent pressure/flow relationships. In addition, the model for the flexible line includes expressions for tube-wall expansion with pressure.

The simulator conserves variables at each node. In electronics, Kirchoff's current law says that the sum of all currents (variables) entering a node must be zero; similarly, Newton's law says that the sum of forces at a node must be zero.

The models of the components contain the relevant relationships among the various variables and the simulator assembles the system of equations governing their interactions. So to create the schematic, the user need only assemble the correct components and make the proper interconnections.

Using a simulation system like this, engineers can examine various aspects of the system's transient response that would be hard to determine any other way. For example, while pressure in the system's outer feedback loop is linearly related to the controlling current in the solenoid's armature, the relationship between pressure in the inner loop and that controlling current is nonlinear. In determining how to make the inner loop most effective at stabilizing pressure, engineers can run system simulations using different damping-orifice diameters and reference voltages.

**FINDING A WEAK LINK.** But the ease of simulating multiple technologies can yield even weightier results than discovering an optimum parameter for a single component. For one thing, the process allows a team to find out quickly which of a component's parameters impact system performance the most.

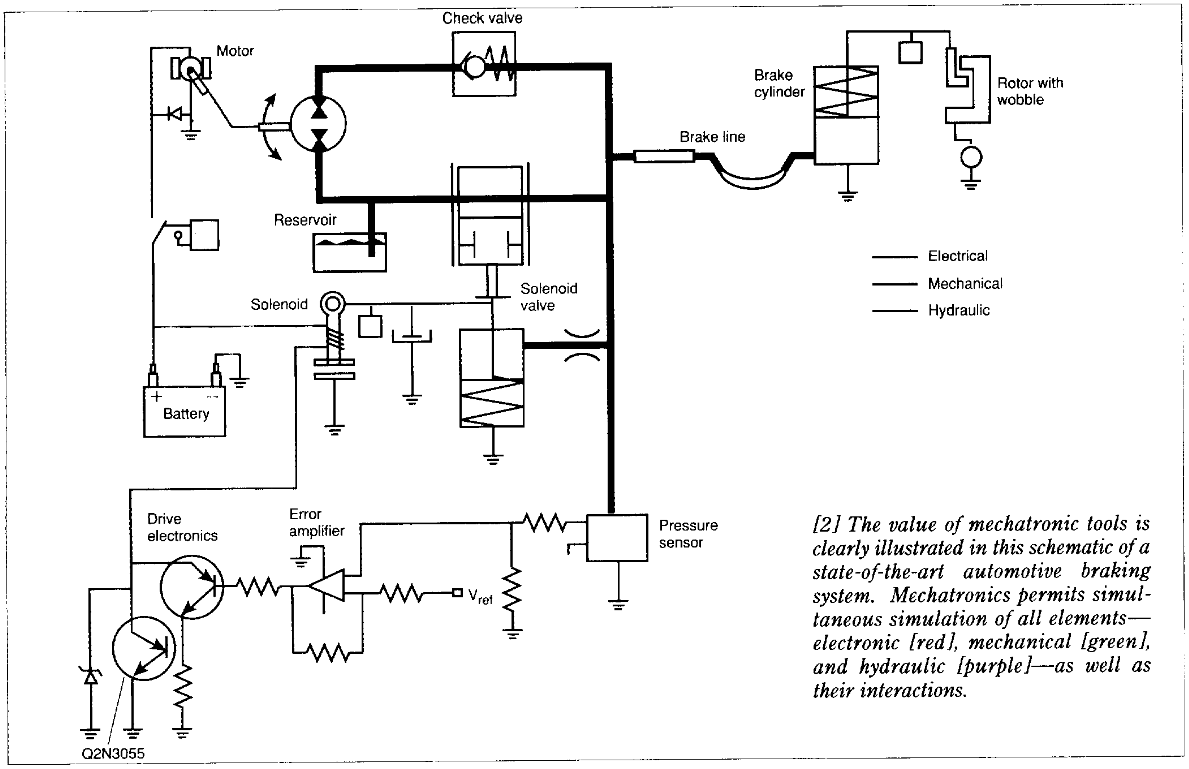
To do that in the case of the braking system, the system is simulated while sequentially varying the value of each parameter by a small amount. The effect of these variations on a given operating characteristic—such as the time it takes the hydraulic pressure to return to normal after the brake has been applied steadily for some time—can then be observed.

