THE FAST NEW WORLD OF FLAT MOTORS

BY STUART F. BROWN

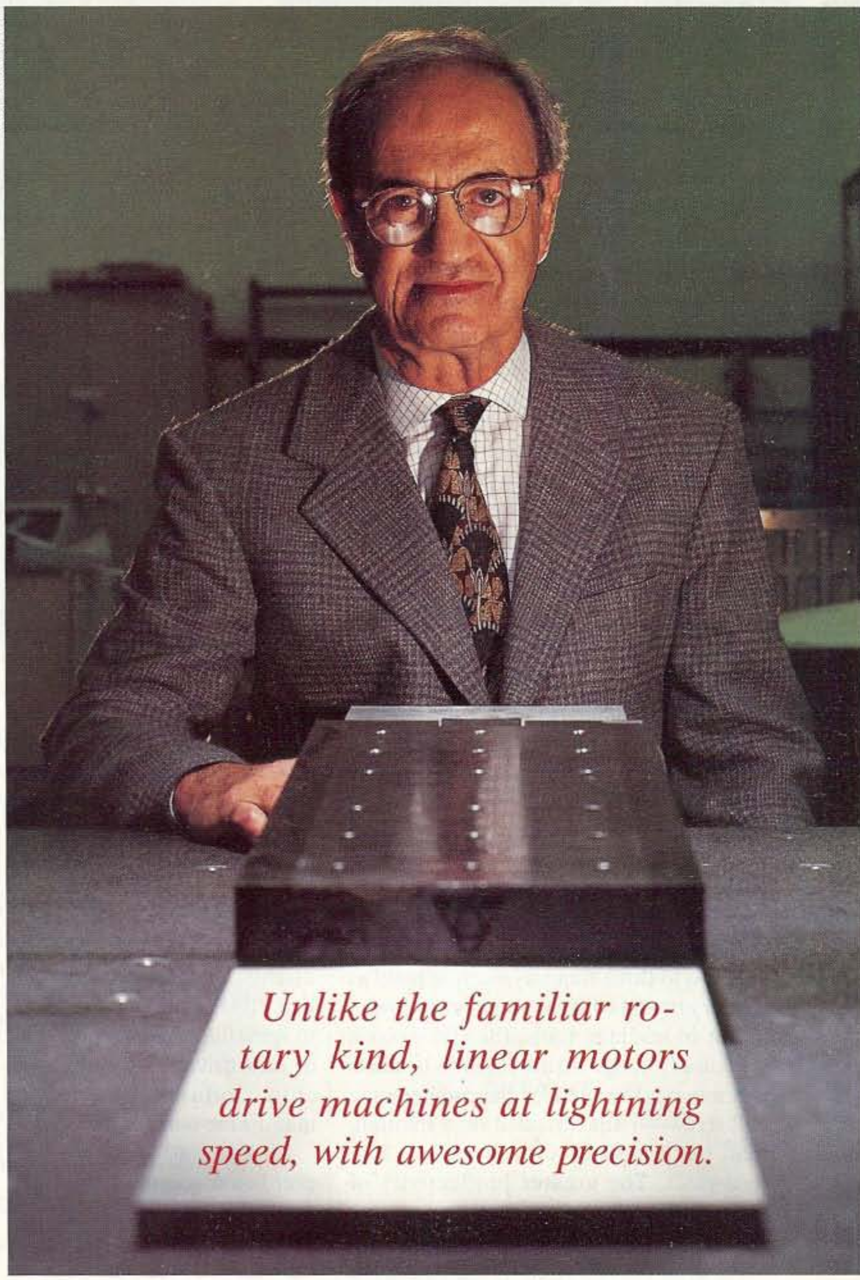
Think of a familiar, round electric motor that's been sliced open and rolled out flat. Instead of rotating, a linear motor shuttles back and forth when electricity is fed to it. Over the years, scads of articles have appeared about futuristic rail-gun weapons and magnetic-levitation railroads in which the train and track are the two parts of a "motor" potentially hundreds of miles long. Here's the news: Flat motors ranging from several inches up to 50 feet long are at work in real-world applications right now.

