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Brakes and Clutches

Technical Articles

- Clutches and Differentials— A New Twist
- Innovative Couplings— Part I

Feature

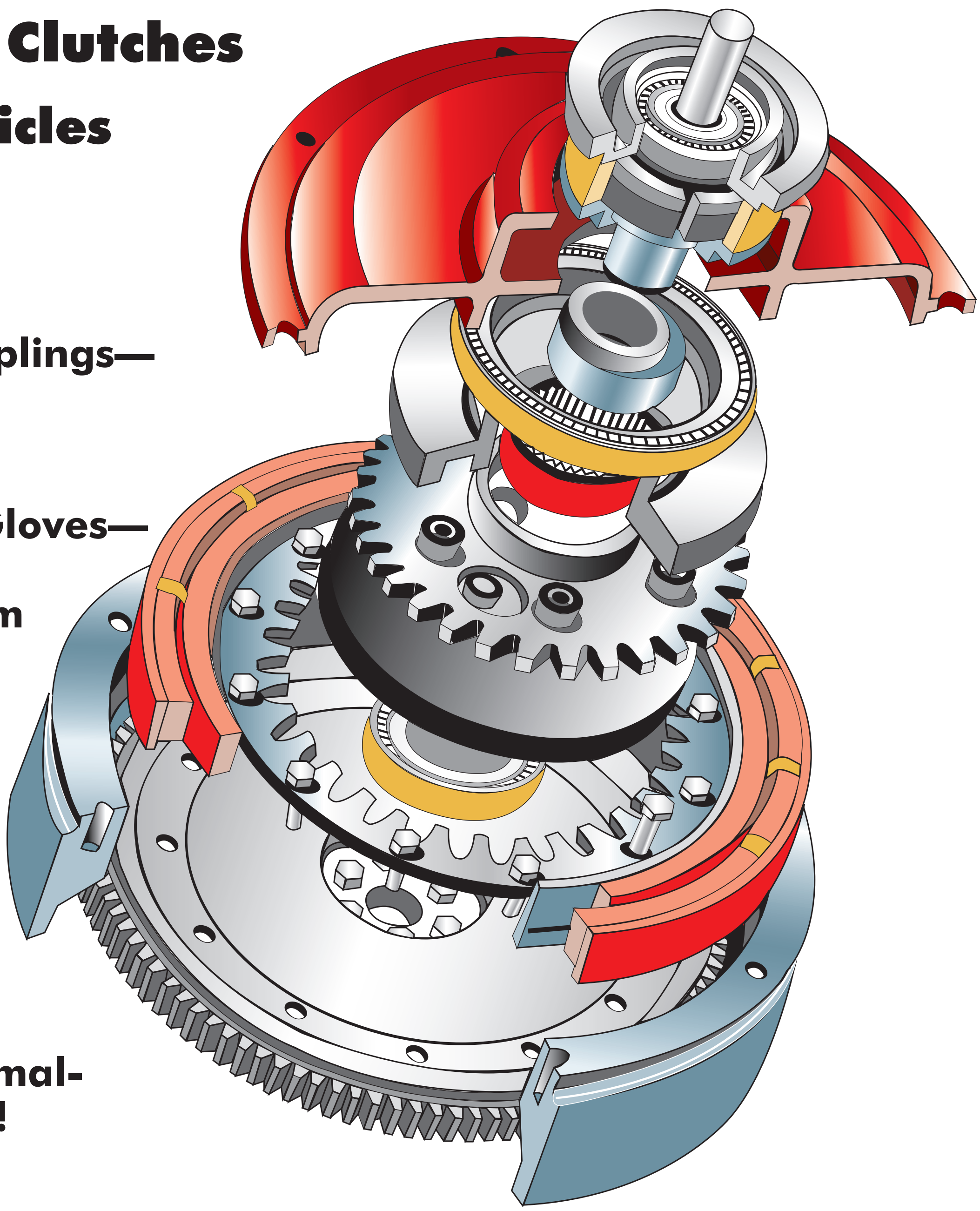
- Dropping the Gloves— Robots in the Operating Room

Case Study

- Brakes and Clutches for Farming

Power Play

- Argonauts— Start Your Thermal-Driven Engines!



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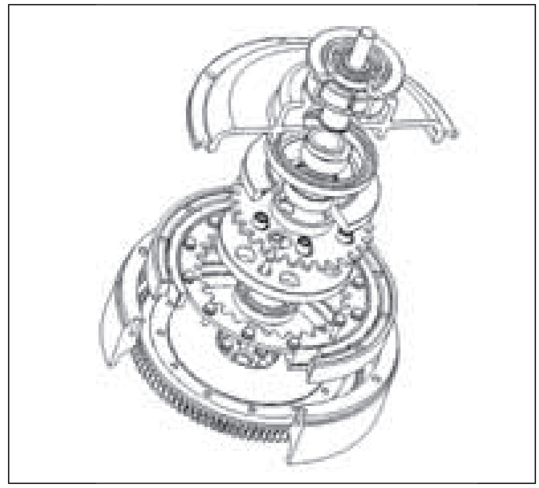
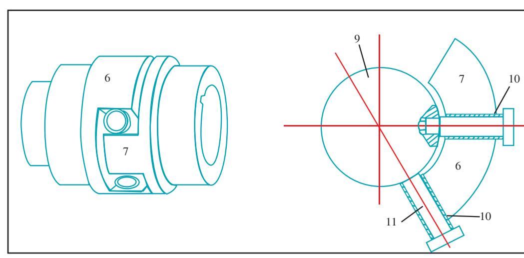
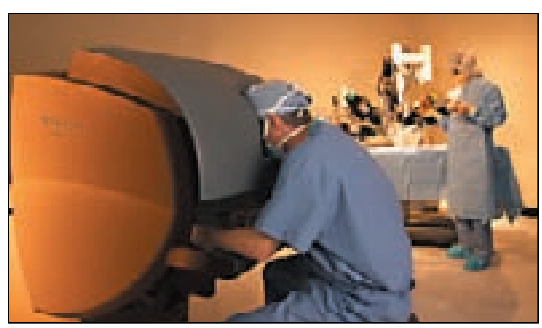


FEATURE ARTICLE



CASE STUDY



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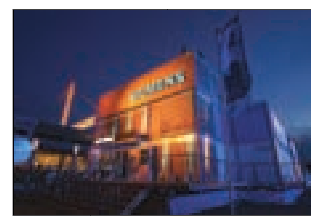
DEPARTMENTS



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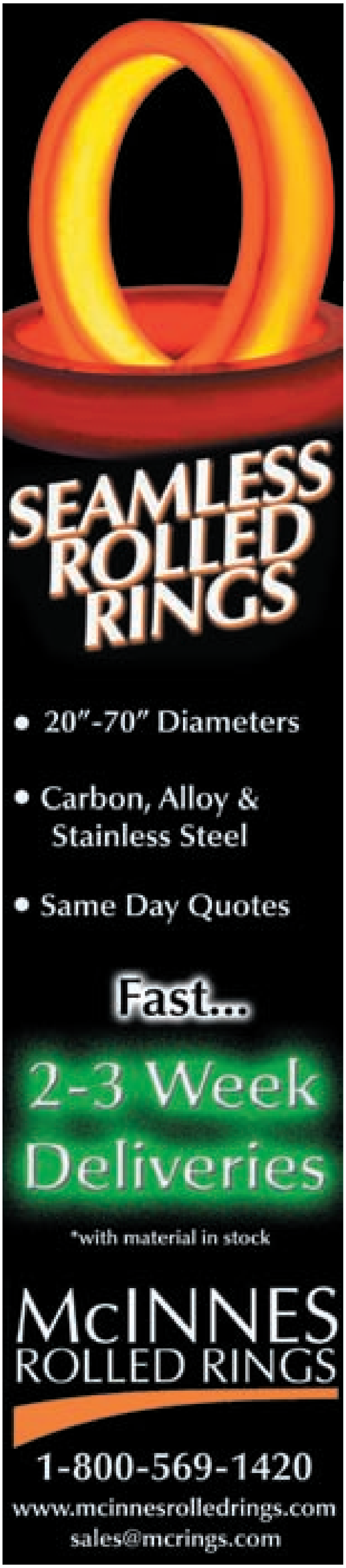

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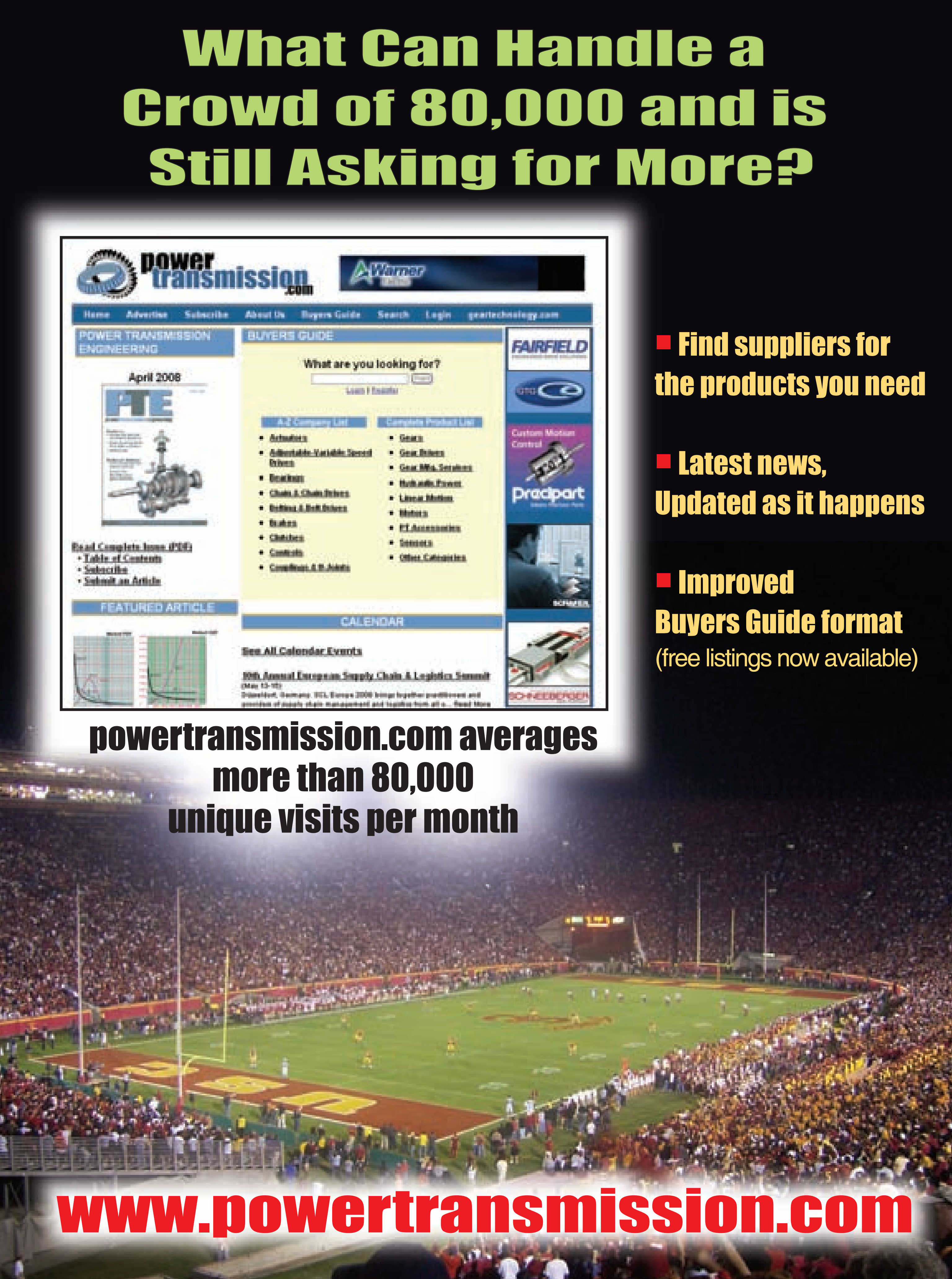

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Less is More: Applied Motion Products

SUPPLIES TWO AUTOMATION SOLUTIONS, ONE UNIT

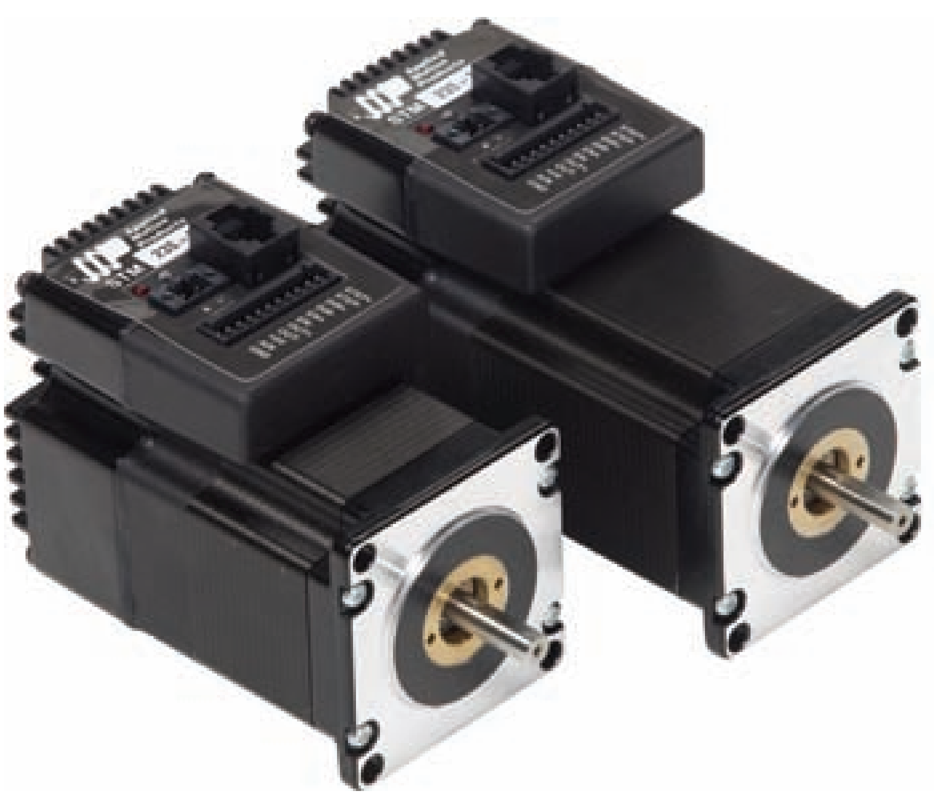
Why buy a stepper drive and motor separate when you can get both in one product? In response to a mounting industry trend to consolidate component parts, conserve space, reduce wiring and minimize costs, Applied Motion Products introduces the STM drive+motor solution, providing a stepper drive and motor two-for.

"Traditionally the motor is housed within the machine while the drive module and controller, if used, are housed in an external control cabinet, requiring that a motor cable run from the control cabinet to the motor," says Richard Hazelwood, engineering services manager for Applied Motion Products. "Because the STM is a combined drive and motor unit, the only additional requirement for operation is that power be supplied, which is likely already distributed around the machine to other devices.

"Many people like the idea of a single unit instead of two; it saves space and wiring and tends to be more cost effective," Hazelwood says.

The first product developed in collaboration with Shanghai partner AMA, the STM drive+motor features advanced current control, electronic damping (anti-resonance) technology, command signal smoothing and torque ripple smoothing. The STM is suited for a range of automation applications, including medical, packaging and semiconductor. The RoHS-compliant and CE-certified standard units are protected against over- and under-voltage, over-temp, motor shorts and motor open phase.

The STM comes in a 92.4 mm length version with output torque up to 125 oz-inch, or a 114.4 mm length version is available offering output torque up to 245 oz-inch. The drive+motor unit supplies three digital inputs, a digital output and an analog output, and users can choose between two communication interfaces. Stall detection and prevention functions are provided by an optional 1,000-line encoder that is part of the motor body, leaving the unit's size unaffected.



In addition to these features, two versions, S and Q, with varying control options, tailor the product towards more specific uses.

"The STM-S version is for those who have an existing step motor controller; it accepts an industry standard pulse and direction signal," Hazelwood says. "The S version also has an oscillator function. This means it can be set to run at a specific speed without an external control. Lastly, it can be controlled by a host PC sending it commands over the serial port."

The STM-Q version provides stand-alone programmability along with real-time host or HMI compatibility. This is achieved through the command set that includes motion, I/O, math functions and program control. "Q is our motion control language. With Q, a drive can be programmed to perform a sequence of moves or operations based on calculation or external signals from other systems," Hazelwood says. "We have systems in place with 'complex motion profiles.' This is where the motor will change speed during a given move distance and systems that communicate to host devices while executing a move sequence."

The STM drive+motor uses several methods to avoid disruptive vibration. The motor functions more smoothly while wear is minimized on the mechanical components due to command signal smoothing, which converts full- or half-step signals into microstep waveform and does away with jerky transitions that emerge from the command signal's velocity profile, according to Hazelwood. Motion is also leveled out using torque-ripple-smoothing technology, which results in low speed torque ripple by modifying waveform. A microstep emulation technique allows motion to occur with less turbulence as the step motor moves less than a full step at a time.

"Some older systems do not have the benefit of being able to supply pulses at the higher frequency required for microstepping, and hence can only control older 'full step drives,' losing the function of smoother motion. We give that function back to those using older systems," Hazelwood explains.

The STM provides advanced current control, which is achieved when a complex current loop uses high-speed, 12-bit current and voltage sampling, real-time math motor modeling and high resolution PWM amplifier control, Hazelwood explains. The motor's parameters are measured and configured by self-test and auto setup features. Electronic damping, or anti-resonance technology, allows for ample use of available torque and eradicates midrange instability for higher motor speeds.

"In the world of step motors, users would purchase a motor with up to twice the necessary torque so that the system resonance found at the mid-range speeds would not cause the motor to 'stall' or fail in the movement it was to perform," Hazelwood says. "Electronic damping prevents this resonance from affecting the system, so the large torque overhead is not needed, thus saving money, or just providing better performance from the existing choice of motor."

For more information:

Applied Motion Products
404 Westridge Drive
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Phone: (800) 525-1609
Fax: (831) 761-6544
sales@applied-motion.com
www.applied-motion.com

H1 Pumps

DESIGNED FOR MOBILE MACHINING

Sauer-Danfoss released the H1 115/130 cc pump as an addition to the H1 family of closed-circuit variable displacement axial piston pumps, which includes the 45/53 cc single pump and the 78 cc single pump.

The H1 pumps are compact and have a high power density for simple installation and more design flexibility. The units have an integral electro-hydraulic servo piston assembly to control the rate and direction of hydraulic flow, according to the company's press release.

"This new generation of H1 pumps will be a popular size for many hydrostatic applications," says Randy Rodgers, Sauer-Danfoss product portfolio manager. "The H1 family of pumps offers the OEM a number of advantages including an increased selection of displacement and product design life, and opportunities to improve vehicle maintenance and operating costs.

"The H1 pumps are built to support next-generation engines as the industry moves toward Tier 4 emission controls," Rogers says. "They are fully PLUS+1 Compliant to interface seamlessly with Sauer-Danfoss' electronic machine control architecture. H1 pumps offer the right displacement, right load life and the right value for the OEM's machine investment."

The H1 family is for high- and medium-power mobile machinery that requires steady, instant propulsion and exact control. The pumps are designed for complex applications demanding high productivity for off-highway industries including agriculture, construction, road building, material handling, forestry and turf care. Rogers says, "H1 pumps are designed for smaller package sizes with a significant reduction in the length of the units, giving design engineers more freedom and flexibility in design."