For the system discussed here, running such a simulation produces the sensitivity values shown in Table 1. The values are obtained by changing each component parameter by a fixed percentage of its value, running a simulation, and noting the percentage change in the operating parameter. In this case, increasing the length of the rigid part of the brake line by 10 percent, to 3.30 meters, produces an increase in rise time of 1.54 ms, or about 3.52 percent of the nominal 44 ms. The ratio of the percentage changes is the sensitivity number; if the rise time decreases for a positive increase, then the sensitivity number is negative.

In this design, evidently, the recovery time is most affected by the battery voltage. If the vehicle had to be operated with a battery that was at less than full charge, this effect could be significant. By examining the table, engineers might decide to reduce the battery's impact on system performance by decreasing the winding resistance of the motor and the inner diameter of the rigid brake line, as well as making the brake line as short as

```
________________ #Declare electrical connections

________________ #Declare mechanical connections
                 #Declare variables/values for:
________________ #    Winding current, ( i, flowing positively from connection p to m)
________________ #    Voltage across the winding, (v, the voltage difference between p and m)
________________ #    Instantaneous inductance value (H)
________________ #    Instantaneous solenoid air-gap (m)
________________ #    Instantaneous flux linkages (Wb)
________________ #    Electromagnetic force (N)
________________ #    Hardstop restraining force (N)
________________ #    Force of return spring (N)

________________ #Calculate the voltage drop across the winding

________________ #Calculate the mechanical displacement of the solenoid armature

________________ #Calculate the spring force based on its stiffness and compression (length minus gap)

               { #If the gap is greater than or equal to zero,
________________ # calculate the inductance from the maximum inductance and inductance
               { # coefficient (changes with gap); hardstop restraining force
                 # will be zero
               { #If the gap is less than zero,
________________ # the inductance will be at maximum value;
               { # calculate the hardstop restraining force from the stiffness
                 # of the hardstop and its mechanical displacement.

________________ #Calculate the instantaneous flux linkage (the instantaneous inductance times current)

________________ #Calculate the electromagnetic force from inductance coefficient,
                 # maximum inductance, and instantaneous flux linkage

________________ #Total current through winding and interwinding capacitance at electrical connections
________________ #Voltage-current time differential relationship
________________ #Sum of forces on mechanical connections
```

*[1] With mechatronic simulators, providing a flexible way in which to build models is extremely important, because several people may be involved in writing portions of the models. In this model of a solenoid written in Mast, the colored type shows how different functions were added by engineers over time to improve the accuracy and capability of the model.*




*[2] The value of mechatronic tools is clearly illustrated in this schematic of a state-of-the-art automotive braking system. Mechatronics permits simultaneous simulation of all elements—electronic [red], mechanical [green], and hydraulic [purple]—as well as their interactions.*

possible. Were it not for this ability to simulate total system performance, such tradeoffs would ordinarily not be considered at the design stage.

**ON THE EDGE.** Besides highlighting design dependencies and component sensitivities, mechatronics tools can point out those operational weaknesses in a design that affect system reliability. The fact that a component might be overstressed during operation is not obvious from the steady-state analysis typically performed for a system.

In the braking system here, consider what happens when the wheel suffers the transverse motion of rotor wobble and the brake fluid is cold. The rotor wobble imposes a sinusoidal force on the brake cylinder, and the increased viscosity of the cold brake fluid boosts the flow resistance in the brake line.

With these conditions, a simulation produces the results shown in Fig. 3. A decrease in flow rate caused by the high viscosity produces a considerable delay between the rise in the pump pressure and that at the brake. Also, the peaks in brake pressure exceed the nominal operating maximum by about 14 percent.