Left and right, up and down, in and out, the moves such machines make are startlingly quick, like that evil creature that stalks the crew of a spaceship in the thriller movie *Alien*. Yet when they slow down, their motion is creamy smooth, calming to watch. This ballet plays out in the workshops at Anorad Corp., a growing, $40-million-a-year company in Hauppauge, New York, that has done much of the pioneering work in making linear motors practical.

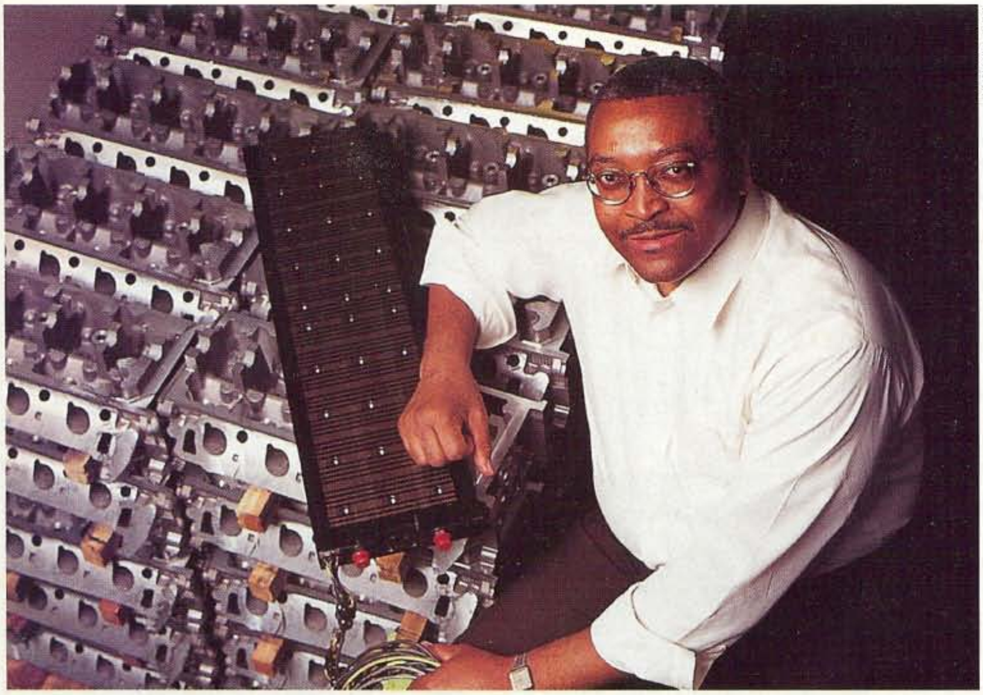
Anorad's flat motors are built into machines that perform such jobs as electronic-component assembly, laser machining, and precision inspection. Designers are studying all sorts of other applications in devices that need to be pushed in a straight line, from elevators to flight simulators to roller coasters. In the future, linear motors produced in great volumes might become cheap enough to propel familiar things like computer printer heads or power windows in cars.

Today the biggest new market is in machine tools, where flat motors make possible greater speed, precision, and flexibility—rapidly switching production from one part to another. "Linear motors are one of the major machinery breakthroughs in the past 100 years," says Richard Ogletree, manager of Ford Motor Co.'s "factory of the future" launch team in Dearborn,

NICK CARDILLICCHIO



Unable to buy linear motors, Anorad Corp.'s Chitayat developed his own.



Ford's Ogletree rests his arm on a linear motor atop a pile of new cylinder heads.

Michigan, which after years of grueling effort has succeeded in integrating them into an experimental production shop.

A flurry of orders has come in from automakers and aircraft companies, which are starting to invest in high-performance metal-cutting equipment incorporating flat motors. The motors are already being used to machine engine blocks at a Chrysler plant in Mexico and huge airframe parts at McDonnell Douglas in St. Louis. In ordering a brace of linear machines, Daimler-Benz has done what German companies almost never do—buy U.S. machines for auto plants in the homeland.

To be sure, flat motors aren't for all uses. Only a small fraction of electrically driven motion is linear. The lion's share of the business will remain with that old workhorse, the rotary electric motor, which has some new wrinkles of its own (see box). With their high-cost magnetic alloys, moreover, linear motors typically cost two to three times as much to build as a rotary model with the same horsepower.