For more information:

Sauer-Danfoss
2800 East 13th Street
Ames, IA 50010
Phone: (515) 239-6000
Fax: (515) 239-6318
www.sauer-danfoss.com

Bosch Rexroth

EXPANDS EXTERNAL GEAR PUMP LINE

Adding two nominal sizes to the SILENCE pump series and optimizing two standard series models, Bosch Rexroth users can choose from over 5,000 pump variants and 500 motor options available in the modular line of external gear units.

The B and G Series pumps have been modified to offer more power. The displacement of the B Series has doubled to seven cubic centimeters per revolution. The G Series now offers displacements up to 63 cubic centimeters per revolution to serve applications in the upper power classes. Versions with cast-iron bodies are now available for special requirements, such as high numbers of load cycles and long service life.

The U and T series have been added to the SILENCE pump family. They feature low noise emissions and vibrations, and they satisfy demands for all displacements between four and 63 cubic centimeters per revolution.

Rexroth's individual or combined multiple external gear pumps are designed for machines and systems with maximum operating pressure of 4,000 psi and cover a speed range up to 6,000 rpm. Low starting pressure exemplifies the external gear motors, and they offer a high power density and high efficiency with economical life cycle costs, according to the company's press release.

For more information:

Eric Deist
Account Coordinator—
Lead Management Services
MarketSense
681 Commerce Street
Burr Ridge, IL 60527
Phone: (630) 654-0170 x115
Fax: (630) 654-0302
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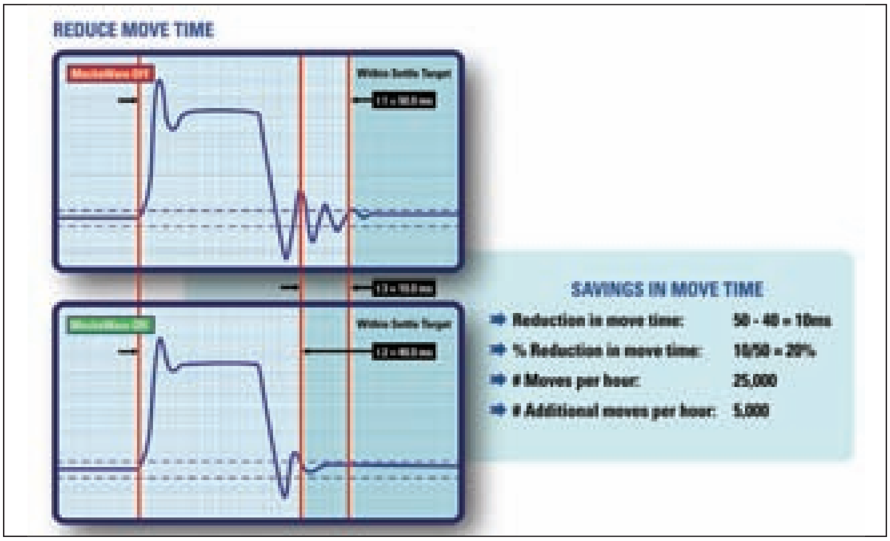


Mechatronic Toolkit

INTEGRATES MECHANICAL, CONTROL SOFTWARE DESIGN

MechaWare 3.0 from Danaher Motion is a special-purpose toolkit for motion system design that allows software and mechanical engineers to work together in designing, testing and modifying custom motion algorithms in less time and cost.

Features include complete capture, logging and visualization tools that enable mechanical, I/O and software data to be combined into a single measurement environment. "What previously took months of development time and often had to be outsourced to specialist consultants, at a cost of tens of thousands of dollars, can now be achieved internally, often in just hours," says Dr. Robert Steele, Chief Technical Officer of Danaher Motion Performance Controls Group.

MechaWare 3.0 has a library of standard function blocks that supply specific information about control theory. The software can merge with third-party tools like *MatLab* and *Simulink* and achieves uninterrupted download of run-time code as well as test and measurement of real-time machine performance. As a result of the libraries, designers can use emerging accelerometer feedback devices, so they can create mechanisms with less weight and stiffness for lighter, faster, smaller and more precise machines.

"With *MechaWare*, mechanical and software engineers now have the ability to merge their expertise seamlessly to produce superior machines quickly and much less expensively," says Bill West, director of performance controls engineering at Danaher Motion. "Users can now iterate their designs faster, while taking advantage of other advanced tools and technologies—all of which leads to more innovative and successful machine designs."

For more information:

Danaher Motion
430 La Patera Lane
Santa Barbara, CA 93117
Phone: (805) 681-3300
www.danahermotion.com
www.synqnet.org

Servo Drive Family

ADDS MULTI-AXIS CAPABLE MODEL

Parker Electromechanical Automation Division introduces the Compax3M industrial servo drives for multi-axis applications. The Compax 3M uses one power supply to power multiple drives and saves cabinet space as all axes are inserted and share a braking resistor.

There are three options for continuous current output: 5, 10 and 15A, all with a 2-inch axis width. A 30A power level with a 4-inch axis width is scheduled for release in the fall. A centralized power supply allows different AC mains voltages to be used on the whole drive combination without adaptive measures. Other features include a single braking resistor and mains filter. The Compax3M can be configured to be a simple drive controlled by a motion controller or a fully intelligent drive programmed in all international standard languages.

For more information:

Parker Electromechanical Automation
5500 Business Park Drive
Rohnert Park, CA 94928
Phone: (707) 584-2417
www.parkermotion.com

Microstepping Driver, Controller

COMBINES INTELLIGENCE AND PERFORMANCE

The R356 microstepping driver and controller from Lin Engineering can output up to three amps of peak current, can handle between +1 to 40 DC volts of input and is capable of microstepping resolutions from 2x to 256x. The microstepping range allows for up to 51,200 miniature steps for each complete revolution on a bipolar 1.8 degree step motor.

Other features include programmable ramps and speeds, software selectable hold and move currents, four user configurable digital I/Os, an optical sensor for homing and a switch closure to ground. The R356 uses RS485 communication, allowing users to make commands from a Windows based program or from Lin Engineerings's graphical user interface, *Lin Control.*

For more information:

Lin Engineering
1990 Russell Avenue
Santa Clara, CA 95054
Phone: (408) 919-0200
Fax: (408) 919-0201
sales@linengineering.com
www.linengineering.com

Megalife Power and Free Conveyor Chains

REQUIRE NO MAINTENANCE

The Megalife range of power and free conveyor chains by Iwis uses a patented link with sintered metal bushes and running rollers to provide maintenance-free operation. The chain links and running rollers are supplied with a lubricant while running by a built-in lubricant reservoir. The sintered bushes are soaked in oil in vacuum conditions while the chain surfaces remain free of lubricant.

These chains apply to packaging and food processing, the electronics industry, PCB production, conveyor systems, wood, glass and ceramics processing and medical engineering. They are recommended for applications in which lubrication is either impossible or not beneficial, including dry ambient conditions, cleanrooms, installations with restricted maintenance access and applications where contamination needs to be prevented, according to the company's press release.

The Megalife chains are low wearing, even in extreme conditions, and the required drive power and chain load are reduced by the sintered metal rollers, which cut friction up to 30 percent. Iwis offers the chains in plastic and hardened steel versions. The steel roller option can be used in a temperature range from –40 degrees Celsius to 160 degrees Celsius, and the plastic rollers can handle up to 80 degrees Celsius. The Megalife conveyor chains are offered with pitches of 12.70 mm and 19.05 mm.

For more information:

Iwis Drive Systems, LLC
3902 Hanna Circle, Suite F
Indianapolis, IN 46241
Phone: (317) 821-3539
Fax: (317) 821-3569
sales@iwisusa.com
www.iwisusa.com

Linear Magnetic Sensors

DESIGNED FOR INDUSTRIAL APPLICATIONS

Infineon Technologies introduces the TLE4997 and TLE4998 programmable linear magnetic sensors used in angle, position and current measurement devices for industrial applications. Both have programmable parameters that include offset, bandwidth, polarity, output clamping, magnet thermal compensation coefficients and memory lock. The TLE4997 sensor provides analog output while the TLE4998 provides SENT or PWM output interfaces.

"Infineon is building on its position as a leading provider of linear hall sensors for the automotive industry with new products that will expand the company's reach to industrial applications such as position, rotation and electrical current measurement," says Bruce Strachan, sensor marketing manager for Infineon Technologies North America Corp.

Both new sensors are surface mount devices operating at three optional ranges: ±50, 100 and 200 m Tesla. The TLE4997 and TLE4998 feature 12-bit resolution and offer low ratiometric error in the range of –40°C to 150°C.

For more information:

Infineon Technologies North America Corp.
640 N. McCarthy Blvd.
Milpitas, CA 95035
Phone: (866) 951-9519
www.infineon.com/us

Hose Guard Products

SURVIVE RUGGED CONDITIONS

A new line of hose protection products from Kurt Hydraulics includes four styles that are designed to prevent premature failure resulting from wear, abrasion and deep cuts in rugged applications. They are available as a complete hydraulic hose, coupling and protection system and are offered in a range of diameters and lengths.

The Spring Wire Guard style slides over a hydraulic hose and protects the hose surface. The corrosion resistant coiled steel wire covering is heavy duty and prevents hose kinking while distributing bending pressure over the length of the hose.

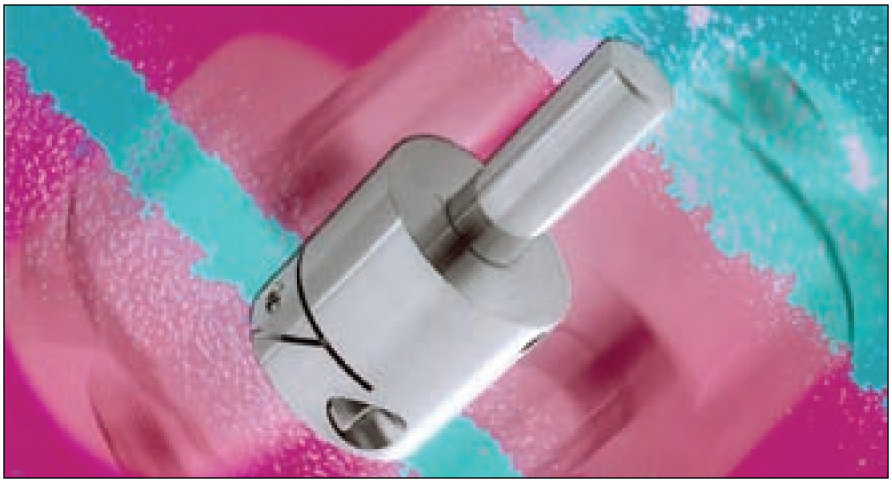
The Spiral Steel Wrap, made from galvanized steel, is the highest level of hose protection in the most severe operating conditions. Depending on an application's tightness, the material covers 80 to 100 percent of a hose's surface.

The Nylon Sleeve Guard provides complete hose coverage. The woven Nylon hose protection product flexes freely, is capable of withstanding thousands of abrasion cycles and slides over the hose quickly for prompt, simple installation.

Shutting down for installation is unnecessary with the Spiral Poly Wrap because it can be installed over existing, positioned hoses and cables. It is made of sturdy-yet-flexible black elastomer with protective beveled edges. It is capable of consolidating several loose hoses and cables into one line and can enter or exit at any point.

For more information:

Kurt Hydraulics
302 Jeffers Street
Lyman, NE 69352
Phone: (866) 257-7995
Fax: (308) 787-1281
kurthyd@aol.com
www.kurthydraulics.com



Shaft Adapters

ELIMINATE NEED FOR SPECIAL SHAFTING

Sterling Instrument's 21-inch and 27-metric-size stainless steel adaptors, referred to as the S52FCY (-, M) Series, offer precision, tight bore tolerances as well as shank and bore/shank concentricity. The adapter's female end is designed to fit 14 shaft diameters from 0.1200" to .4998" (3 mm to 12 mm) and features the Fairloc integral fastening system. The male side of the adapter features shafts in diameter from 0.1247" to 0.4997" (3 mm to 12 mm).

The Fairloc patented integral hub fastener does away with marred shafts, permits frequent phase adjustment, timing and position adjustment, and Fairloc adds positive metal-to-metal fastening strength along each hub section.

The integral hub fastener has two slots machined into the hub, radially and angularly. This produces a transverse wedge attached to the solid portion of the hub on one side. A cantilevered clamping section results, which has a tapped hole to accept a cap screw passing through a clearance hole in the solid part of the hub. The cap screw passes into a threaded hole in the transverse wedge section. Once the screw tightens, the cantilevered section clamps the shaft. The screw tightens and releases without damaging the shaft or altering the torque-transmitting abilities.

For more information:

Sterling Instrument
2101 Jericho Turnpike
P.O. Box 5416
New Hyde Park, NY 11042
Phone: (516) 328-3300
Fax: (516) 326-8827
http://sdp-si.com/web/html/newprdshafts7.htm

Larger INTEGRAmotor Twice as Powerful

The latest addition to Bodine Electric Company's INTEGRAmotor product line is the 34B/FV, a 24-volt brushless DC motor with a 34B frame. It combines a PWM speed control, brushless DC motor and optical encoder. The 34B/FV is twice as powerful as any Bodine model, providing 187 watts and up to 100 oz.-in. continuous torque.

The larger framed model features a regulated 24 VDC power supply, and an integrated control receives inputs from an external motion controller or programmable logic controller (PLC). The external controller accepts closed-loop feedback provided from an enclosed 1024 PPR and an optical encoder. The 34B/FV can be combined with several types of gearheads—parallel shaft, right angle or hollow shaft—and output speeds run between 0.3–500 rpm with

continued

rated torque up to 350 lb–in.

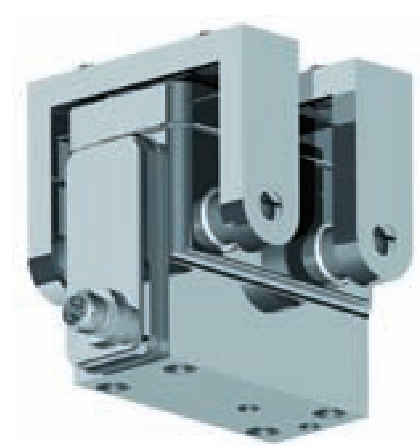
Designed as a more affordable alternative for applications in need of stepper or high-end servo systems, the 34B/FV is capable of replacing brush-type DC motors that operate continuously or in applications where contamination from carbon dust must be avoided. The INTEGRAmotors are used in medical equipment, packaging machines, conveyor systems, printing and photo finishing machinery as well as factory automation applications. They are available with food-grade gearhead lubricants.

For more information:

Bodine Electric Company
2500 West Bradley Place
Chicago, IL 60618
Phone: (773) 478-3515
Fax: (773) 478-3232
info@bodine-electric.com
www.bodine-electric.com

Specialized Gripper

EQUIPPED FOR FOOD-HANDLING



Techno-Sommer Automatic's GGL-3060 food gripper is manufac-tured according to IP69K standard, so it resists high-pressure and high-temperature—

washdown—cleanings. The stainless steel design resists corrosion and is a compact size. The gripper also complies with DIN 1672-2 guidelines for hygienic food production machinery, meaning it is safe around food.

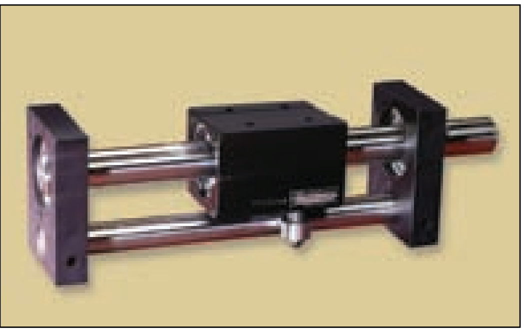
The gripper's jaws open to a full 180 degrees, which allows it to clear material below it. An angular design allows for up to 33 Nm (24 lb/ft) of gripping torque, and sensors are used to sense jaw position.

For more information:

Techno-Sommer Automatic
2101 Jericho Turnpike
New Hyde Park, NY 11040
Phone: (800) 819-3366
Fax: (516) 358-2576
grippersupport@techno-sommer.com
www.techno-sommer.com

Linear Indexing Drive

RESISTS CLOGGING, JAMMING



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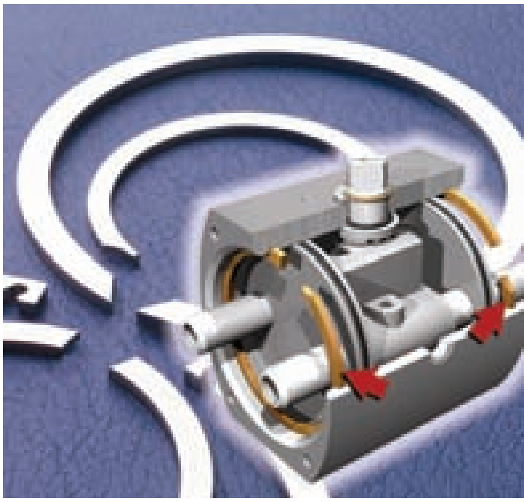

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The Ikona Clutch and Differential

Dr. John Colbourne, Sasha Tesic and Vladimir Scekic

Abstract

This paper describes two devices—a clutch and a differential—which are based on the Ikona continuously variable transmission (CVT). This CVT is essentially an internal gear pair, in which the pinion is mounted on an eccentric that can drive or be driven by an electric motor/generator, thus providing a variable ratio. Since this arrangement allows for "branching" of energy flow, it can be classified as summation-type CVT. The range of ratios depends on the input speed. For example, with an input speed of 600–2,000 rpm, the ratio can be anything from infinite to about 1:2.

When the CVT is used as a clutch, it would replace the friction-plate clutch in vehicles with standard transmissions, and the fluid torque converter in automatic transmissions. In these existing devices, energy is wasted during modulation from standstill, and at every gear change, while the engine speed is altered to match the speed of the gearbox input shaft. In the case of the fluid torque converter, energy is also lost during acceleration, due to the inefficiency of the device whenever the engine speed differs from the speed of the converter output shaft. The new clutch will be referred to as the electric torque converter. Any excess energy is converted into electrical energy, and either stored in the battery, or reintroduced into the system through the motor/generator. With very efficient energy recovery, modulation of the clutch can be very smooth, which is particularly advantageous when a vehicle starts from rest on an uphill slope. Since no friction element is involved, and only a fraction of torque is being manipulated, the modulation can be repeatable regardless of conditions. Finally, in a hybrid vehicle arrangement, the clutch can be used to maintain the engine at its optimum speed (within limits), regardless of the road speed and the gearbox ratio.

Similar principles apply to the Ikona differential. Unlike today's limited slip differentials, the Ikona differential allows full torque to be transmitted through one drive wheel, even though the other drive wheel may have completely lost traction. Unlike traditional differentials that allow wheels to rotate at different speeds, the Ikona differential forces the wheels to do so. Accordingly, when the vehicle is changing direction, the differential can be used to control the speed of each drive wheel, thus providing active torque steering.

Introduction

The Ikona CVT consists of an internal gear pair, in which the pinion is mounted on an eccentric, as shown in Figure 1. The eccentric is connected to an electric motor/generator, whose speed can be modulated, thus providing the variable ratio. The CVT can be used as a clutch (Fig. 2), replacing the plate clutch in a standard transmission, or the fluid torque converter in an automatic transmission. When the CVT is used in this manner, it will be called an electric torque converter.

The CVT can also be adapted to form a differential (Fig. 3).