A report on stresses generated by the simulation for all technologies appears in Table 2. Clearly, while the increased pressure pushes the flexible portion of the brake line close to its rated value, the hydraulic system is not overstressed. (The model actually includes several lumped segments to approximate the distributed hose length.) The only component that exceeds its maximum rating is one of the transistors in the drive circuit, which is overstressed during a pressure transient that occurs at 700 ms. Yet the average power of this transistor is only 19.7 percent of its rated value.

## 1. Mechatronic sensitivity analysis of hydraulic braking system

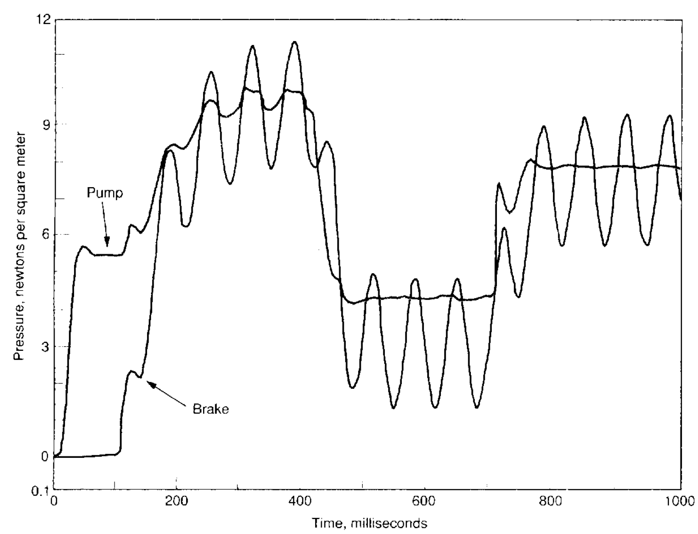
| Element | Parameter name | Nominal value | Sensitivity |
|---|---|---|---|
| Battery | Terminal voltage | 12 V | 2.91 |
| Motor | Winding resistance | 190 mΩ | 0.86 |
| Rigid line | Inner diameter | 4 mm | 0.357 |
| | Length | 3 m | 0.352 |
| Motor | Winding inductance | 5 mH | 0.292 |
| | Torque constant | 0.2 Nm/A | 0.186 |
| Pump | Displacement | 5 μm³ | 0.0541 |
| Solenoid | Inductance | 160 mH | -0.0489 |
| Fluid | Viscosity | 0.14 Ns/m² | 0.00702 |
| Orifice | Area | 0.03 μm² | -0.00529 |
| Mass | Mass | 0.5 gram | -199 E-6 |
| Sensor | Bandwidth | 300 rad/s | 68 E-6 |
| Armature/spool | Damping | 20 N/m/s | -54 E-6 |

**MYRIAD USES.** As the preceding example illustrates, mechatronics can greatly benefit the automotive industry. No wonder, then, that use of mechatronics tools is becoming common at the Big Three U.S. auto makers. And in England, Jaguar Cars Ltd., Coventry, has applied mechatronics to the design of an active suspension system.

But there are a host of other applications that could benefit. According to reports in the April 1994 issue of the journal *Mechatronics*, experimenters at the Agricultural and Food Research Council's Silsoe Research Institute, Bedford, England, have applied the technique to designing robotic systems for such diverse agricultural pursuits as automatically harvesting mushrooms and grading potatoes.

Closer to home, mechatronics is being used for designing manufacturing lines for surface-mount components, improving board rework stations, and assembling and testing mixed-technology boards.