But in machine tools, the flat motor's cost disadvantage shrinks to 30% because it eliminates the need for the cumbersome ball screw—a nut threaded on a spinning shaft that translates a rotary motor's spin to a push. The greater productivity of multimachine "cells" using linear motors can tip the economics in their favor, sometimes dramatically. Mass-production efficiencies will undoubtedly open up more uses for the motors. Anorad Corp. projects that the total business, now estimated at $60 million a year worldwide, could grow to $250 million by 2000.

Nobody is more pleased by the surging interest in linear motors than Anwar Chitayat, Anorad's innovative president and CEO. Using electromagnetics to create precisely controllable linear motion is an idea that has been tried for years, but it took the labors of Chitayat, 66, to give it the needed shove. Born into an Iraqi Jewish family, Chitayat came to the U.S. in the late Forties to get an engineering education. He ended up staying, did a stint in the U.S. Army working on radars in Alaska, and founded Anorad (the name is an acronym for "Anwar's own R&D") in 1972. The plan was to build fast, high-accuracy machines for companies like IBM, which wanted to speed up the assembly of disk drives and multichip modules used in mainframe computers.

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As demand grew for ever faster and more precise machines, Chitayat became dissatisfied with the subtle jitters and delayed responses inherent in conventional ball-screw mechanisms. "About 15 years ago I got interested in linear motors and began asking motor manufacturers if they could build me about 1,000 of them," Chitayat recalls. "They couldn't see any profit in it and said no. So I decided to make my own."

The effort paid off in the Eighties, when Chitayat was awarded a handful of patents for linear-motor innovations. These included high-efficiency electric coils and methods for producing them, and ways to solve, with liquid cooling, overheating problems in high-powered versions. Anorad also developed computerized control systems that gave its linear-motor drives the ability to accelerate and decelerate with lightning speed, while coming to rest within one micron (less than one-ten-thousandth of an inch) of a desired position. These advances overcame such tough motion-control problems as handling fragile silicon wafers in chipmaking plants. Today more than 30,000 Anorad motors are gliding back and forth in special machinery where speed, extreme smoothness, and high precision are needed.

Flushed with success, Chitayat decided to crank up the volume and drive down production costs by getting more machinery builders interested in linear motors. It was a tough sell until a few years ago, when word got around that Ford Motor Co. was using his motors in a proof-of-concept system for producing major engine components. "All sorts of people starting asking us about linear motors when they heard the name Ford," Chitayat says.

During the mid-Eighties, Ford had decided to find an answer to a long-standing problem: the huge cost and inflexibility of transfer-machining systems. Transfer lines, as the shop-floor guys call them, are custom-built marvels—sometimes longer than a football field—that are designed to produce a specific part in very high volume. As rough foundry castings move through them, hundreds of whirring stationary spindles tap, drill, and mill holes, transforming the castings into gleaming engine blocks or cylinder heads. The catch is that a big, brainless, hard-tooled transfer line can only make the part it's designed for, and can't be taught a new routine.

With consumer preferences shifting more rapidly, Ford wanted the flexibility to make quick product changes. This required tooling that could be reprogrammed to make small to medium-size batches of parts in response to market demands. Thus the company turned to machining centers—computer-controlled, single-spindle machines with automatic tool changers—that can perform a multitude of operations on a part clamped in them. Trouble was, the centers available from toolmakers' catalogues were often too slow for the pace of an auto plant.

The job of canvassing machinery makers and university research groups worldwide in a search for the building blocks of a superfast machining center fell to Richard Ogletree, 54, of Ford's factory-of-the-future launch team. Trained as an electronics engineer, Ogletree has worked in several parts of the company's manufacturing operations, his two most recent assignments focused on flexible machining.

Observations with a stopwatch, Ogletree recalls, revealed that existing machining centers wasted a lot of time moving the cutting tool to and from locations on the part or fetching new tools. Too little time was devoted to actually cutting metal. The ball-screw mechanisms in the machining centers could move the spindle to and fro at about 300 inches per minute. Ogletree wanted the spindle to hustle ten times as fast, like a hummingbird harvesting nectar from flowers. That led him to linear motors. Anorad was brought into the program, and Ford eventually got options to buy 16% of the privately held company's stock.