In this case the internal gear is meshed with two pinions, each mounted on separate eccentrics, so there are two outputs with independently controllable ratios. The electric torque converter and the differential are the subjects of U.S. provisional patent applications 577088002 pro and 577088003 pro.

Description of the CVT Clutch/Electric Torque Converter

The Ikona gear is an internal gear pair, described in patents US5505668 and EP770192B1. Compared with conventional involute gear pairs, it has the following advantages. First, the difference between the tooth numbers can be as low as one. Secondly, the contact ratio is high, meaning that a gear pair can transmit a larger torque than an involute gear pair of similar size. Thirdly, the backlash is minimal. All these properties are important when the gear pair is used to form a CVT.

Along similar principles, a solar epicyclic gear system can be used, in which case the following has to be satisfied:

$(N_{ring}/N_{sun}) * \omega_{in} = (1 + N_{ring}/N_{sun}) * \omega_{out} - \omega_{sun}$

where

N_{ring} and N_{sun} represent the number of teeth on the ring gear and sun-pinion respectively, ω_{in}, ω_{out} and ω_{sun} stand for rotational speeds of flywheel, output shaft and sun-pinion, respectively. This embodiment may be referred to as the Solar CVT Clutch. More detailed analysis of this type of arrangement may be the subject of another paper.

When the CVT is used as a clutch/electric torque converter, the internal gear is connected to the engine output—generally the flywheel—and the pinion is connected to the input shaft of the gearbox. The pinion and internal gear tooth numbers will depend on engine and vehicle properties; for the purpose of this paper we may work with those numbers being respectively 19 and 20. This means that the geometrical clutch input/output ratio would be 20:19, (i.e., close to 1.0:1) if the eccentric were held stationary. However, for the situation where the eccentric is allowed to rotate around its own axis, the relation between the input, output and eccentric angular velocities is given by:

$$20 * \omega_{int} = 19 * \omega_{pinion} + \omega_{ecc} \quad (1)$$

where ω_{int}, ω_{pinion} and ω_{ecc} are the three angular velocities.

When solved for the transmission input speed, Equation 1 becomes:

$$\omega_{pinion} = \frac{(20 * \omega_{int} - \omega_{ecc})}{19} \quad (2)$$

When solved for ω_{ecc}, for case $\omega_{pinion} = 0$, equation (2) becomes:

$$\omega_{ecc} = 20 * \omega_{int} \quad (3)$$

The input and output torques T_{int} and T_{pinion} are related to the eccentric torque T_{ecc} as follows (*note: torque equations do not consider internal losses*):

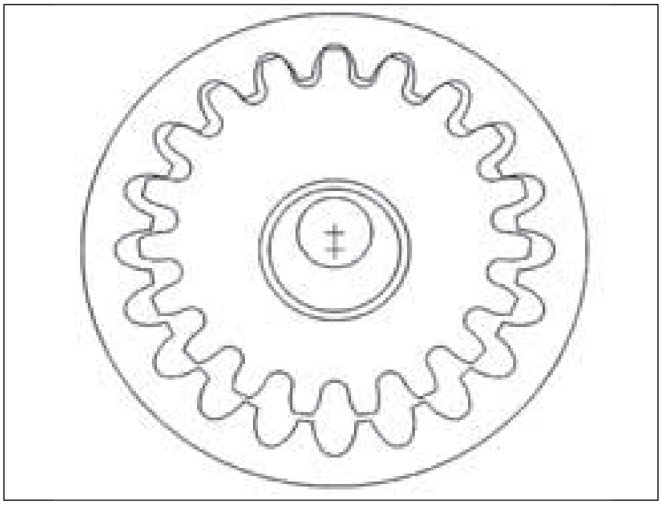

Figure 1—Ikona CVT.

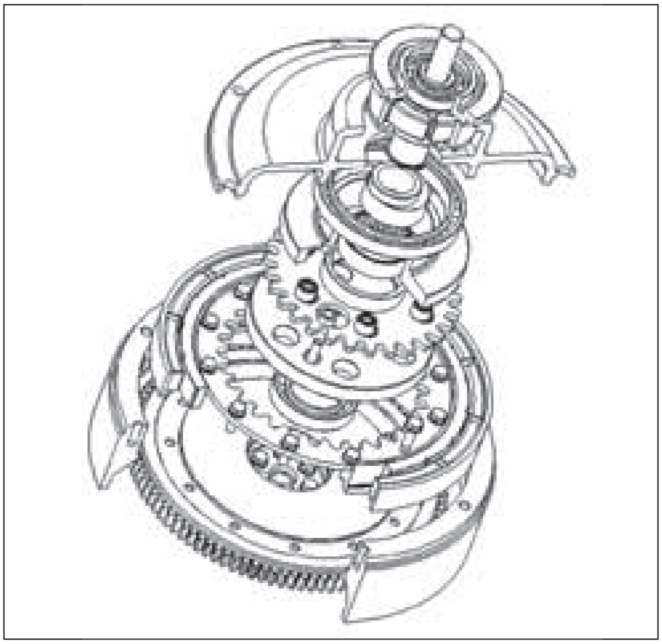

Figure 2—Sectional exploded view of Ikona CVT clutch.

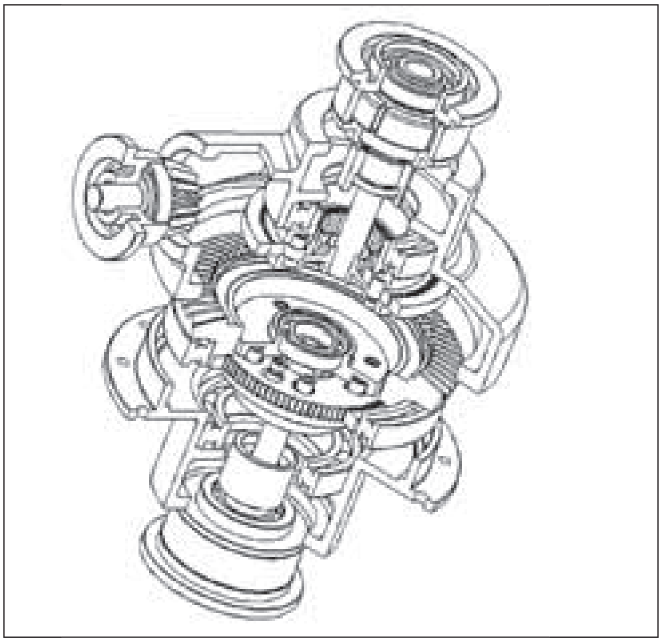

Figure 3—Sectional exploded view of Ikona CVT differential.

$$T_{int} = 20 * T_{ecc} \quad (4)$$

$$T_{pinion} = 19 * T_{ecc} \quad (5)$$

Looking at Equations 1–5, we may find that:

• It is possible to keep the transmission input shaft stationary ($\omega_{pinion} = 0$) while the engine is running ($\omega_{int} \neq 0$).

• In order to provide this condition, the eccentric needs to spin at 20 times engine speed ($\omega_{ecc} = 20*\omega_{int}$ for 19/20 teeth combination).

• By modulating the eccentric speed from $\omega_{ecc} = 20*\omega_{int}$ to $\omega_{ecc} = 0$, we can achieve transmission input shaft modulation from $\omega_{pinion} = 0$ to $\omega_{pinion} = (20/19)*\omega_{int}$.

• Modulation of the transmission input torque from T= 0 to $T = T_{nominal}$ can be achieved by manipulation of the eccentric torque, which represents only 1/19 of T_{pinion} (1/20 of T_{int}).

In all vehicles, the engine speed will differ from the gearbox input shaft speed when the vehicle starts from rest, and during and immediately after each gear change. In addition, in vehicles with automatic transmissions, the torque converter will allow the engine to turn faster than the gearbox input shaft during acceleration in order to provide smooth running and more torque.

The process of speeding up the output shaft of a clutch and matching its speed to the input shaft (flywheel) is called clutch modulation. The power of modulation at any given moment can be calculated by:

$$P = T_{eng} * \omega_{eng} - T_{gboxinput} * \omega_{gboxinput} \quad (6)$$

While the exact values of T_{eng} and $T_{gboxinput}$ may not be known, it is clear that there is excess power from the engine during the situations listed above. The total energy of modulation will then be given by:

$$E = \int_{t_1}^{t_2} P * d_t \quad (7)$$

Obviously, in systems with single-energy path, the energy of modulation will be released within the clutch/converter. In order to prevent overheating and/or premature wear on these devices, both power and duration of modulation need to be limited. This, in turn, may lead to shock-loading other components of the drivetrain and/or to an uncomfortable ride in the vehicle. An alternate solution is to provide an auxiliary branch in the energy path and to direct the energy of modulation through that auxiliary branch. Ideally, we may convert that energy into useful work or store it in another form for future use, thus minimizing waste and improving efficiency.

In the Ikona CVT clutch, the difference between the speeds of the engine and the gearbox input shaft is accommodated by the CVT gear pair and the rotation of the eccentric. The energy of modulation is used to spin the eccentric, which drives the motor/ generator attached to it. (In spinning the eccentric to alter the ratio between the engine speed and the gearbox input speed, the motor/generator will be referred to as a modulating motor/generator.) This energy is then converted into electrical energy, which is fed into the vehicle battery. In cases where extra energy is required, as we will see shortly, the energy is fed from the battery into the motor/generator, which then acts as a motor and adds to the engine torque.

For example, when the vehicle starts from rest, the eccentric will be turned initially at 20 times the engine speed, so that the vehicle remains stationary, as seen in Equation 2. For many vehicles, the idle speed of the engine would be about 700–900 rpm, so the eccentric would be controlled to turn at 14,000–18,000 rpm. However, it is often advantageous to increase the engine speed when starting from rest, particularly for heavy commercial vehicles when starting on an uphill slope, in order to prevent stalling. The engine speed can be increased to about 1,500–2,000 rpm before the vehicle moves, thus providing greater torque, and the eccentric would then be controlled to turn at 30,000–40,000 rpm. This is a high speed for the modulating motor/generator, but not unattainable. Many modern electric motors, with permanent magnets and in the 10 kW range, are in fact most efficient at speeds of 30,000–40,000 rpm, and the eccentric would only turn at these high speeds for very short periods of time.

To accelerate the vehicle from zero speed until the gearbox changes from first to second gear, one need only reduce the speed of the eccentric, which can be easily and repeatedly done by loading the modulating motor/generator. As seen in Equation 4, the torque required for the eccentric is only equal to the engine torque divided by 20, so this is quite practical. Finally, electric motors/generators typically provide torque curves that are perfectly suited for this kind of duty.

When the eccentric is not turning, we can see from Equation 1 that the (synchronous) engine speed is equal to the gearbox input shaft speed, multiplied by 19/20. If the engine turns faster than the synchronous speed, the eccentric must rotate in the same direction as the engine. If the engine turns slower, the eccentric must rotate in the opposite direction.

When the engine is driving the vehicle, and the eccentric turns in the same direction as the engine, we can show by a simple force analysis that the eccentric will drive the modulating motor/generator so that electric energy will be fed into the vehicle battery. If the eccentric turns in the direction opposite to the engine, the eccentric will need to be driven by the motor/generator so that energy is drained from the battery.

If the vehicle is driving the engine—e.g., on a steep downhill slope—the engine torque is reversed. In this case the eccentric will be driven by the motor/generator when it turns in the same direction as the engine, and will drive the modulating motor/generator when it turns in the opposite direction.

These conclusions enable us to determine the flow of energy in various phases of the vehicle motion.

In spinning the eccentric to alter the ratio between the engine speed and the gearbox input speed, the motor/generator will be referred to as a modulating motor/generator. For example, when the vehicle starts from rest, the engine speed is faster than the synchronous speed, so the eccentric turns in the same direction as the engine, and the generator feeds energy into the vehicle battery.

The situation is similar whenever there is an upward change of gear. Immediately after the gear change, the engine is turning faster than the synchronous speed; to allow for the different speeds, the eccentric must be rotated in the same direction as the engine, so the eccentric will again drive the generator, and energy will be fed into the battery.

On a downhill slope, or when the vehicle is slowing down, the accelerator pedal is released and we have engine braking. The engine speed is then less than the synchronous speed, so the eccentric turns in the direction opposite to the engine; but since the engine torque is reversed, the eccentric will once again drive the generator, feeding energy into the battery.

The last case to be considered is the downward change of gear. There are generally two possible reasons for downward gear change.

The first is that the vehicle is slowing down preparing to stop. If the engine was turning at synchronous speed before the gear change, it will be turning at less than the synchronous speed immediately after. As the vehicle slows down the engine torque is again reversed, and the eccentric will again drive the generator.

The second reason for a downward gear change is that the accelerator pedal is depressed, either to provide acceleration or because the vehicle is traveling uphill. In this case, the downward gear change causes the speed of the gearbox input shaft to increase, so that immediately after the gear change the engine is turning at less than the synchronous speed. The eccentric is then turning in the direction opposite to the engine, and must be driven by the motor. This is the one situation where energy is required from the battery. As compensation, the extra power exerted by the electric motor helps the vehicle to accelerate, or to maintain its speed up an incline.

In summary, in most instances where energy is wasted by conventional clutches or fluid torque converters, the Ikona CVT clutch uses that energy to drive the modulating motor/generator, thus charging the battery. In the one situation where the Ikona CVT clutch draws power from the battery, this power is used to improve the performance of the vehicle. It is important to note, however, that in the form described, drawing energy from the battery increases the power going into the gearbox, but leaves the gearbox input torque unchanged. The input torque to the gearbox is related to the engine torque by Equations 4 and 5:

$$T_{pinion} = T_{int} \cdot \left(\frac{19}{20}\right) \quad (8)$$

The spinning eccentric allows the gearbox input speed to turn faster than the synchronous speed, and since the torque remains constant, the gearbox input power is increased. This is now higher than the engine output power, and the difference is made up by the power drawn from the battery.

In order to increase the torque availability and reduce the number of times energy is converted from one form to another (efficiency issues), another electrical machine may be integrated in line with the main torque path (flywheel, ring gear). This machine is called the converting motor/generator. By this addition, any electricity generated in the modulating generator may be directly used within the converting motor, thus increasing torque available to the clutch and reducing the number of energy conversions. The end result of this process is similar to that achieved with fluid torque converters, albeit with better overall efficiency and a few extra features possible. The converting motor/generator may offer several other opportunities for improved performance and economy, many of those being applied in modern hybrid (ICE-electrical) vehicles.

To sum up, the Ikona CVT clutch/electric torque converter offers several significant advantages over the traditional, friction plate clutches and fluid torque converters in that:

• The speed of the eccentric can be repeatedly modulated by the controlling computer, so that every gear change, and the starting from rest, will be completely smooth.

• Energy of modulation normally lost to heat and wear, is recovered in the form of electricity.

• The size of the CVT clutch/electric torque converter will be considerably less than that of the plate clutch or the fluid torque converter, which it replaces. This is because of the high contact ratio of the Ikona gear pair, mentioned earlier, which reduces the size of the gear pair required to transmit the engine torque.

• It may be possible to control the eccentric speed so that the engine turns most of the time at or near its most efficient speed, regardless of the vehicle speed or gearbox ratio. This feature would probably require more continuous energy interchange with the battery than the other advantages described above. It is therefore more suitable for hybrid vehicles, where the battery capacities are much larger.

• The CVT clutch/electric torque converter may replace starter-motors and alternators thus further improving on cost, ease of packaging and mechanical complexity.

Description of the differential

The layout of the Ikona CVT used as a differential is essentially the same as that shown in Figure 1. The only difference is that the internal gear is meshed with two pinions, and each pinion is mounted on its own eccentric. In a rear-wheel-drive vehicle, the internal gear would be attached to the hypoid gear, while in a front-wheel-drive, it would be attached to the gearbox output shaft. Each pinion would drive one of the vehicle wheels. (If used as center differential for AWD or 4WD vehicles, each pinion would drive an input to axle differentials.)

When a vehicle rounds a corner, the driving wheels must turn at different speeds, in order to avoid extreme tire wear. A conventional differential allows the drive shafts to turn at dif-

continued

ferent speeds, with the average speed equal to the differential input speed, and the torques in the two output shafts being equal. A problem with this device occurs if one wheel loses traction, for example when it rests on ice. The torque on this wheel falls to zero, causing the torque on the other driving wheel also to become zero. The second wheel stops turning, and the first wheel turns at twice the speed of the differential input.

This problem is partly avoided by the use of a limited slip differential. In this case, when the first wheel loses traction and starts to spin, a reduced torque is maintained on the second wheel, sometimes by the use of a plate clutch. When a vehicle is in motion, this reduced torque is generally enough to continue the motion. But for a vehicle starting from rest, the torque may not be enough to start the vehicle, when one wheel has lost its traction.

In the Ikona differential, the speed of each output shaft is determined by the speed of the corresponding eccentric, and these are controlled separately by the vehicle computer. If the gear pair has N_{pinion} and N_{int} teeth, and the eccentrics do not turn, then the differential output shafts will rotate at the speed of the differential input multiplied by (N_{int}/N_{pinion}). Since the speed differential between any two wheels or axles on a vehicle is, typically, very low, we can afford high tooth count in the pinion and ring gear, thus minimizing the torque required on the eccentric. For illustration purposes, a mid-size vehicle traveling at 100 km/h only requires 200–250 rpm speed differential between the right and left side wheels for full steering input (under 11 m turning circle). If we work with 20,000 rpm maximum motor/generator (eccentric) speed, this translates into 79/80 tooth combination. This further means that the motor/generator only needs to be capable of less than 2 percent of the total torque being transmitted.

As before, this speed is called the synchronous output speed. In straight vehicle motion, the output shafts will both turn at the synchronous speed. When the vehicle turns, the computer could be programmed to allow the shafts to turn at their natural speeds, which depend on the vehicle speed and the radius of the vehicle path. However, this differential has an important advantage over conventional differentials. The computer will be programmed to control the eccentric speeds, so that the wheels are forced to turn at the correct speeds, corresponding to the vehicle speed and the radius of its path. This feature of the differential provides active torque steering.

A second advantage of the Ikona differential is its response when one wheel loses traction. The torque applied to this wheel will fall to zero, but there is no reason why the wheel should start to spin, since its speed is controlled by the speeds of the differential input and the eccentric. If the position of the accelerator pedal is unchanged, both wheels will continue to turn at the same speeds they had before the first wheel lost its traction. And the entire torque from the differential input will then be transmitted to the second drive wheel, which means its torque will double in magnitude.

In conclusion, the Ikona CVT differential offers several advantages over the traditional, open, limited slip and locking differentials:

- Instead of merely allowing different wheel speeds through torque equality, it enables us to impose a desired speed to each powered wheel individually.
- It allows improved vehicle stability through active torque steering capability.
- It allows vehicle steering even without controlling the direction of steering wheels; it is applicable to track vehicles.
- When applied to track vehicles, it allows improved performance and fuel economy through recovering energy normally lost to friction braking.

Summary

The Ikona tooth form has received recognition for its suitability in high-ratio, cycloid-type reduction units. As with all units utilizing cycloid architecture, the high ratio is achieved between the eccentric and either the pinion (wave plate on SM Cyclo and equivalents) or the ring gear (pin housing on SM Cyclo and equivalents). It is very important to note that, providing the eccentric is restrained from rotation, the ratio between the ring gear and the pinion is near 1:1, which makes it suitable for "coupling" application. (As a general rule, we need to work with the highest tooth count practical, since this will allow us the lowest eccentric torque for any given application.) When used as such, and by allowing the eccentric to rotate in a controlled manner, we effectively create a CVT coupling suitable for speed modulation.