The difficulty is not in finding places




*[3] When the braking system shown in Fig. 2 is simulated with a real-world condition (in this case, rotor wobble), the nonobvious effects (here, a significant delay between the rise in pump and brake pressure) can be seen immediately.*

## 2. Mechatronic stress analysis of hydraulic braking system

| Element | Parameter name | Derated value | Actual value | At time from start: | Ratio of actual to derated values |
|---|---|---|---|---|---|
| Transistor q2n3055 | Maximum power | 100 W | 137 W | 700 ms | 137% |
| Each flex line element | Maximum pressure | 12 MPa | 11.4 MPa | 378 ms | 95.3% |
| Transistor (as above) | Maximum Vce | 50 V | 27.5 V | 701 ms | 55.1% |
| Zener diode | Maximum power | 240 W | 97.4 W | 701 ms | 40.6% |
| Pump | Maximum torque | 20 Nm | 8.12 Nm | 370 ms | 40.6% |
| Transistor (as above) | Maximum Ic | 20 A | 6.03 A | 445 ms | 30.7% |
| | Average power | 100 W | 19.7 W | N.A. | 19.7% |
| Zener diode | Average power | 240 W | 410 mW | N.A. | 0.171% |

where mechatronics can be applied, but in locating people familiar enough with the concepts to employ them successfully, according to Doug Johnson, vice president of Analogy. Unlike their counterparts in Japan, where mechatronics has been taught at the University of Tokyo for the last two decades, U.S. companies have had trouble tracking down engineers schooled in mechatronics.

Part of the problem is that many North American universities have had little success in fitting mechatronics within traditional course structures. The current structure of universities into departments of electrical, mechanical, civil, chemical, and other engineering departments is not conducive to setting up interdisciplinary studies.

But this situation is changing. Mechatronics is now surfacing at several centers of higher education: the universities of Arkansas, California at Berkeley, Kentucky, Louisiana State, and Penn State, as well as Rensselaer Polytechnic Institute.

The University of Arkansas in Fayetteville offers a course in electronic manufacturing processes that is part of the electrical, industrial, and computer-systems undergraduate curricula, while the University of California at Berkeley has just developed a master's program in mechatronics patterned on that offered at the University of Tokyo.

Students at the University of Kentucky, Lexington, may use its Center for Robotics and Manufacturing Systems in their graduate work. The center serves both as a research facility and a place where surface-mount technology is being developed for industry.

At Louisiana State University in Baton Rouge, undergraduate students at the Intelligent Manufacturing Systems Laboratory learn about automated manufacturing with a mechatronic cell in which to configure computers, robots, a computer numerically controlled milling machine, and a lathe. The lab works in conjunction with laboratories for computer-integrated management, advanced workstation designs, and machining processes.

**TO PROBE FURTHER.** Several books discuss the development of mechatronics in Japan. Among the more interesting ones are *Mechatronics, Japan's Newest Threat* by V.D. Hunt (Chapman and Hall, New York, 1988) and *Inside the Robot Kingdom: Japan, Mechatronics, and the Coming Robotopia* by F.L. Schodt (Kondansha International, Tokyo, 1988).

The IEEE is informative about mechatronics in several of its publications. The *IEEE Transactions on Components, Hybrids, and Manufacturing Technology* contains many papers on the subject and the Institute's latest magazine, *IEEE Robotics & Automation,* has some articles on the topic. The journal *Mechatronics* presents a good picture of developments in Europe, as well as important developments in Asia and the Americas. It is published eight times a year by Elsevier Science Ltd., Oxford, England.

Among the conferences focusing on mechatronics is the IEEE International Conference on Robotics and Automation, which will be held next May 22–27 at the Nagoya Congress Center in Japan. Among those to be held in the near future is the International Conference on Mechatronics and Machine Vision in Practice ($M^2VIP$), which is set for Sept. 13–15 at the Marriott Hotel in Surfers Paradise, Queensland, Australia. It is jointly sponsored by the IEEE, IE Australia, and the University of Southern Queensland.

On the other side of the globe, the Joint Hungarian-British Mechatronics Conference will be held Sept. 21–23 in Budapest at the Thermal Hotel. This conference is a combination of Mechatroninfo, a conference that has been held in Hungary five times since 1985, and the U.K. Mechatronics Forum, which has convened three times. ◆