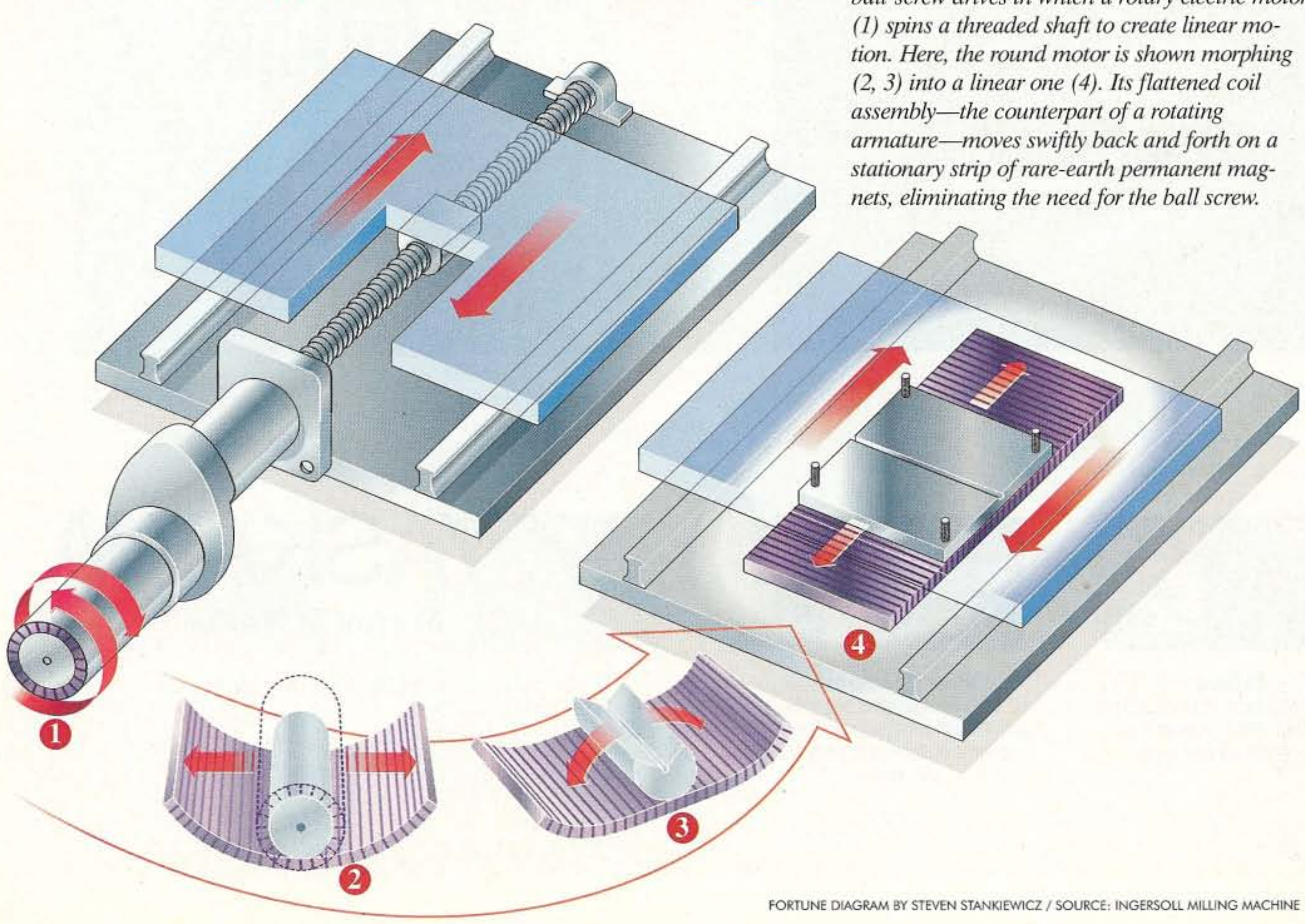
Realizing that an experienced machine-tool builder was needed to bring the program to fruition, Ford then forged an alliance with Ingersoll Milling Machine of Rockford, Illinois. Together, engineers from the three companies slogged through several years of problem solving and several generations of prototypes. The effort, carried out under great secrecy at Ingersoll, resulted in fast machines that can be used to make all sorts of parts in quantities that don't justify the expense of a transfer line.