The Ikona CVT can be used as the basis of a clutch and of a differential. In both cases, these new devices have considerable advantages over existing clutches and differentials, the most notable ones being:

- Utilization of energy normally lost to heat
- Controllability
- Repeatability

Ikona CVT-based clutches, torque converters and differentials can become active, rather than passive, members of any vehicle, greatly contributing to vehicle efficiency, dynamics and safety.

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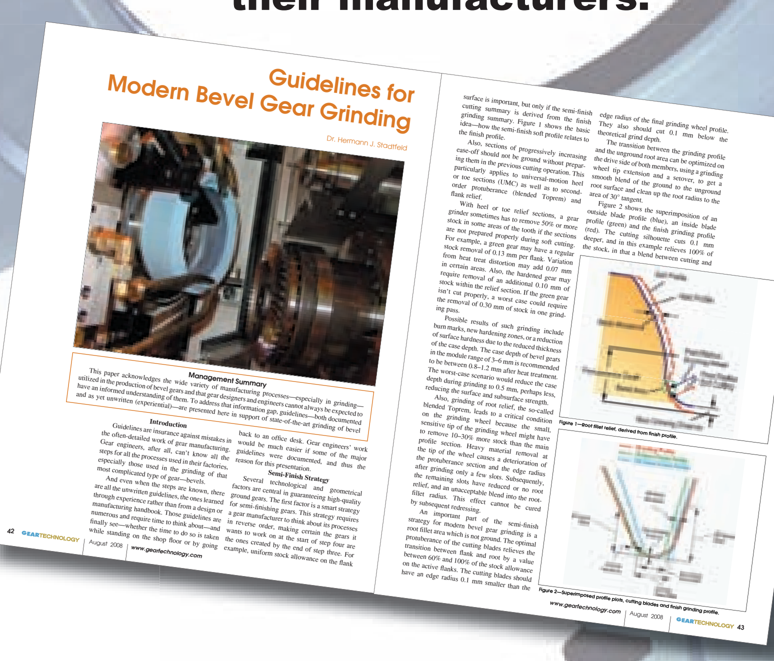

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Selection and Performance

CRITERIA FOR POWER TRANSMISSION COUPLINGS—

PART I

Eugene I. Rivin

"A flexible coupling, although it is relatively small and cheap compared to the machines it connects, is a critical aspect of any shaft system, and a good deal of attention must be paid to its choice at the design stage." —from the Resolution of the First International Conference on Flexible Couplings

Introduction

Power transmission couplings are widely used for modification of stiffness and damping in power transmission systems, both in torsion and in other directions (misalignment compensation). Technical literature on connecting couplings is scarce and is dominated by trade publications and commercial coupling catalogs. Many coupling designs use elastomers in complex loading modes; some couplings have joints with limited travel distances between the joint components accommodated by friction; often, couplings have severe limitations on size and rotational inertia, etc. These factors make a good coupling design a very difficult task, which can be helped by a clearer understanding of the coupling's functions. Stiffness values of couplings in both torsional and misalignment directions, as well as damping of couplings in the torsional direction, have a substantial, often determining, effect on the drive system dynamics. Torsionally flexible couplings are often used for tuning dynamic characteristics (natural frequencies and/or damping) of the drive/transmission by intentional change of their stiffness and damping.

The purpose of this article is to distinctly formulate various couplings' roles in machine transmissions, as well as to formulate criteria for comparative assessment, optimization and selection of coupling designs. To achieve these goals, a classification of connecting couplings is given and comparative analyses of commercially available couplings are proposed.

General Classification of Couplings

According to their role in transmissions, couplings can be divided into four classes:

1. ***Rigid Couplings***. These couplings are used for rigid connection of precisely aligned shafts. Besides the torque, they also transmit bending moments and shear forces if any misalignment is present, as well as axial force. The bending moments and shear forces may cause substantial extra loading of the shaft bearings. Principal application areas of rigid couplings are: long shafting; space constraints preventing use of misalignment-compensating or torsionally flexible couplings; and inadequate durability and/or reliability of other types of couplings.

2. ***Misalignment-Compensating Couplings***. These are required for connecting two members of a power transmission or motion transmission system that are not perfectly aligned. "Misalignment" means that components—coaxial by design—are not actually coaxial, due either to assembly errors or to deformations of subunits and/or foundations. The latter factor can be of substantial importance for large turbine installations (thermal/creep deformations leading to drastic load redistribution between the bearings) and for power transmission systems on non-rigid foundations (such as ship propulsion systems). Various types of misalignment as they are defined in AGMA standard 510.02 are shown in Figure 1. (*Editor's note: AGMA 510.02 has been superseded by ANSI/AGMA 9009 - D02- Nomenclature for Flexible Couplings, and the newer standard uses slightly diffrent terminology. The older version is used here for illustrative purposes.*) If the misaligned shafts are rigidly connected, this leads to their elastic deformations, and thus to dynamic loads on bearings, to vibrations, to increased friction losses, and to unwanted friction forces in servo-controlled systems. Purely misalignment-compensating couplings have torsional deformations and misalignment-compensating deformations decoupled from movements associated with misalignments.

3. ***Torsionally Flexible Couplings.*** Such couplings are used to change dynamic characteristics (natural frequency, damping and character/degree of nonlinearity) of a transmission system. The changes are desirable or necessary when severe torsional vibrations are likely to develop in the transmission system, leading to dynamic overloads. Designs of torsionally flexible couplings usually are not conducive to compensating misalignments.

4. ***Combination Purpose Couplings***. These combine significant compensating ability with significant torsional flexibility. The majority of the commercially available connecting couplings belong to this group. Since the torsional deformations and deforma-

continued

Nomenclature	
D	External diameter
d	Internal diameter
L	Length
F_{com}	Radial force, or bending moment
F_t	Tangential force
R_{ef}	Effective radius
T	Transmitted torque
μ	Friction coefficient
k	Stiffness factor
k_{com}	Combined stiffness of elastic connectors
E	Radial misalignment
D_p	Pitch Diameter
θ	Angular misalignment
L_{eq}	Sound pressure level
η	Efficiency
k_{sh}	Shear stiffness
ψ	Relative energy displacement
V	Potential energy
P_t	Tangential force
W	Energy per coupling revolution
β	Loss factor of rubber

tions due to misalignments are not separated/decoupled by design, changes in torsional stiffness may result in changes in misalignment-compensating stiffness, and vice versa. These couplings will be discussed in detail in Part II of this article, which will appear next issue.

Rigid Couplings

Typical designs of rigid couplings are shown in Figure 2.

Sleeve couplings as in Figures 2a and 2b are the simplest and the slimmest ones. Such a coupling transmits torque by pins (Fig. 2a) or by keys (Fig. 2b). The couplings are difficult to assemble/disassemble, as they require significant axial shifting of the shafts to be connected/disconnected. Usually, external diameter $D = (1.5–1.8)\ d$, and length $L = (2.5–4.0)\ d$.

Flange couplings (Fig. 2c) are the most widely used rigid couplings. Two flanges have machined (reamed) holes for precisely machined bolts inserted into the holes without clearance (no backlash). The torque is transmitted by friction between the contact surfaces of the flanges and by shear resistance of the bolts. Usually, $D = (3–5.5)\ d$, and $L = (2.5–4.0)\ d$.

A split-sleeve coupling (Fig. 2d) transmits torque by friction between the half-sleeves and the shafts and, in some cases, also by a key. Their main advantage is ease of assembly/disassembly.

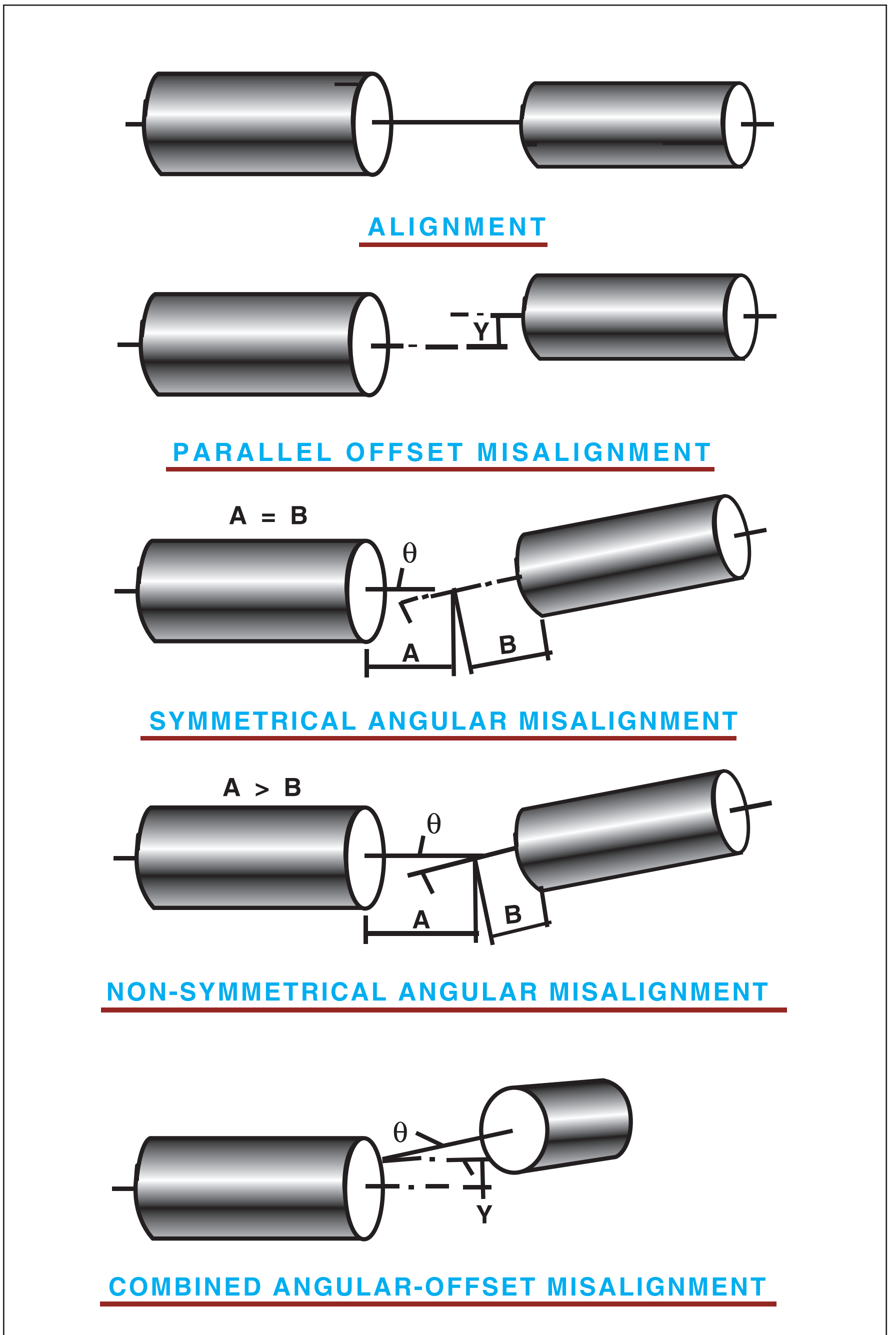

Figure 1— Types of coupling misalignment.

Misalignment-Compensating Couplings

Misalignment-compensating couplings are used to radically reduce the effects of imperfect alignment by allowing a non-restricted or a partially restricted motion between the connected shaft ends in the radial and/or angular directions. Similar coupling designs are sometimes used to change bending natural frequencies/modes of long shafts. When only misalignment compensation is required, high torsional rigidity and, especially, absence of backlash in the torsional direction, are usually positive factors, preventing distortion of dynamic characteristics of the transmission system. The torsional rigidity and absence of backlash are especially important in servo-controlled systems.

To achieve high torsional rigidity together with high compliance in misalignment directions (radial or parallel offset, axial, angular), torsional and misalignment-compensating displacements in the coupling have to be separated by using an intermediate compensating member. Typical torsionally rigid, misalignment-compensating couplings are Oldham couplings, which compensate for radial misalignments (Fig. 3a); gear couplings, which compensate for small angular misalignments (Fig. 3b); and universal or Cardan joints, which compensate for large angular misalignments (Fig. 3c). Frequently, torsionally rigid "misalignment-compensating" couplings, such as gear couplings, are referred to in the trade literature as "flexible" couplings.

Usually, transmissions designed for greater payloads can tolerate higher misalignment-induced loads. Accordingly, the ratio between the load generated in the basic misalignment direction (radial or angular) to the payload (rated torque or tangential force) is a natural design criterion for purely misalignment-compensating (torsionally rigid) couplings.

Selection criteria for misalignment-compensating couplings. Misalignment-compensating (torsionally rigid) couplings are characterized by the presence of an intermediate compensating member located between the hubs attached to the shafts being connected and having mobility relative to both hubs. The compensating member can be solid or comprising several links. There are two basic design subclasses:

- Subclass A—couplings in which the displacements between the hubs and compensating member have a frictional character (examples include conventional Oldham couplings, gear couplings and Cardan joints).
- Subclass B—couplings in which the displacements are due to elastic deformations in special elastic connectors.

For Subclass A, the radial force F_{com}, or bending moment, acts from one hub to another and is caused by misalignment; only radial misalignments are addressed below. F_{com} is a friction force equal to the product of friction coefficient μ and tangential force F_t at an effective radius R_{ef}, $F_t = T/R_{ef}$, where T is the transmitted torque:

$$F_{com} = \mu \frac{T}{R_{ef}} \qquad (1)$$

The force F_{com} does not depend on the misalignment magnitude. This is a negative feature, since a relatively small real-life misalignment may generate high forces acting on bearings of the connected shafts. Since motions between the hubs and the compensating member are of a "stick-slip" character, with very short displacements alternating with stoppages and reversals, μ might be assumed to be the static friction ("stiction") coefficient.

When the rated torque T_r is transmitted, then the selection criteria is

$$\frac{F_{com}}{T_r} = \frac{\mu}{R_{ef}} \qquad (2)$$

A lower friction and/or larger effective radius would lead to lower forces on

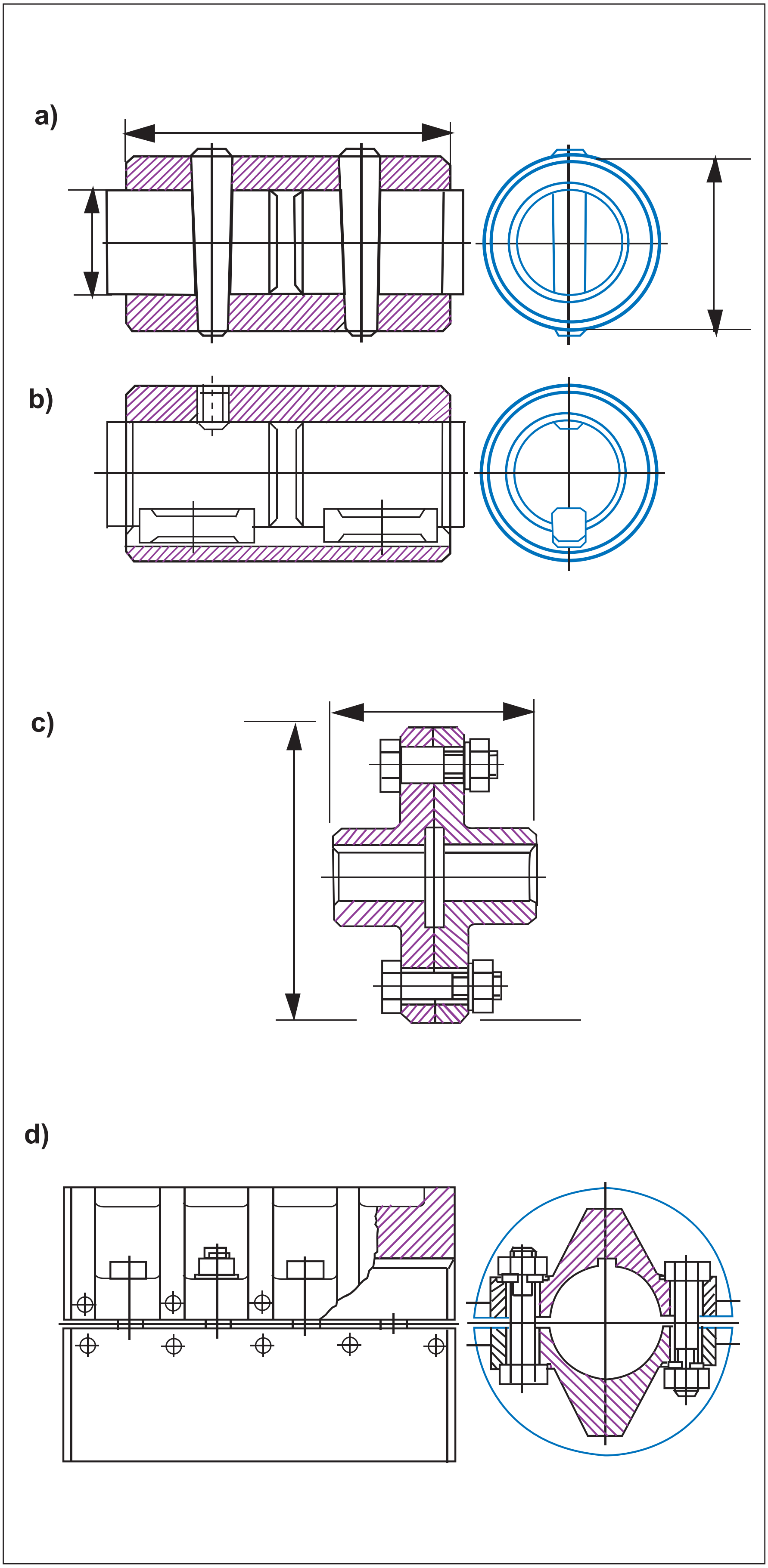

Figure 2—Typical designs of rigid couplings: simple designs, which transmit torque by pins (a) or keys (b); flange couplings (c) and split-flange designs (d).