Ogletree proudly shows a visitor through his experimental, low-volume machine shop, which grinds away in a clean, well-lit corner of a Dearborn plant mainly devoted to making four-cylinder Escort engines on conventional equipment. The experimental "cell" consists of two clusters of beige-painted, high-speed machining centers bearing the Ingersoll nameplate. Robotic material-handling equipment transports the workpiece—cylinder heads and blocks for 4.6-liter V-8 luxury-car engines—from machine to machine.

In the cylinder-head machining cell, just four machining centers, each with a single versatile, fast-moving spindle, do the work of hundreds of fixed, single-purpose spindles on a transfer line. Linear motors shuttling in three axes (known as *x*, *y*, and *z*) are the motive force positioning the spindles, which in turn are powered by fast rotary motors. Behind the cabinetry and safety-glass windows that separate machine operators from the wild action going on inside, shiny chips and milky-looking cutting fluid fly in all directions. A tool stabs momentarily into the workpiece, retracts, relocates, and repeats the attack, all around the part's periphery. *Voilà!* Now there are holes for all

When Going Flat Is an Advantage

Traditional machine tools use relatively slow ball-screw drives in which a rotary electric motor (1) spins a threaded shaft to create linear motion. Here, the round motor is shown morphing (2, 3) into a linear one (4). Its flattened coil assembly—the counterpart of a rotating armature—moves swiftly back and forth on a stationary strip of rare-earth permanent magnets, eliminating the need for the ball screw.



FORTUNE DIAGRAM BY STEVEN STANKIEWICZ / SOURCE: INGERSOLL MILLING MACHINE the bolts that attach the cylinder head to the engine block.

The Ford engineers proceeded cautiously over a period of months as they opened up these machines to full throttle, so as to learn from small glitches rather than catastrophes. Currently, the two cells produce three V-8 engine blocks and five cylinder heads each hour. By tripling the number of machines in the two work cells, Ogletree says, the shop could boost output to a medium-volume level. The machines boast versatility to spare. If a production logjam arose somewhere else in Ford, he says, "we could go to work on an entirely different cylinder head very quickly and very cheaply, just by reprogramming the machines and changing the fixtures that hold the parts."

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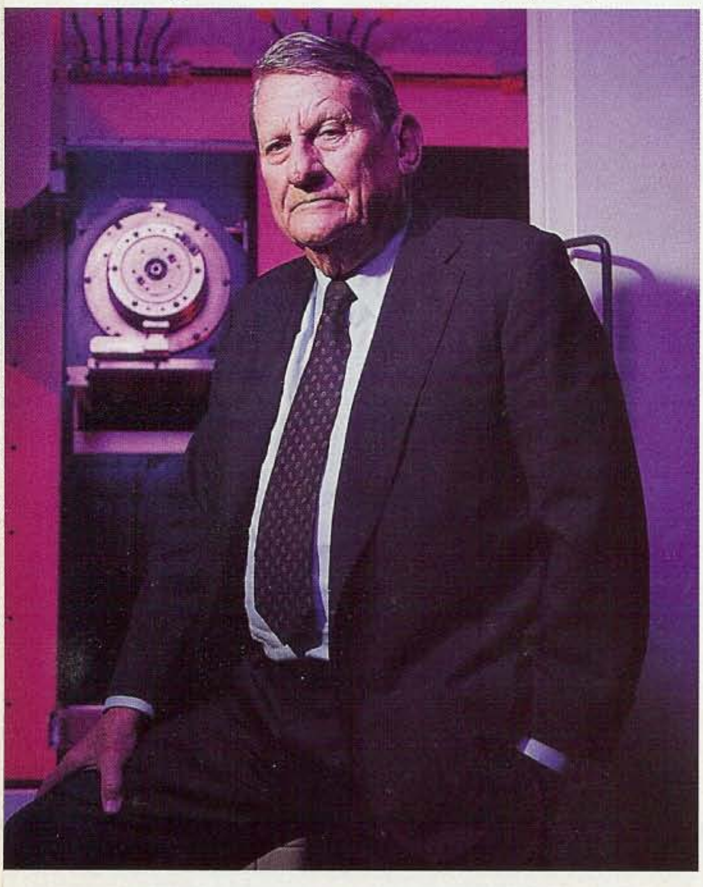
Ogletree's collection of high-speed equipment is viewed by Ford as a test bed, a demonstration to the organization of what can be done. "We will be using more of this technology as we build new plants," Ogletree says. "Everybody in manufacturing is looking for high speed and flexibility, and now it works." Numbers that spill from his lips leave little doubt that the cells are a better mousetrap. True, each high-speed machining center costs about $900,000, twice as much as a conventional one. But because they run faster, fewer are needed, along with fewer robots, gantries, and conveyors to relay parts from one machining center to the next. The whole installation still winds up costing about 20% more. But the bottom line is that it turns out 2½ times as much work.