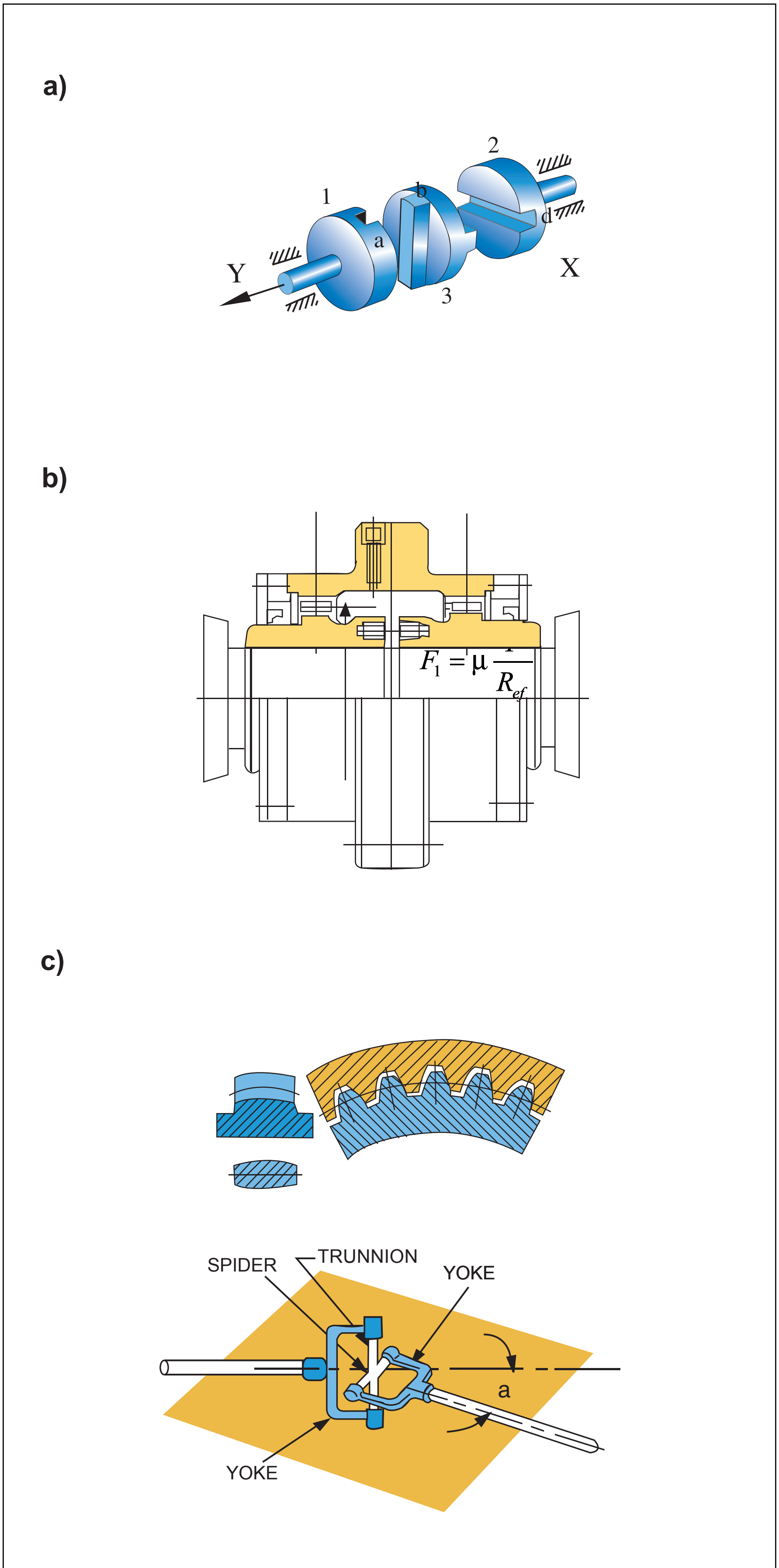

Figure 3—Torsionally rigid, misalignment-compensating couplings: Oldham couplings (a), gear couplings (b) and universal joints or Cardan joints (c).

the bearings.

For Subclass B, assuming linearity of the elastic connectors,

$$F_{com} = k_{com}\, e \qquad (3)$$

Where e = radial misalignment value, and k_{com} = combined stiffness of the elastic connectors in the radial direction. In this case,

$$\frac{F_{com}}{T_r} = \frac{k_{com}}{T_r}\, e \qquad (4)$$

Unlike the Subclass A couplings, Subclass B couplings develop the same radial force for a given misalignment, regardless of the transmitted torque; thus they are more effective for large T_r. Of course, a lower stiffness of the elastic connectors would lead to lower radial forces.

Conventional Oldham couplings, gear couplings and u-joints (Subclass A). Misalignment-compensating couplings are used in cases where a significant torsional compliance can be an undesirable factor and/or a precise alignment of the connected shafts cannot be achieved. Universal joints (u-joints or Cardan joints) are used in cases where the dominant type of shaft misalignment is angular misalignment. Use of a single joint results in a non-uniform rotation of the driven shaft, which can be avoided by using double joints or specially designed "constant velocity" joints. Compensation of a radial misalignment requires using two Cardan joints and relatively long intermediate shafts. If bearings of the u-joint are not preloaded, the joint has an undesirable backlash, but preloading of the bearings increases frictional losses and reduces efficiency. More sophisticated linkage couplings are not frequently used, due to the specific characteristics of general-purpose machinery, such as limited space, limited amount of misalignment to compensate for, and cost considerations.

While u-joints use sliding or rolling (needle) bearings, both Oldham and gear couplings compensate for misalignment of connected shafts by means of limited sliding between the hub surfaces and their counterpart surfaces on the intermediate member. The sliding has a cyclical character, with double amplitude of displacement equal to radial misalignment e for an Oldham coupling and $D_{p}\theta$ for a gear coupling (Ref. 5), where D_p is the pitch diameter of the gears and θ is the angular misalignment. If a radial misalignment e has to be compensated by gear couplings, then two gear couplings spaced by distance L are required, and $\theta = e/L$. Such a motion pattern is not conducive to good lubrication, since at the ends of the relative travel, where the sliding velocity is zero, a metal-to-metal contact is very probable. The stoppages are associated with increasing friction coefficients, close to the static friction values. This is the case for low-speed gear couplings and for Oldham couplings; for high-speed gear couplings, the high lubricant pressure due to centrifugal forces alleviates the problem (Ref. 5).

Figure 3a shows a compensating (Oldham) coupling, which—at least theoretically—allows the connection of shafts with a parallel misalignment between their axes without inducing nonuniformity of rotation of the driven shaft and without exerting high loads on the shaft bearings. The coupling comprises two hubs, (1) and (2), connected to the respective shafts and an intermediate disc (3). The torque is transmitted between driving member (1) and intermediate member (3), and between intermediate member (3) and driven member (2), by means of two orthogonal sliding connections, a-b and c-d. By decomposition of the misalignment vector into two orthogonal components, this coupling theoretically assures ideal radial compensation while being torsionally rigid. The latter feature may also lead to high torque-to-weight ratios. However, this ingenious design finds only an infrequent use, usually for noncritical, low-speed applications. Some reasons for this are as follows.

For the Oldham coupling, radial force from one side of the coupling (one hub-to-intermediate member connection) is a rotating vector aimed in the direction of the misalignment and with the magnitude

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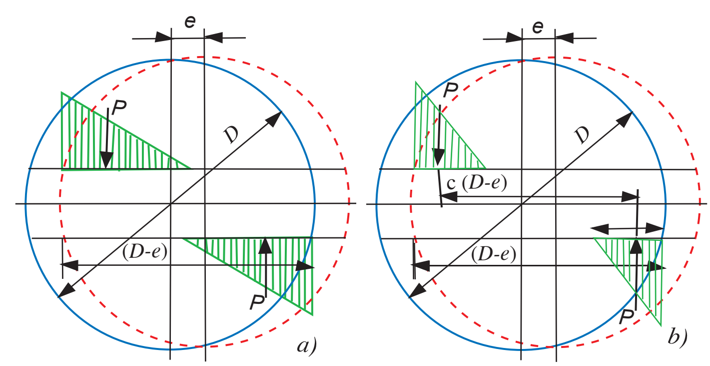

Figure 4—Stress distribution between the contacting surfaces a and b of hub and intermediate member of the Oldham coupling shown in Figure 3a, assembled without clearance (a) and with clearance (b).

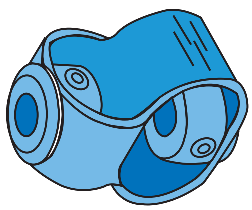

Figure 5—Kudriavetz coupling.

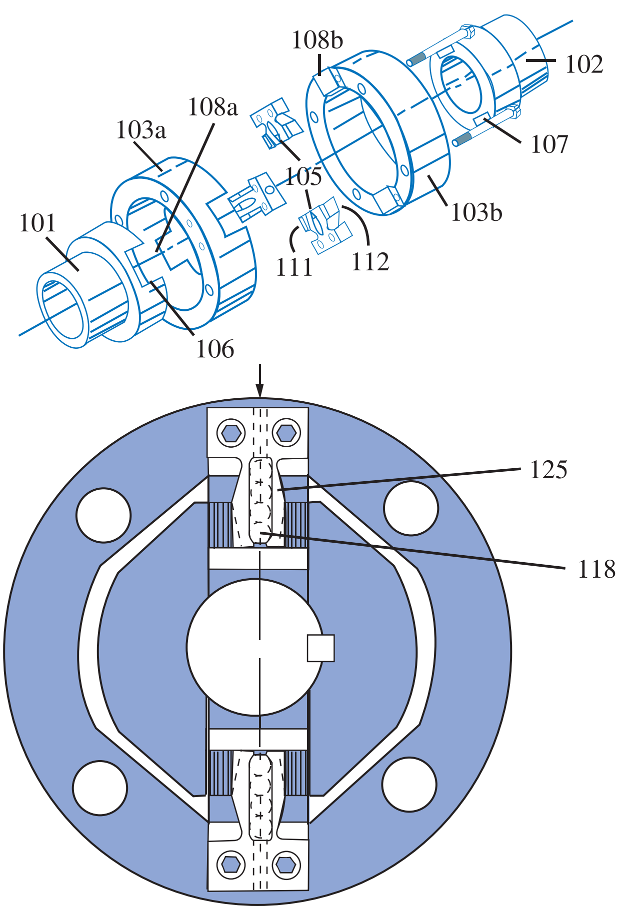

Figure 6—A torsionally rigid, misalignment-compensating coupling.

$$F_1 = \mu \frac{T}{R_{ef}} \quad (5)$$

whose direction reverses abruptly twice during a revolution. The other side of the coupling generates another radial force of the same amplitude, but shifted 90 degrees. Accordingly, the amplitude of the resultant force is

$$F_r = \sqrt{2}\mu \frac{T}{R_{ef}} \quad (6)$$

Its direction changes abruptly four times per revolution. Similar effects occur in gear couplings. An experimental Oldham coupling (T_r = 150 N-m, external diameter D_{ex} = 0.12 m, e = 1 mm and n = 1,450 rpm) exerted radial force on the connected shafts F_{com} = 720 N.

The frequent stoppages and direction reversals of the forces lead to the high noise levels generated by Oldham and gear couplings. A gear coupling can be the noisiest component of a large power-generation system (Ref. 6). A sound pressure level L_{eq} = 96 dBA was measured at the experimental Oldham coupling described above.

Since a clearance is needed for normal functioning of the sliding connections, the contact stresses are non-uniform with high peak values (Fig. 4). Figure 4a shows stress distribution between the contacting surfaces a and b of hub (1) and intermediate member (3) of the Oldham coupling shown in Figure 3a assembled without clearance. The contact pressure in each contact area is distributed in a triangular mode along the length $0.5(D - e) \approx 0.5D$. However, the clearance is necessary during assembly, and it increases due to inevitable wear of the contact surfaces. Presence of the clearance changes the contact area as shown in Figure 4b, so that the contact length is $1 \approx 0.3(D - e) \approx 0.3D$ (or the contact length is $0.5c(D - e)$, $c \approx 0.68$), thus significantly increasing the peak contact pressures and further increasing the wear rate. This leads to a rapid increase of the backlash, unless the initial (design) contact pressures are greatly reduced. Such non-uniform contact loading also results in very poor lubrication conditions in the stick-slip motion. As a result, friction coefficients in gear and Oldham couplings are quite high, especially in the latter.

Experimental data for gear couplings show μ = 0.3–0.4. Similar friction coefficients are typical for Oldham couplings. The coupling components must be made from a wear-resistant material (usually heat-treated steel) since the same material is used both for the hub and the intermediate disc structures and for the sliding connections. Friction can be reduced by making the intermediate member from a low-friction plastic, such as ultra-high molecular weight (UHMW) polyethylene, but this may result in a reduced rating due to lowered structural strength.

Because of high misalignment-compensating forces, deformations of the coupling assembly itself can be very substantial. If the deformations become equal to the shafts' misalignment, then no sliding will occur and the coupling behaves as a solid structure, being cemented by static friction forces. It can happen at misalignments below $e \approx 10\text{-}3D_{ex}$. This effect seems to be one of the reasons for the trend toward replacing misalignment-compensating couplings by rigid couplings, such as the rigid flange coupling in Figure 1c, often used in power generating systems.

Due to internal sliding with high friction, Oldham and gear couplings demonstrate noticeable energy losses. The efficiency of an Oldham coupling for $e/D_{ex} \leq 0.04$ is

$$\eta = 1 - 3.2\mu \frac{e}{D_{ex}} \quad (7)$$

For μ = 0.4 and $e = 0.01D_{ex}$, η = 0.987 and for μ = 0.3, η = 0.99. Similar (slightly better due to better lubrication) efficiency is characteristic for single-gear couplings.

This inevitable backlash in the gear and Oldham connections is highly undesirable for servo-controlled transmissions.

Oldham couplings and u-joints with elastic connections (Subclass B). The basic disadvantages of conventional Oldham and gear couplings (high radial forces, jumps in the radial force direction, energy losses, backlash, nonperformance at small misalignments, noise) are all associated with reciprocal, short travel, poorly lubricated sliding motion between the connected components. There are several known techniques of changing friction conditions. Rolling friction bearings in u-joints greatly reduce fric-

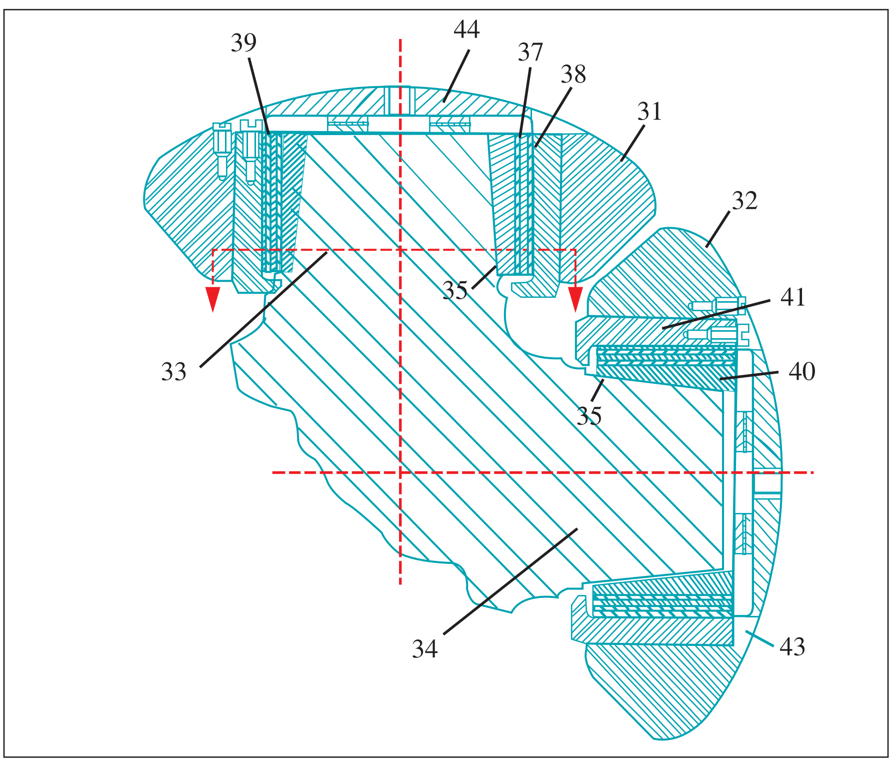

Figure 7—A large u-joint with thin-layered, rubber-metal bearings.

tion forces. However, they do not perform well for small-amplitude reciprocal motions. In many applications, shafts connected by u-joints are installed with an artificial 2–3° initial misalignment to prevent jamming of the rolling bodies.

Another possible option is using hydrostatic lubrication. This technique is widely used for rectilinear guide ways, journal and thrust bearings, screw and worm mechanisms, etc. However, this technique seems impractical for rotating systems with high loading intensity (and thus high required oil pressures).

Replacement of sliding and rolling friction by elastically deformable connections can resolve the above problems. Figure 5 shows a "K" or "Kudriavetz" coupling made from a strong, flexible material (polyurethane) connected with the hubs by two "tongues" each. If the connected shafts have a radial offset, it is compensated by bending of the tongues, thus behaving like an Oldham coupling with elastic connections between the intermediate member and the hubs. If the connected shafts each have an angular misalignment, the middle membrane behaves as a "cross," while twisting deformations of the tongues create kinematics of a u-joint. As a result, this coupling can compensate large radial misalignments (~2.4 mm for a coupling with external diameter of D = 55 mm), as well as angular misalignments of ±10 degrees. The torque ratings of such couplings are obviously quite low; e.g., a coupling with outside diameter D = 55 mm has a rated torque T_r = 4.5 N-m.

Since displacements in the sliding connections a-b and c-d in Figure 3a are small (equal to the magnitude of the shaft misalignment), the Oldham coupling is a good candidate for application of the thin-layered rubber metal laminates (Ref. 1). Some of the advantages of using laminates are their very high compressive strength, up to 100,000 psi (700 MPa), and insensitivity of their shear stiffness to the compressive force. This property allows the preloading of the flexible element without increasing deformation losses.

Figure 6 (from Ref. 2) shows such an application. Hubs 101 and 102 have slots 106 and 107, respectively, whose axes are orthogonal. The intermediate disc can be assembled from two identical halves 103a and 103b. Slots 108a and 108b in the respective halves are also orthogonally oriented. Holders 105 are fastened to slots 108 in the intermediate disc and are connected to slots 106 and 107 via thin-layered rubber-metal laminated elements 111 and 112 as detailed in Figure 6b. These elements are preloaded by sides 125 of holders 105, which spread out by moving preloading roller 118 radially toward the center.

This design provides for all kinematic advantages of the Oldham coupling without creating the above-listed problems associated with conventional Oldham couplings. The backlash is totally eliminated since the coupling is preloaded. For the same rated torque, the coupling is much smaller than the conventional one due to the high load-carrying capacity of the laminates and the absence of stress concentrations like ones shown in Figure 4b. The intermediate disc (the heaviest part of the coupling) can be made from a light, strong material, such as aluminum, since it is not exposed to contact loading. This makes the coupling suitable for high-speed applications.

The misalignment compensation stiffness and the rated torque can be varied by proportioning the laminated elements (their overall dimensions, thickness and number of rubber layers, etc.). The loads on the connected shafts are greatly reduced and are not dependent on the transmitted torque since the shear stiffness of the laminate does not depend on the compression load.

To derive an expression for efficiency of the Oldham coupling with laminated connections, let the shear stiffness of the connection between one hub and the intermediate member be denoted by ksh and the relative energy dissipation in the rubber for one cycle of shear deformation by ψ. Then, maximum potential energy in the connection (at maximum shear e) is equal to

$$V_1 = k_{sh} \frac{e^2}{2} \tag{8}$$

and energy dissipated per cycle of deformation is

$$\Delta V_1 = \psi k_{sh} \frac{e^2}{2} \tag{9}$$

Each of the two connections experiences two deformation cycles per revolution; thus the total energy dissipated per revolution of the coupling is

$$\Delta V = 2\Delta V1 = 2\psi k_{she}{}^2 \tag{10}$$

Total energy transmitted through the coupling per revolution is equal to

$$W = P_t \pi D_{ex} = 2\pi T \tag{11}$$

where $P_t = T/D_{ex}$ is tangential force reduced to the external diameter D_{ex} and T is the transmitted torque. Efficiency of a coupling is therefore equal to

$$\eta = 1 - \frac{\Delta V}{W} = 1 - \frac{\psi k_{sh}}{\pi T} e^2 = 1 - \frac{k_{sh} \tan\beta}{T} e^{2} \tag{12}$$

where β is the loss factor of the rubber.

For the experimentally tested coupling (D_{ex} = 0.12 m), the parameters are: a laminate with rubber layers 2 mm in thickness; ψ = 0.2; k_{sh} = 1.8 x 105 N/m; T= 150 N-m; e = 0.001 m; thus η = 1 – (0.2 x 1.8 x 105 x 10-6)/150π = 1 – 0.75 x 10-4 = 0.999925, or the losses at full torque are reduced 200 times as compared to the conventional coupling.