Ford's plant in Cologne, Germany, will be the company's first to get a suite of high-speed machinery for large-volume production of transmission parts. Those machines, supplied by Ex-Cell-O GmbH in Eislingen, Germany, are equipped with linear motors built by Anorad's German competitor Kraus Maffei. Plants in the U.S., Ogletree says, will get high-speed machines as older equipment is retired.

Building linear machine tools took sweat, says Gaylord.



TODD BUCHANAN

Edson Gaylord, Ingersoll's chairman, shares the enthusiasm for linear motors but is quick to put in a kind word for transfer lines. Ingersoll knows all about them, having built the first one in this country in 1924 for Henry Ford's Model T production line. "The transfer line is still a wonderful machine if you have a product you can sell in large numbers," observes Gaylord, a blunt veteran of the machinery wars with the presence of a compact John Wayne. He's a grandson of Winthrop Ingersoll, who founded the company in 1887. "The transfer line can make you money hand over fist. But flexible machines are the way to go when you are producing less than 100,000 parts a year."

As for linear motors, Gaylord tempers his upbeat message with recollections of how much engineering it took to integrate them into a salable machine. "We thought learning how to make these things work was going to take three years, and now it's been 11," he says. The company got its linear baptism when it built an experimental machine for Boeing, which proved that moving very fast was indeed possible. But even more important than speed, the engineers discovered, was the linear motor's innate ability to accelerate and decelerate much more quickly than ball screws or other mechanisms. Turning this discovery into product required time and sweat.

"It's a real trick," Gaylord says, "to be able to start a machine from zero, get it up to 3,000 inches per minute, and back down to zero in a very, very short amount of time—while being accurate to a fraction of a thousandth of an inch. That problem occupied us for seven or eight years. Now our latest machines spend only 15% of their time accelerating and decelerating; the rest of the time they are going full speed. This is what you have to do to compete with all those spindles on a transfer machine."

Some potential showstoppers had to be overcome before Ingersoll could exploit the wonderful dynamics of linear motors. One was the spindle, which has to turn at very high speeds—20,000 rpm and faster—to smoothly cut metal at prodigious rates. Other challenges included developing computer control systems with feedback loops fast enough to keep pace with the machines, and relentlessly pursuing better cutting-tool materials and designs. All too often the solution to one problem begot another. Crank up the speed, break the tools. Improve the tools, crank up more speed, and break them again. And so forth.

Finally, using finite-element analysis software—which allows designers to visualize complex stress patterns and decide where they need to add or subtract metal —helped engineers create the strong, lightweight machine frames needed to accelerate like a drag racer. Traditionally, machine-tool designers achieved rigidity by adding more cast iron, but you can't do that with parts that need to move ultrafast.

It was all worth it. Ingersoll, which has spent more than a century fearlessly devising one-of-a-kind, special-order machines for all manner of fascinating uses, now finds itself with two standard "high-velocity machining" models that will be produced in numbers of more than one. "It's a real shock to our culture to build two things that are the same," says Gaylord. To avoid shattering the world-view of its entire enterprise, Ingersoll has created a separate high-velocity machine division to spearhead the foray into repetitive production.

For the first time in 50 years, the company exhibited at the huge International Machine Tool Show, held earlier this year in Chicago. The HVM 60 high-velocity machining center Ingersoll trucked to the show attracted lots of attention and was bought by Remmele Engineering of New Brighton, Minnesota. Remmele will use it to make engine crankcases for Bombardier's Seadoo personal watercraft.