Test results for the conventional and modified Oldham couplings having D_{ex} = 0.12 m have shown that the maximum transmitted torque was the same, but there was a 3.5 times reduction in the radial force transmitted to the shaft bearings with a modified coupling. Actually, the coupling showed the lowest radial force for a given misalignment compared with any commercially available compensating coupling, including couplings with rubber elements. In addition to this, the noise level at the coupling was reduced by 13 dBA to L_{eq} = 83 dBA. Using ultra thin-layered laminates for the same coupling would further increase its rating by at least one order

continued

of magnitude, and may even require a redesign of the shafts to accommodate such a high transmitted load in a very small coupling.

U-joints transmit rotation between two shafts whose axes are intersecting but not coaxial (Fig. 3c). A u-joint also has an intermediate member ("spider" or "cross") with four protruding pins ("trunnions") whose intersecting axes are located in one plane at 90° to each other. As in the Oldham coupling, two trunnions having the same axis are movably engaged with journals machined in the hub ("yoke") mounted on one shaft, and the other two trunnions, with the yoke attached to the other connected shaft. However, while the motions between the intermediate member and the hubs in the Oldham coupling are translational, in the u-joint these motions are revolute. This design is conducive to using rolling friction bearings, but the small reciprocating travel regime under heavy loads requires derating of the bearings.

A typical embodiment of the u-joint with thin-layered rubber-metal bearings (Ref. 3) is illustrated in Figure 7 for a large-size joint. Figure 7 shows two basic units (out of four constituting the universal joint): yoke-trunnion-elastomeric bearing sleeve (parts 31, 33 and 35 respectively) and yoke-trunnion-elastomeric bearing sleeve (parts 32, 34 and 35, respectively). Sleeves (35) comprise rubber-metal laminates (37) having sleeve-like rubber layers (38). Separating them and bonded to them are sleeve-like thin, reinforcing, intermediate metal layers (39) and inner (40) and outer (41) sleeve-like material layers bonded to the extreme inner and outer sleeve-like rubber layers. The inner and outer metal layers of the laminated bearing sleeve are made thicker than the intermediate metal layers, since they determine the overall shape of elastomeric bearing sleeves.

The inner surface of the inner layer (40) is made tapered and conforming with the tapered outer surfaces of trunnions 33 and 34. The outer surface of the outer layer (41) is made cylindrical and conforming with the internal cylindrical surface of the bore in yoke 31. Each bearing sleeve (35) is kept in place by a cover (44) abutting the end surface (43) of the outer metal layer (41). The cover is fastened to the outer metal layer and to the yoke by bolts. A threaded hole is provided in the center of the cover.

Before assembly, the wall thickness of the elastomeric bearing sleeve (a sum of total thickness of rubber layers, intermediate metal layers and inner and outer metal layers) is larger than the annular space between the inside surface of the bore in the yoke (31) and the respective outside surface of the trunnion (33). The difference between the wall thickness of the bearing sleeve and the available annular space is equal to the specified preloading compression deformation of the elastomeric bearing sleeve. To perform assembly operation, the tapered bearing sleeve is inserted into the wider opening of the tapered annular space between the internal surface of the bore and the external surface of the trunnion and pressed into this space by a punch shaped to contact simultaneously both end surfaces. Wedge action of the tapered connection between the conforming inner surface of metal layer 40 and outer surface of trunnion33 results in expansion of metal layer 40, in compression (preloading) of rubber layers and in gradual full insertion of the bearing sleeve into the annular space between the yoke and trunnion. The simultaneous contact between the pressing punch and both end surfaces of inner metal layer 40 and outer metal layer 41 assures insertion of the bearing sleeve without inducing axial shear deformation inside the bearing sleeve, which can cause distortion or even damage of the bearing sleeve.

To disassemble the connection, bolts attaching the cover to the yoke are removed, and then a bolt is threaded into a hold until contacting the end surface of the trunnion. The further threading of the bolt pushes the outside cover together with the outer metal layer of the bearing sleeve, to which the cover is attached by bolts. The initial movement causes shear deformation in the rubber layers until disassembly protrusions engage with the inner metal layer, thus resulting in a uniform extraction of the bearing sleeve.

It is highly beneficial that u-joints with the rubber-metal laminated bearings do not need sealing devices and are not sensitive to environmental contamination (dirt, etc.).

The efficiency analysis for such u-joints is very similar to the analysis for the modified Oldham coupling. The efficiency of the joint is

$$\eta = 1 - \frac{\Delta V}{W} = 1 - \frac{\psi k_{tor}}{\pi T}\alpha^2 = 1 - \frac{k_{tor}\tan\beta}{T}\alpha^2 \qquad (13)$$

where k_{tor} is the torsional stiffness of the connection between the intermediate member and one yoke. It can be com-

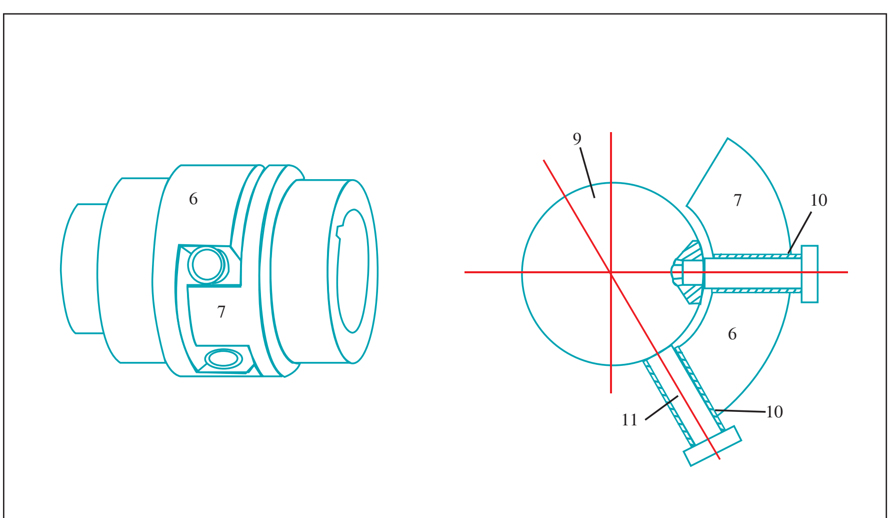

Figure 8—A modified spider coupling.

pared with efficiency of a conventional u-joint where d is the effective diameter of the trunnion bearing, 2R is the distance between centers of the opposite trunnion bearings, and μ is the friction coefficient in the bearings.

$$\eta = 1 - \mu \frac{d}{R}\frac{1}{\pi} \left(2\tan\frac{\alpha}{2} + \tan\alpha \right), \quad (14)$$

A comparison of Equations 7 and 14 with Equations 12 and 13, respectively, shows that while efficiencies of conventional Oldham couplings and u-joints for a given e, α are constant, efficiency of the modified designs using rubber-metal laminated connections increases with increasing load (when the energy losses are of the greatest importance). The losses in an elastic Oldham coupling and u-joint at the rated torque can be 1–2 decimal orders of magnitude lower than the losses for conventional units. Due to high allowable compression loads on the laminate (in this case, high radial loads), the elastic Oldham couplings and u-joints can be made smaller than the conventional units with sliding or rolling friction bearings for a given rated torque. The laminates are preloaded to eliminate backlash, to enhance uniformity of stress distribution along the load-transmitting areas of the connections, and to increase torsional stiffness. Since there is no actual sliding between the contacting surfaces, the expensive surface preparation necessary in conventional Oldham couplings and u-joints (heat treatment, high-finish machining, etc.) is not required. The modified Oldham coupling in Figure 6 and the u-joint in Figure 7 can transmit very high torques while effectively compensating large radial and angular misalignments, respectively, and having no backlash since their laminated flexible elements are preloaded. However, for small-rated torques, there are very effective and inexpensive alternatives to these designs whose kinematics are similar. These alternatives are also backlash-free.

One is a Kudriavetz coupling, shown in Figure 5. Another alternative is a modified spider or jaw coupling whose cross section by the mid-plane of the six-legged spider is shown in Figure 8 (Ref. 4). In this design the elastomeric spider of the conventional jaw coupling shown in Figure 10a is replaced with a rigid spider (9, 11) carrying tubular sleeves or coil springs (10) supported by spider pins (11) and serving as flexible elements radially compressed between cams (6 and 7) protruding from the respective hubs. If the number of spider legs is four, at 90° to each other, then the hubs have relative angular mobility, and the coupling becomes a u-joint with angular mobility greater than 10°, but with much higher rated torque than an equivalent size Kudriavetz coupling.

Purely misalignment compensating couplings described in this section have their torsional and compensating properties decoupled by introduction of the intermediate member. Popular bellows couplings have high torsional stiffness and much lower compensating stiffness, but their torsional and compensating properties are not decoupled, so they are representatives of the "combination purpose couplings" group, which will be discussed in detail in Part II of this article, which will appear next issue.

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Eugene I. Rivin *was a Principal Staff Engineer at Ford Motor Co., from 1976–1981. Since 1981 he has been professor at Wayne State Univ. Major professional achievements of Dr. Rivin are in transmission dynamics, vibration/noise control, machine tools/tooling, robotics, advanced machine elements, creative problem solving. He published many monographs, book chapters and articles. Most recent books: "Mechanical Design of Robots," 1988; "Stiffness and Damping in Mechanical Design," 1999; "Passive Vibration Isolation," 2003; "Innovation on Demand," 2005 (with V. Fey). He authored/co-authored 60+ patents, with some inventions widely implemented worldwide. Out of this number, 18 patents relate to power transmission components (gears, flexible and rigid couplings, keys and other rigid interfaces/connections for machine tools and other mechanical systems). He is an elected Fellow of the International Academy of Production Engineering Research (CIRP), of ASME, and of SME.*

GEAR- OR ACTUATOR-DRIVEN,

These Bots are Cutting-Edge

Jack McGuinn, Senior Editor

A surgeon at the controls of an Intuitive da Vinci surgical system. The surgeon—via the 3Dviewfinder/monitor and with the help of a surgical assistant—directs the robot's four available arms to where they need to be in order to perform a surgical procedure. (Source: Intuitive Surgical.)

Robots are everywhere these days—bots in the factory, bots in space, bots at the airport, bots in the movies and much, much more. But robots in the operating room?

And why not? They may not have the sex appeal of a George Clooney back in his ER days, but they'll certainly have a much longer run. In truth, surgical robotics has been around since the early 90s, but today's OR robots are more Dr. Who than Dr. Kildare.

Nora Distefano, marketing communications and services specialist for California-based Intuitive Surgical, Inc., provides some historical perspective relative to the da Vinci robot system.

"The original prototype for Intuitive Surgical's da Vinci surgical system was developed in the late 1980s at the former Stanford Research Institute under contract to the U.S. Army. While initial work was funded in the interest of developing a system for performing battlefield surgery remotely, possible commercial applications were even more compelling. It was clear to those involved that this technology could accelerate the application of a minimally invasive surgical approach to a broader range of procedures.

"In 1995, Intuitive Surgical was founded to test this theory. In January 1999, Intuitive launched the da Vinci surgical system, and in 2000, it became the first robotic surgical system cleared by the FDA for general laparoscopic (abdominal) surgery. In the following years, the FDA cleared the da Vinci system for thoracoscopic (chest) surgery for cardiac procedures performed with adjunctive incisions, and urologic and gynecologic procedures."

Today, according to Distefano, Intuitive's robots are "practicing" in most U.S. metropolitan centers and in more than 25 countries around the world.

Once one gets past the Brave New World fact that robots are here to stay—in the operating room and practically everywhere else—what sets robots apart from their human counterparts is their ability to perform highly delicate surgical procedures by way of the smallest incision possible. This "key-hole" procedure, as it is known, results in much less tissue damage to the patient and thus a much faster recovery time. What's more, the risk of post-operative infection is greatly reduced.

Back near the other coast, Ft. Lauderdale-based Mako Surgical Corp. has its own stable of robotic surgical stars, if on a lesser scale due to the company's brief history. While the much more established Intuitive focuses on a wider variety of surgeries, Mako's niche is orthopedic procedures, especially knees and other joints.

"We're starting out with minimally invasive knee replacement or knee resurfacing surgery, and our platform can potentially be used in many other areas of orthopedic surgery," says Rony A. Abovitz, Mako chief technology officer. "Our technology on its own is attracting significant, key opinion leaders. Orthopedic surgery has been fairly static for 20–30 years in terms of implant design and implementation—nothing really earth-shattering going on there; same carpentry-like tools—so bringing in a tactilely guided robotics platform really captures their imagination. So we're getting a lot of like-minded thought leaders because of this technology platform. When they work with us, they want to see orthopedic surgery get to the next level."

Speaking of technology, the two companies take distinctively different approaches in the design and implementation of their robots.

Intuitive takes a somewhat more traditional direction in robot technology in that they incorporate gears—plastic, aluminum and stainless steel; hobbed and molded—along with cables, bands and timing belts, to power their progeny. But there is one constant among all robotry—power and motion control.

"Drivetrain design is a critical part of the da Vinci system," says Sal Brogna, Intuitive vice president of engineering. "We endeavor to design a system that faithfully represents all the delicate hand motions that a surgeon must use during surgery. In the da Vinci, this means very precise motion between the master and slave manipulators. We accomplish this by having drivetrains of very low friction, high stiffness and virtually no backlash.

"In total, each da Vinci system has 39 servo-controlled axes of motion. We have an additional 17 axes that provide passive motion for system setup."

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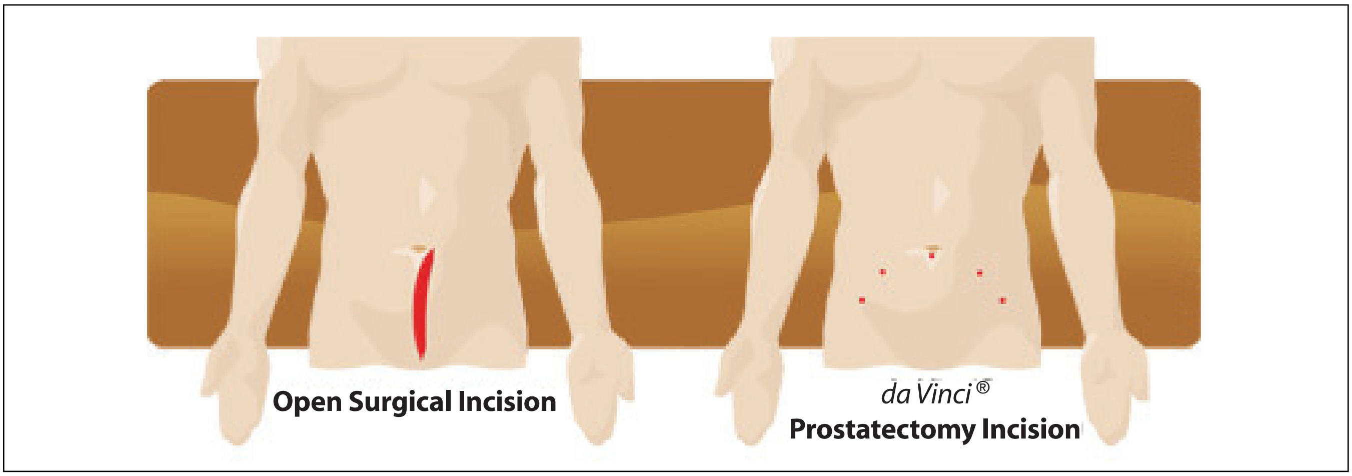


An example of one of robotic surgery's greatest benefits—"key hole" incisions, as seen in this prostatectomy illustration. The smaller incision means faster healing, reduced body trauma, infection risk and shorter hospital stays. (Source: Intuitive Surgical.)

Given that there are 27 bones in the human hand—each with a specific motion and motor control function—it is understandable why such a complex amalgam is necessary. To accomplish it, Brogna says Intuitive recruits engineers from the robotics or medical device industry. But, surprisingly enough—no surgeons.

"We have a team of clinical engineers," says Brogna. "These are a unique group of people that have both technical training and medical training. They help the design engineers translate design approaches to surgeon needs. They work intimately with both the surgeons and the design engineers. We also send our design staff out to the field to observe procedures done with the da Vinci system."

Returning to the robot technology/design issue, Mako takes a quite different approach to precise motion and power transmission control—i.e., no gears. For their bots, actuation is where the action is.

"(Our robot) is singularly designed not to use gears," says Abovitz, "but it's a very novel, interesting transmission. Everyone thinks about robots having gears, but ours uses a tension cable drive transmission, which has the benefits of the tension cable, which offers very low friction and incredibly good back-drivability. With our system, you're also able to have great haptic (tactile) control. So as a robot actually designed to enable haptics—probably one of the first (robotics) platforms designed to do that—the idea of this robot was to put your hands on it, so it can be manipulated anywhere from its tip to the entire length of the arm.

"You can move it around with smooth, low-friction transmission. There's a mode the robots use called a neutral-gravity mode; while weightless you can move it around very easily to a mode where it is incredibly stiff and is force-controlled, and it is basically providing torque resistance."

Accomplishing these tasks are in essence the work of the tension cable drive transmission; that and a number of proprietary, DC servo motors and actuators. The intricate yet relatively powerful motors do the yeoman's work throughout the Mako robotic system. Together, the motors and actuators afford the robot an ease and fluidity of motion along with the capability to stop instantaneously, when needed; which is, of course, quite often in the performance of surgery.

"So the robot lets you simulate the virtual physical constraints we want to help guide a surgeon and his tool," says Abovitz. "The key is the tension cable transmission system which is free of gears; it's a novel, proprietary system. So what (the surgeon) gets is a continuous transmission in a very smooth motion—from stiff to free range of motion instantly.

"It's a cable transmission, so if you think of what a gear does—connected to a motor moving other gears—we've got these cable transmission drives that are connected to these proprietary motors that drive other cable transmission parts of the robot. So, to a degree, what you think of as a gear—we have this tension cable drive. Adds Abovitz, "There are different sorts of continuous transmission systems that are non-geared."

Mako Surgical, specializing in knee and other joint orthopedic surgeries, including knee replacement and resurfacing, relies on its patented Tactile Guidance System for enhanced haptics.

Mako's surgeon-friendly Tactile Guidance System consists of a robotic arm with a haptic—or sense-of-touch—capability for precise bone resection and bone-saving cutting. (Source: Mako Surgical.)

Whether it is actuators or gears, there is one area where Intuitive and Mako find common ground—software. And as you can well imagine, we're not talking off-the-shelf programs. These are proprietary, extremely robust designs that—along with hardware—are the heart of both company's robots.

"Our system is strongly software-based," says Intuitive's Brogna. "We have a terrific staff of embedded software and system analysis engineers that develop the software for our product. Software controls all elements of our motion control, user interface and safety systems.

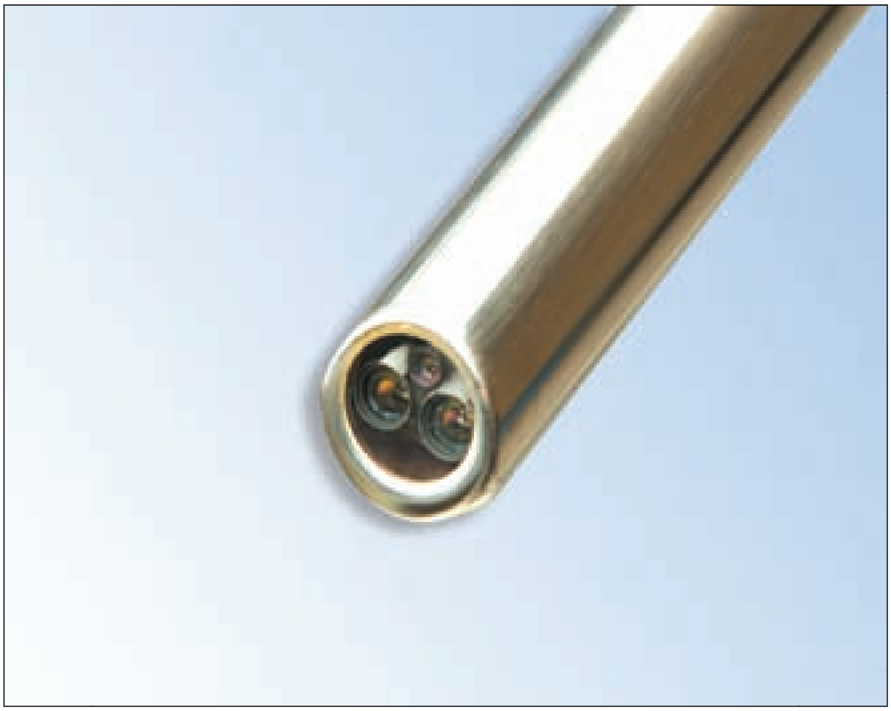
"It is incredibly challenging to develop the software. All software must operate in real time, so code must be very efficient and execute quickly."

At Mako, same thing.

"Software is a major component," says Abovitz. "In our system there are two main computing architectures—one is the control system for the robotic arm, and we have a program that communicates to our higher-level surgeon application software. We write and develop most of the software here. The robot control software is based using a *QNX* platform—a real-time operating system—and when you write to *QNX* you can have probably the fastest possible control over your robotic hardware and firmware. The *QNX* operating system is great for that.

In explaining the visualization side of the software, Abovitz explains that surgeons work from a 3D model—gained via CAT scan—of a reconstruction of the patient's knee. There is also a large screen positioned in front of the surgeon (providing the term "operating theater" an entirely new dimension) displaying real-time updates and 3D pictures as the surgeon—with the robot as his proxy—sculpts away at the knee in need of reconstruction.

"The software provides visualization guidance to the surgeon who does not have great visualization due to the small incision they are working through." Abovitz says. "And the robot provides tactile guidance; it constrains where the instrument (scalpel, etc.) can go. The surgeon is free to move inside the incision, but



A close-up of the scope that provides 3D imaging of the surgical area.

Intuitive's "Fourth Arm" is an integral part of its da Vinci system. The first two arms represent the surgeon's left and right hand and hold the surgical instruments. The third arm positions the 3D imaging scope, and an optional fourth arm is for adding an additional surgical instrument, effectively giving the surgeon three hands to work with. (Source: Intuitive Surgical.)

when or if he's going to the wrong place it feels like he's hitting a piece of glass or a constraint. Basically, it locks him into where he should be working."

In essence, both Intuitive's and Mako's robot systems have fail-safe mechanisms. Should there be some event—a power outage, perhaps—that makes proceeding with the surgery risky, the robot will shut down completely. Aside from that, the tactile capability specific to both bots alerts the surgeon as to whether he or she is working on the exactly correct area in need of repair. That's because the mentioned visualization software prevents the surgeon from entering an incorrect or unaffected area.

What, you might be asking at this point, are a surgical robot's limitations? Intuitive's Distefano points out some concerns, such as an extended learning curve on the part of surgeons and surgical staff, prolonged OR time or loss of haptics when compared to open surgery.

"Clinical studies suggest that although OR times are higher at first, they decline significantly with experience and soon become equivalent or comparable to those times measured with open procedures," she says. "Studies also suggest that loss of haptics as compared to open surgery is compensated for with significantly improved visualization, dexterity, control and ergonomics."

(By the way, should you be shopping for a robotic surgeon, Intuitive's lists at about $1.5 million and Mako's at $795,000.)

This is pretty impressive stuff, but what will the next generation of surgical robots look like?

"We believe that surgical robots will become a standard form of healthcare in hospitals in many settings and disciplines," says Distefano. "The added precision, visualization, articulation and data fusion that surgical robots provide are widely applicable to treatment.

"In addition, orthopedic, catheter-control and other medical robots will also take their place in healthcare. The use of automation in surgery and healthcare will progress slowly—autonomous robots for use in healthcare will start by taking on particular tasks, rather than whole procedures."

In other words, look for robots to be taking your temperature and monitoring your blood pressure at hospitals of the future.

For Abovitz, the anticipated upgrades should translate to elevated confidence in surgeons and peace of mind for patients.

"If you put robotics together with a human in the right way, the outcome should be like the surgeon's best day, every day. It's like taking an average golfer and every day he's Tiger Woods. The ultimate vision is the best doctor on his best day—everyday, everywhere."

(*PTE reader web poll question: If you had a choice, which would perform your surgery?*)

A. Robot-assisted surgeon
B. Surgeon only
C. No preference

(*Log onto powertransmission.com/poll/ to vote and see how others voted.*)

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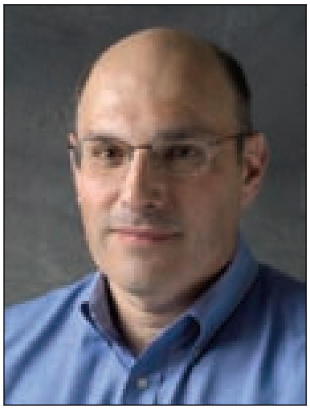
The Mako surgical robot system. (Source Mako Surgical.)



Sal Bragna, Intuitive Surgical vice president of engineering.

Bovine Bliss

BRAKE APPLICATION KEEPS COWS HAPPY AND COMFORTABLE AT DAIRY FARMS

Matthew Jaster, Associate Editor

Photo provided by Igor Spanholi.

A happy cow is a more productive cow. Ask any dairy farmer and they'll tell you an upset cow will not provide as much milk as one that is comfortable. BouMatic, a Wisconsin manufacturer of cow-milking equipment, is in the business of making cows happy, and by doing so, keeping its customers happy as well.

A few years ago, BouMatic needed a brake design to keep a rotary gate from crashing down on the cows when they exited the milking stalls at dairy farms. Anthony Esch, product manager-cow traffic systems at BouMatic, had initially attempted to use a hydraulic ram to solve the problem.

"Adjusting the flow controls for the proper speed was difficult, and if air got into the hydraulic ram, it would throw off the braking of the reel," Esch says.

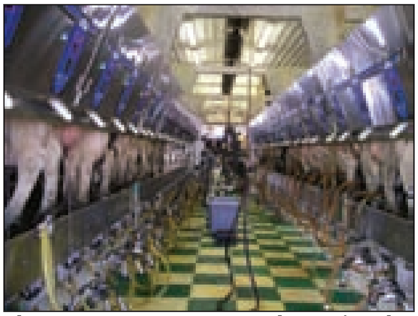
Although it's hard to imagine a group of engineers sitting around a table pondering an application to ensure the contentment of cows, that's exactly what the company did when they contacted Mach III Clutch Inc. in Walton, Kentucky for a new brake design.

"BouMatic needed a brake to hold both the closed and open positions of a rotary gate in a cow-milking parlor," says Lesli Riehemann, president at Mach III. "The brake prevents the gate from rotating in the event one or more of the cows would push against it during the milking process. If the gate rotated, it would crash down on the other cows in the stall."

According to Riehemann, Mach III worked with BouMatic's engineering department for several weeks when the application was first presented by a Wisconsin distributor, Techmaster, Inc.

continued

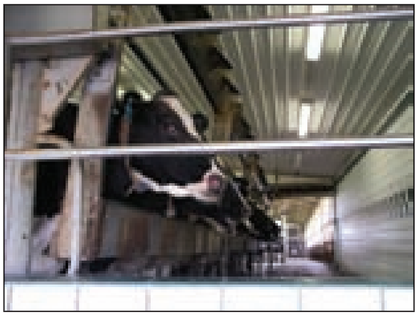
"One unique challenge was determining the torque requirement because it involved estimating the amount of force a cow was capable of applying to the gate," Riehemann says. "BouMatic opted for a 5" and 6" diameter, double-disc standard brake that was not covered or sealed. As the brakes were located inside an enclosure, we believed they'd have enough protection from moisture to allow proper function."



The rotary gate, seen here in the closed position, keeps the cows safe during the milking process.

Esch says that the exit system on the Xcalibur stall milking system is a balanced reel that makes a 180-degree turn to exit the cows out of the milking parlor. The reel is turned by using an air cylinder attached to a ratcheting sprocket through the use of a roller chain. This cylinder turns the sprocket that is on the shaft to rotate the reel.

"Once the reel is turned about 90 degrees, air is applied to the brake to stop the reel in the horizontal position to allow the cows to walk out. After 5 to 10 seconds, the air brake releases and allows the reel to slowly rotate the last 90 degrees to allow for another group of cows to file in to be milked," Esch says.



Water is used everywhere in the milking parlor, which made it difficult to keep the original brake assembly clean.

After supplying the standard brake models for about a year, BouMatic began to have customer complaints about brake failure and limited torque capacity. The company sent some of the failed brakes back to Mach III for evaluation.

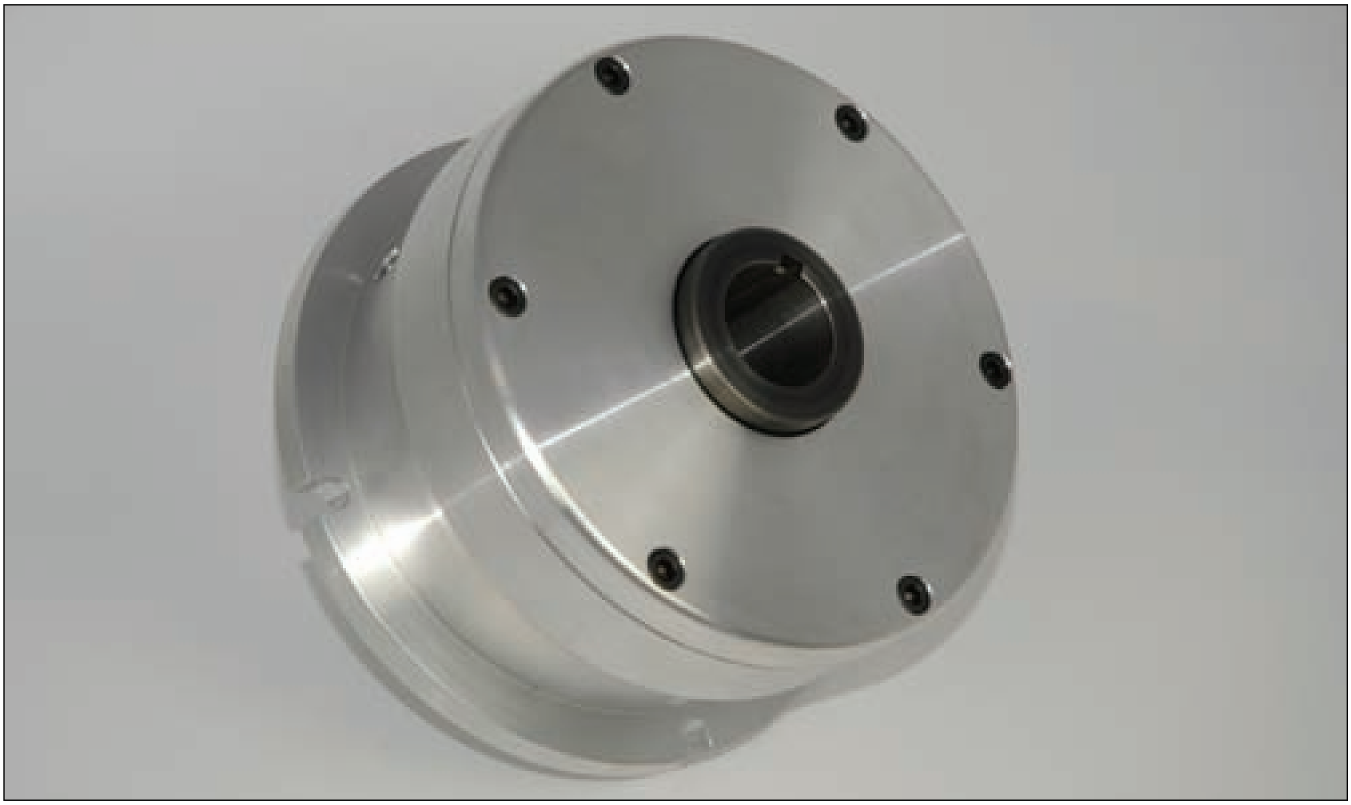
"Rusting and corrosion were clearly causing problems, so I traveled to meet with a BouMatic engineer and our distributor to review the problem and discuss possible solutions," Riehemann says. "We also visited a dairy farm where our brakes were installed so I could get a better feel for the environmental conditions."

It was determined that despite the enclosure on the gate, the equipment was getting washed down with hoses and power sprayers, and water was finding its way into the brakes, contaminating the friction linings and causing brake failure.

"Water is used everywhere in the milking parlor, and unfortunately the first couple of installations used a brake assembly that was open to the environment," Esch says.

A simple fix would be to manufacture the same brake using corrosion resistant materials such as stainless steel and to provide a better enclosure. This, unfortunately, would have cost three times more than the standard design, and BouMatic was not willing to absorb the costs.

"Instead, our engineers went back to the drawing board and came up with an enclosed brake design in both 5" and 6" sizes made from standard materials," Riehemann says. "To resolve the complaint of inadequate torque, the surface area of the pis-



The brake provided by Mach III was customized with solid housing to protect from contamination.

ton was increased and a third disc was added."

Riehemann states that this design was accomplished without adding to the overall length. It also doubled the torque capacity with only a cost increase of 10 percent. The new enclosed brake models have been utilized on BouMatic equipment without any other failures for the past four years.

After Mach III began supplying the new covered and sealed brakes to BouMatic, an engineer in Holland contacted the company about brakes for a chain conveyor at a processing facility in Indiana. Mach III provided a prototype within 48 hours and delivered 55 covered and sealed 8" diameter brakes within two months.

The work done in Indiana was very similar in design to the brakes needed for BouMatic. The biggest difference was that the brakes had to be electroless nickel-plated, and the aluminum components had to be anodized to meet food safety standards.

"You'll find covered and sealed Mach III clutches in automatic carwashes at thousands of gas stations across the United States," Riehemann says. "There are also enclosed Mach III products on machinery producing and packaging Kraft cheese, Cloverhill Bakery pastries, Jack Lin's beef jerky and Minute Maid juices."

Riehemann says that all requests for quotes are met with a single question. Is this for a new or existing application? New inquiries are sent to the engineer team who continue to ask questions. If a catalog product suits the application, the initial work is done.

"We typically have a new design finalized within a week of the initial inquiry and deliver the product in three to four weeks," Riehemann says. "Customers are pleasantly surprised by the prices at which we offer specialized products. Henry Ford certainly would not have approved of our manufacturing model, but it's been working for us for nearly 45 years, so we figure we must be doing something right."

Esch seems to think so.

"A happy cow likes consistency and a calm working environment. One thing we can do to provide this environment is to equip our BouMatic milking parlors with the most reliable equipment available."

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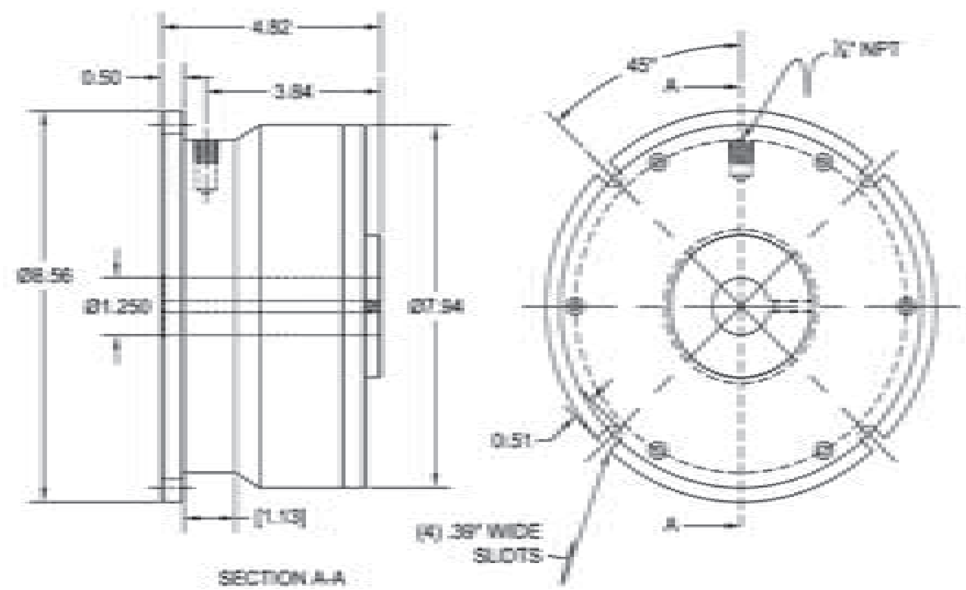
www.machiii.com



An outline of the revised brake designed by Mach III.

Siemens exiderdome Debuts in Chicago

BRINGING AUTOMATION, ENERGY EFFICIENCY TO A CITY NEAR YOU

Experience the world of energy efficiency and automation at a whole new level. Following a successful excursion across Asia, Russia, Mexico and Canada, Siemens Energy & Automation brings the World of Automation—exiderdome—traveling technology expo and learning laboratory to the United States.

The U.S. tour kicked off at Chicago's Navy Pier on July 22 and continues through Detroit, Boston (October 20–24), New York (November 1–7), Charlotte (December 8–12)—and, in 2009—Orlando, Los Angeles, Denver and Houston.

"At Siemens Energy & Automation, we sell productivity, and exiderdome tells this story through multimedia shows, demos, training sessions and more," says Dennis Sadlowski, president and CEO of Siemens Energy & Automation. "With exiderdome, we are showing our commitment to our customers by meeting in their backyard to discuss how our solutions drive productivity in their industries."

Spanning 10,000 square feet on two levels, the exiderdome is a modular building composed of 55 containers, seven of which are devoted to showcasing 137,000 products in seven technology categories: commercial and industrial power infrastructure; industrial controls; drives and motors; motion control; discrete automation—in two containers—and process automation.

Four atrium walls function as portable multi-media displays projecting a high-definition visual recording highlighting Siemens and its U.S. market. Exiderdome also functions as a learning laboratory with training and educational events each day. Siemens executives and outside experts lead the learning events on current developments in security, energy and environment, innovation, productivity and other current business challenges.

"The building itself has a very high 'wow' factor, but it's the content—the multimedia show, the tour and the opportunity to interact with experts in their fields—that gets the real conversations started," says Thomas Varney, vice president of communications for Siemens. "Our experience has shown that we can translate those conversations into stronger customer relationships."

On one hand the exiderdome is about education, technology and advancements and transmitting these ideas to Siemens' current and potential customers.

High-definition visual recordings are projected on exiderdome's with walls to highlight Siemens and its U.S. market.

"Technology today has changed dramatically from technology of even two years ago," Varney says. "Engineers should know what's out there and how up-to-date technology can improve a company's overall performance and productivity, making it more competitive and successful in the marketplace, which results in a stronger relationship with Siemens."