Other car companies have already voted with their wallets for Ingersoll's high-velocity machines. Ironically, though Ford collaborated on the arduous R&D that made them work, Chrysler has been quicker to place orders. The automaker has a suite of five in its Toluca, Mexico, plant machining 5.9-liter V-8 engine blocks for its popular Ram pickup truck. Additional machines on order will boost the total at the plant to 17, including five for machining cylinder heads, as production ramps up to 85,000 engines yearly.

Gaylord is particularly proud of the machines now being readied for shipment to Daimler-Benz in Germany, where they will be used to produce cylinder heads for a small, vanlike "Swatch" vehicle that goes into production next summer. "This is really a landmark order," he crows, "because the German automobile companies never, ever buy machines made in the U.S. We called on them for 17 years before we sold them a cutting tool—and it was made in Germany. But they gave us this business because they think we've got the technology of the future."

Aircraft companies, too, are finding uses for linear-motor-powered machines. Dennis Bray, Ingersoll's vice president for heavy machines, says customers in the U.S. and Europe have ordered two huge systems, each about 80 feet long. They'll make large, complex parts such as airliner wing spars that have very thin stiffening ribs for strength and lightness.

McDonnell Douglas in St. Louis is using a custom-built Ingersoll machine equipped with linear motors to mill 18-foot-long cargo-ramp bulkheads out of single slabs of aluminum for the Air Force C-17 transport plane. "We are running at five to ten times the cutting speed we used to get on conventional machines," says Larry Kuberski, group manager of strategic modernization. "The surface finish and accuracy of the parts are excellent, and very little handwork is needed to complete them."

Faced with the growing demand for linear motors, Anorad's Chitayat decided that it's to his company's advantage to license his technology to bigger companies, while keeping up the R&D needed to advance the state of the art. Both Fanuc Ltd. of Japan and Kollmorgen Corp.'s motion technologies group in Radford, Virginia, have signed agreements to produce the company's linear-motor designs. Siemens Energy & Automation in Elk Grove, Illinois, has developed complete motion-control systems using Anorad motors.

For the near term, toolmakers look like the strongest market for flat motors. Builders like Mitsui Seiki of Japan showed linear-motor-driven precision-measuring systems at the Chicago trade show, and Kingsbury Corp. of Keene, New Hampshire, has launched its version of a high-speed machining center, which it calls the Cyber-Cell. A number of machine-building giants, including Cincinnati Milacron, also have linear-motor programs under way.

Chitayat likes to look ahead to higher-volume uses that will come as linear motors get cheaper. The company hopes to introduce a new generation within a year that will use a more powerful, less costly magnetic alloy and that will benefit from fully automated production methods. In two years, Chitayat predicts, prices will be less than half what they are today. "Before long," the inventor muses, "people will find all sorts of ways to use these motors." ■

Rotary Motors With Brains

The microelectronics revolution has breathed new sophistication into those cylindrical standbys, rotary electric motors. The shrinking size and cost of silicon circuits has enabled Baldor Electric of Fort Smith, Arkansas, one of the industry's most venerable names, to package together a motor and a compact adjustable-speed control, or inverter, in a product called Smart Motor. "Not long ago the inverter was bigger than the motor, and now the opposite is true," says Darryl Van Son, Baldor's manager of market research and planning. In industrial uses, these motors can be set to run at constant torque to power a steady-speed conveyor, or to handle variable-torque loads such as pumps and blowers that need to change speed on the fly.

Baldor also builds sophisticated motor-and-control units called vector drives that use fast microprocessors to control voltage and current separately. The drives incorporate rotary encoders that send speed and position information back to the control unit in digital form. Advantage: precise control of speed and torque. A vector drive can even develop full torque at zero rpm, enabling a motor to stop and hold a heavy load in an exact position.

Looking down the rotary road, Baldor is studying so-called predictive-maintenance software like that used in nuclear power plants. It can monitor and analyze the current a motor draws for much the same reason that a doctor listens to your heart. "This method can actually sense how many balls are in the bearings in a motor, and which are wearing out," says Van Son. "This can be very valuable information in industries that are running processes 24 hours a day, where every minute of downtime costs a fortune."

But Baldor is wary of linear motors. A few years ago, when the company was supplying controls used in the high-speed machining centers Ingersoll built for Ford, it considered a joint venture to produce Anorad's linear models. But after reviewing some of the complexities of developing manufacturing equipment, Baldor decided to stick with what it understands best: the round stuff.