After the U.S. leg of its journey, exiderdome is set to appear in Brazil and South Africa. As the number one foreign investor in electrical engineering and electronics in America, according to the Organization for International Investment, and with $19.8 billion in U.S. revenues in 2007, the U.S. holds special significance for Siemens, and the Windy City was a natural choice as the starting point for the North American visit.

"The United States is the company's largest market, and Siemens' roots run deep in the Chicago area where we have been operating for nearly 120 years," says Heinrich Hiesinger, CEO of Siemens industry sector. "Combined with its proximity to our customers, Chicago ranks as one of the top areas for potential market growth and is the ideal place to launch our U.S. tour."

Siemens executives couldn't be clearer in the messages they are conveying with exiderdome.

"This tour is about our commitment to the U.S. market and our belief in the long-term strength of American manufacturing," Varney says. "We want our customers to see that, because of our size and reach, we can offer them more ways to strengthen their operations than any other automation technology supplier.

"We want to show our American customers that we are the only company in the world that can put together this kind of program with all of our own components."

October 28–29—Practical Solutions for Processing Productivity: Hidden Savings Through Better Blending, Drying, Cooling and More. DoubleTree Hotel, Oak Brook, IL. This two-day conference is organized by *Plastics Technology* magazine and is believed to be the market's first technical event aimed specifically at helping processors make better use of their auxiliary equipment. Technical presentations combine with a hands-on workshop format that complements the 20 or so auxiliary equipment suppliers that will be participating as presenters. The program consists of a series of morning sessions, lunchtime panel discussion, and afternoon breakout workshops where processors will learn more about state-of-the-art in feeding, cooling, robotics, drying, etc. For more information, visit *www.ptonline.com/conf/practicalprocessing/index.html*, or contact Matthew Naitove at *mnaitove@ptonline.com* or (646) 827-4848 x7102.

October 28–30—Coil Winding, Insulation and Electrical Manufacturing Exhibition and Conference. Donald E. Stephens Convention Center, Rosemont, IL. The Coil Winding, Insulation and Electrical Manufacturing Exhibitions (CWIEME) is a focused event devoted to components, machinery and materials used in the manufacture and repair of electric coils, motors and transformers. Attendees will view products and services from 172 participating companies from Belgium, Brazil, Canada, China, France, Germany, India, Israel, Italy, Japan, Korea, Mexico, Poland, Romania, Slovenia, South Korea, Spain, Switzerland, Taiwan, UK and the United States. Co-located and running concurrently to the exhibition is INDUCTICA Chicago 2008, a three-day technical conference specializing in Miniature & Micro Coils; Magnetic Materials (including magnetic fluids and gels) as well as the traditional topics such as Motors, Generators and Transformers; Electromagnetic Field Simulation and Testing; Test and Measurement; and Electromagnetic Design. For more information, visit *www.coilwindingexpo.com*.

November 18–19—RoboDevelopment Conference & Exposition 2008. Santa Clara Convention Center, Santa Clara, CA. RoboDevelopment is the international technical design and development event for the personal, service and mobile robotics industry. The event is designed to be an educational forum and trade show addressing the technical issues with designing and developing commercial robotic products. Technical professionals will learn about developing next-generation personal, service and mobile robots, and the exposition brings hands-on access to the latest design and development solutions for mobile robotics and intelligent systems technology. Some topics include the requirements for robots to navigate with minimal human intervention and be both able to detect anomalies and deal with them effectively; how robots can be designed to manage limited resources, including power and computation, and use them in an efficient manner; and the languages and operating systems, as well as hardware and software platforms that can help optimize design and development while producing robust commercial products. For more information, visit *www.robodevelopment.com*.

Misumi technical seminar.

November 11—Free Configuration Technical Seminar: Designing a Better Machine Faster with the Configuration Component. Lancaster Host Conference Center, Lancaster, PA. Misumi USA Inc. conducts this technical seminar, which is scheduled from 11:00 am to 3:00 pm. Engineers will learn methods to avoid time and performance issues associated with machine builds. Misumi's manager of product development, Mike Melone is presenting the seminar, after which he will answer questions from attendees. A complimentary lunch and global atomic traveling alarm clock are included for each attendee. For more information and to register, visit *www.misumiusa.com/techseminars.aspx.*

December 10–12—Introduction to Metallurgical Lab Practices. ASM International Headquarters, Materials Park, OH. This beginning level course is designed for people with basic or limited familiarity to a materials lab or metallurgical lab practices and non-technical professionals like those in sales or purchasing. The students will learn metallography through sectioning, mounting, grinding, polishing and etching samples. Optical microscopes with digital imaging systems will be used to create photomicrographs. Other equipment that will be used includes micro- and macrohardness, tensile and impact testing and scanning electron microscopy (SEM). Attendees will receive a thorough overview of these lab procedures. For more information, visit *www.asminternational.org.*

Vestas

EXPANDS IN COLORADO

A Vestas blade factory and a nacelle assembly factory are set to take root in Brighton, CO, the wind technology company announced in August. The nacelle plant manufactures wind turbine housings including gearboxes, generators and transformers and will be the first of such Vestas facilities in the United States. The blade factory will complement an existing one in nearby Windsor, CO.

"I am delighted that we have found the location for our new blade factory, and we look forward to beginning operation in our first manufacturing cluster in the USA," says Ole Borup Jakobsen, president of Vestas Blades A/S. "I am confident we will maintain our good relationships with the authorities in Brighton and Weld County as we continue to develop this new Vestas site."

Brighton was chosen for its central location, convenient access to rail services and highway infrastructure along with the proximity to Windsor. A technology and production engineering office will also be created at the Brighton location in order to equip the factories with quality and continuous improvement competencies, according to a press release.

"We are extremely pleased to be building Vestas' largest nacelle assembly factory to date. Denver and the surrounding areas give us direct access to a large, qualified workforce, and this was one of the primary reasons for choosing Brighton," says Soren Husted, president of Vestas Nacelles A/S. "Our new factory will be designed according to the most efficient lean manufacturing principles, and we expect Brighton to become the center for Vestas Nacelles' activities in the USA."

The Brighton facilities are scheduled to be operational by July 2010. The blade-manufacturing facility represents a $180 million investment, yielding 1,800 blades a year and 650 new jobs. The nacelle assembly plant is an investment of $110 million, creating 1,400 nacelles a year and 700 new jobs. According to a press release from the Colorado governor's office, Vestas also intends to build the world's largest tower-manufacturing site in Colorado, although the location has not yet been announced.

"On behalf of the people of Colorado, I am grateful that Vestas has chosen to once again invest in our state," says Bill Ritter, Colorado's governor. "This is a tremendous boon for all of Colorado, not just Brighton. By bringing more than 1,350 additional jobs here, Vestas is cementing its standing as one of Colorado's pioneering partners in the new energy economy.

"I look forward to continuing the relationship for years to come. My administration has worked closely with Vestas to make the Brighton project a reality. This only adds momentum to our efforts to diversify our economy and grow these modern-energy industries of the future."

Hydraulic Drive Systems Specialist

ACQUIRED BY REXROTH

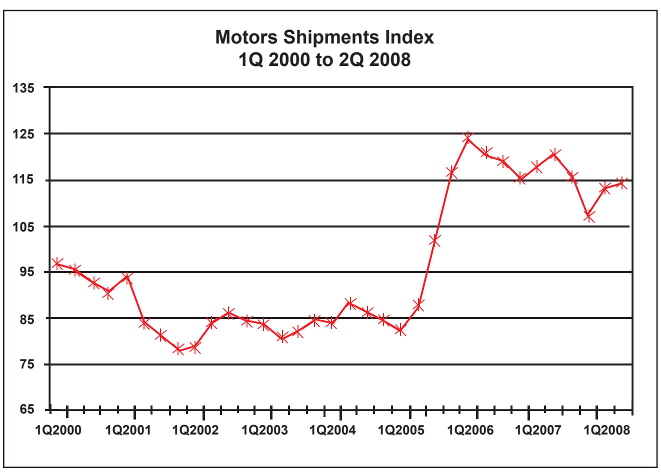
A contract was signed in July for Bosch Rexroth's acquisition of Hägglunds Drives AB, an international supplier of complete hydraulic drive systems based in Mellansel, Sweden. The sale is subject to approval by authorities.

Hägglunds Drives develops, manufactures, markets and services entire drive system solutions for applications that require high torque and variable speed. The company's drive systems are employed by industries such as mining, material handling, marine and offshore, recycling, sugar, pulp and paper. Hägglunds Drives' products are also used in ethanol-producing machines.

Hägglunds Drives posted sales of 200 million euros in 2007, employing about 900 people. The company has U.S. production sites in San Antonio and Columbus, Ohio in addition to offices in more than 20 countries.

"The acquisition of Hägglunds Drives expands our industrial hydraulics portfolio, and by this we gain new potential in growing markets, such as renewable energies, and mining and materials handling," says Dr. Albert Hieronimus, chairman of the executive board of Bosch Rexroth AG.

Second Quarter Domestic Motor Shipments Increased



NEMA's Motors Shipments Index registered a modest gain in the second quarter of 2008 with domestic shipments up 1.1 percent; however, on a year-over-year basis the index fell 5.1 percent and has been on the decline for six of the last seven quarters, according to NEMA.

The demand for integral horsepower motors was high for the second quarter and has only posted one quarter of declining shipments in the past four years, NEMA says. Fractional horsepower motors have been weak in comparison.

Materials Research Society

NAMES NEW EXECUTIVE DIRECTOR


Dr. Todd Osman

Dr. Todd Osman has been named new executive director for the Materials Research Society (MRS), succeeding John Balance after 25 years in the position.

"We are very excited about Todd and the leadership role he will play in growing MRS," says MRS president Cynthia Volkert. "MRS has a culture and tradition of innovation and technical excellence, and Todd has the vision, knowledge and drive to move MRS forward. The combination will be extremely powerful and beneficial to Materials Science Engineering around the world."

Osman possesses technical and leadership experience in both the industrial and non-profit sectors. He was a key player in the creation of the Pennsylvania NanoMaterials Commercialization Center, and served as a founding board member. He was also the technical director for the Minerals, Metals and Materials Society (TMS), where he developed initiatives in energy, environmental impact and sustainability, according to an MRS press release.

Osman has also worked as a researcher and technical manager for United States Steel Corp., researching and developing coated-steel products, one of which was granted a U.S. patent.

In speaking of the MRS, Osman says, "The scientific community, and society as a whole, face many critical challenges. But there is not a consensus on a sustainable energy portfolio, and STEM (science, technology, engineering and mathematics) education initiatives need greater participation. (MRS's) focused advocacy efforts provide a strong foundation as we continue to promote scientific and engineering responses to these challenges."

Osman received B.S., M.S. and Ph.D. degrees in materials science engineering from Case Western Reserve University, and has authored numerous articles on commercial and social impact nanomaterials, materials for nuclear power, computational materials science and engineering, product development and mechanical metallurgy.

Aerotech

OPENS SISTER COMPANY IN JAPAN

Pittsburgh-based Aerotech, Inc., a supplier of precision motion control products and systems, opened a full-service subsidiary company in Tokyo this spring, the company announced. The new company—Aerotech KK—will be managed by Tadashi Imai, and will provide application engineering, sales and customer service for the Japan market, as well as for other Asian customers and sales partners. The company also has similar operations in Germany and the U.K.

Aerotech's new Tokyo facility.

Industrial Revenue Bond

ISSUED TO VAN ZEELAND MFG.

Wisconsin Governor Jim Doyle announced a $1,211,250 Industrial Revenue Bond allocation to Van Zeeland Manufacturing, Inc. of Little Chute, Wisconsin. The company manufactures power transmission products that include sprockets, gears and pulleys. The bond will help Van Zeeland construct and equip a planned 25,000-square-foot facility, expanding production capacity by 20 percent. The company's $4.1 million investment will create eight new jobs.

"One of the top priorities of my administration is to help move industries, companies and communities forward and ensure there are good, family-supporting jobs for our citizens," Doyle says. "I am pleased to help Van Zeeland Manufacturing,

continued

Inc. with an expansion project that brings jobs and investment to the area."

An Industrial Revenue Bond is a bond issued by local governments that is free of federal taxes. The proceeds of the bond are loaned to a new or expanding business for development projects, and the interest rate is generally below the going prime rate.

Sumitomo Machinery Corp. of America

PROMOTES NATIONAL SALES MANAGER, OPENS PLANT IN MEXICO

Matthew G. Roberson

Matthew G. Roberson has been promoted to national sales manager for Sumitomo Machinery Corporation of America (SMA). He will report to the CEO/President at the Chesapeake, VA headquarters. Roberson previously served as the regional vice president of sales in the Northeast USA, and he has over 20 years of experience in the power transmission industry.

"Matt possesses a passion for our business, loyalty to our company and employees and a leadership style that brings out commitment and enthusiasm by those fortunate to work directly with him," says Ronald J. Smith, CEO/President of SMA.

In other news from SMA, a new facility was opened on August 1 in Guadalajara, Mexico. The Guadalajara location is the third SMA plant in Mexico, including facilities in Monterrey and Mexico City. As the second largest city in Mexico, next to Mexico City, Guadalajara has a large industrial base with many local OEMs.

"The expansion into Guadalajara reflects part of SMA's long-term growth strategy for its Latin American operations," says Jim Solomon, vice president and CFO of SMA. "The establishment of this new facility allows Sumitomo to better serve its customers in the Guadalajara region of Mexico. We look forward to the opportunity to expand our relationship with existing customers in the area while increasing our market potential in the area."

Woodward Governor

ACQUIRES MPC PRODUCTS CORPORATION

MPC Products Corporation of Skokie, IL and Woodward Governor Company of Fort Collins, CO have reached a stock purchase agreement for Woodward to acquire MPC for a value near $383 million. MPC, which has been led by Joseph and Vincent Roberti for over 45 years, manufactures electro-mechanical motion control systems, mostly for aerospace applications. With net sales of $195 million for its last fiscal year, MPC will become a wholly-owned subsidiary of Woodward upon completion of the sale.

"We anticipate that, together, Woodward and MPC will deliver substantial benefits through an improved focus on aerospace energy control solutions. MPC's actuation, motor, sensor and electronic capabilities complement our fluid energy and motion control technologies and will improve our systems' offerings," says Tom Gendron, chairman and CEO of Woodward. "We believe our global footprint will enhance MPC's business to achieve stronger growth going forward."

Woodward plans to form the basis of a fourth business segment with MPC, Airframe Systems, due to the nature of MPC's main product lines, which include electric motors and sensors, analog and digital control electronics, rotary and linear actuation systems and flight deck and fly-by-wire systems. Companies like Boeing, Bombardier, Raytheon and Lockheed Martin use MPC's products in commercial and military aerospace programs for applications such as critical flight-control, radar and electro-optical drives.

"Woodward is a very strong, active company," says Joan Roberti, a member of the MPC Board of Directors. "We feel the combination of MPC and Woodward will give both companies an opportunity for improved growth and expansion, and with Woodward's support, MPC can further improve its leadership role in the industry."

Got News?

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Thermal Power Helps Plumb Ocean's Depths

The ocean is full of secrets. Knowledge of its movement can help scientists and researchers predict when there's going to be a drought in California, excessive rainfall on the East Coast or when crops might not make it through a season in Africa. Since the 1970s, scientists have utilized autonomous underwater vehicles (AUVs) to study coastlines, currents and ocean circulation in order to get a better understanding of climate change, pollution and marine life.

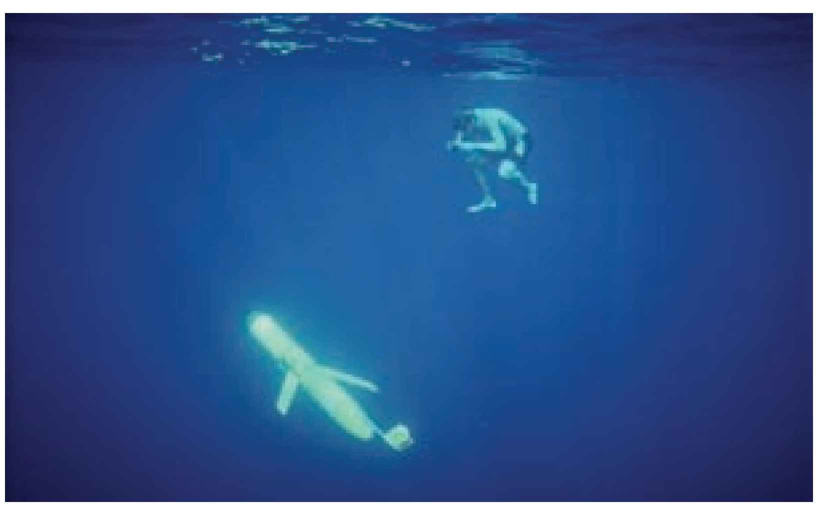
While most of these vehicles use battery-powered motors and mechanical pumps for power transmission, the Slocum thermal glider is the only one powered by the ocean itself. Named after Joshua Slocum, the first man to single-handedly sail around the world, these gliders have been used for military surveillance, oceanic research and underwater communication networks for organizations like the Woods Hole Oceanographic Institution (WHOI) and Rutgers University.

"Doug Webb retired from Woods Hole in 1982 and started Webb Research to better enable us to see into the world's oceans," says Clayton Jones, senior director at Teledyne Webb Research in Falmouth, Massachusetts. "In 1986, he sketched a drawing in his lab notebook for a thermal engine that harvests energy from the thermocline of the ocean."

Typically AUVs are motorized, propeller-driven vehicles that can only be counted on for short, aquatic trips. The Slocum gliders can endure months of rigorous testing. So much so, that the team at Teledyne Webb would eventually like to see a thermal glider travel uninterrupted around the world.

"In the early days, people didn't believe a thermal glider could work," Jones says. "Today, you might find a fleet of gliders moving through a hurricane or typhoon in a coordinated fashion."

WHOI scientist Dave Fratantoni and postdoctoral scholar Benjamin Hodges prepare to lower the thermal glider into the ocean in December 2007.



David Sutherland, a student in the Physical Oceanography Department, joins an ascending glider during a test run in the Bahamas.

In order to move through the ocean, the Slocum thermal glider relies on thermal stratification between warm and cold water temperatures. According to Jones, as the glider dives to 1,200 m, a wax-like substance freezes, making room for some oil in a flexible tube. At the inflection depth, the glider uses the accumulator-stored oil to change buoyancy and begin to rise back to warmer waters. The wax then thaws and expands, forcing the oil in the flexible tube back into the accumulator for the next dive cycle.

Slocum gliders follow a saw-tooth pattern, surfacing once in awhile in order for the data to be sent by satellite feed back to the lab. "The glider is really just a data truck," Jones says. "We're building and designing the equipment so science institutions and universities can go out there and conduct the necessary fieldwork."

Rutgers, for example, is currently "flying" a glider non-stop across the Atlantic. Jones notes that technology allows anyone with a computer to track its progress. "This moves away from traditional science as the information is available to the public in real time," Jones says. "It used to take weeks or months to get the information and write the technical papers. Technology has changed the way we look at the ocean."

With 120 gliders delivered to more than 13 countries and 40 different organizations, it seems the thermal glider sketch in Doug Webb's notebook in 1986 paved the way for some interesting innovations in oceanic research.

"Doug dreams up the ideas," Jones says, "and it's my job to help whittle them down into some form of reality and get them into the water."

For more information on the Slocum glider, visit *www.webbresearch.com*. To view the active deployments at Rutgers University, visit *www.marine.rutgers.edu/cool/auvs*.