December 2010

PTE

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Motion Control for Medical Devices

- Custom Motors for a Surgical System
- Pumping Out the Jams—With Sensors

Technical Articles

- Motor Drive Technology—What's Next?
- Actuators for Ambient and Cryo Apps

Power Play

The Copenhagen Wheel

Motors Motors Motors

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MARATHON ELECTRIC

IRONHORSE

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2 hp, 180V	$335.00	$2,242.00	$1,217.00	$2,301.00

www.automationdirect.com/motors

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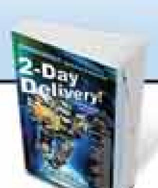

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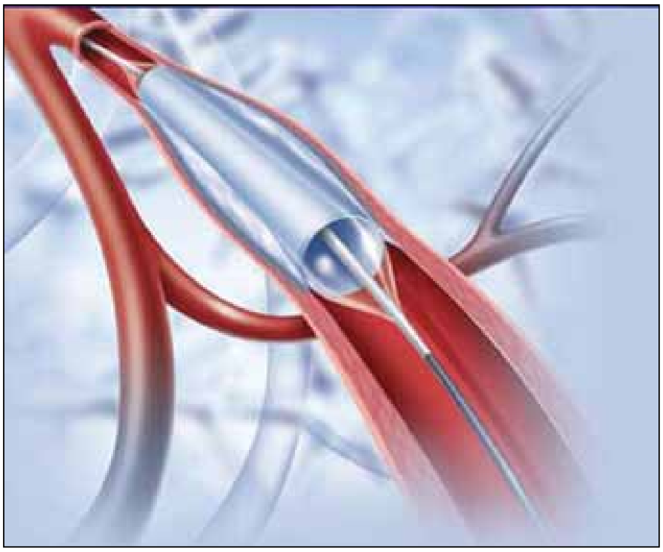

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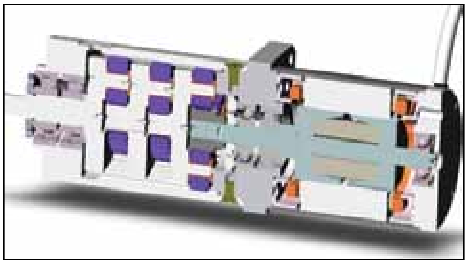

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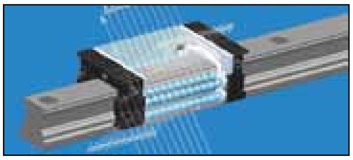

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There are moments in life
when even business takes a back seat…

*On behalf of all the folks at **Forest City Gear**, we wish you a very Merry Christmas and happy holiday season. It's during this special time of year, as we reflect on family and friends, when we're most thankful for the blessings we've received. Sometimes, especially in the tough economy we've experienced this year, it's good to pause and just say thank you to all our business associates. We really appreciate your business and the continued confidence you place in our abilities.*

Wendy Young   *Fred Young*

FOREST CITY GEAR

11715 Main Street, Roscoe, IL 61073 815-623-2168

PTE powertransmissionengineering®

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Photo courtesy of Stafford Manufacturing Corp.

Wear-Resistant Coating

INCREASES RELIABILITY OF HIGH-OUTPUT, HYBRID AND STOP-START ENGINES

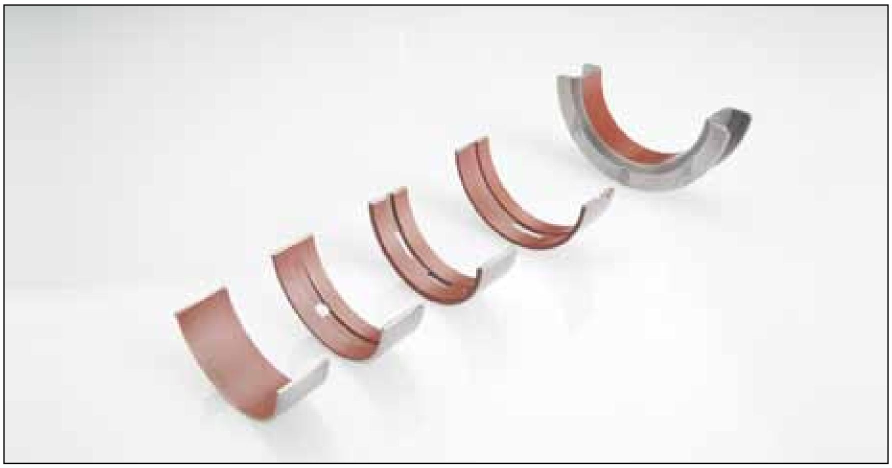
The IROX bearing overlay can increase the life of bearing shells and crankshafts in extreme applications (courtesy of Federal-Mogul).

Federal-Mogul Corporation has expanded the performance capabilities of engine bearings by developing a polymer coated bearing shell that can reduce fuel consumption and CO_2 emissions by withstanding mechanical loads produced by heavily boosted engines. IROX addresses the lubrication challenges associated with frequent engine re-starts found in hybrid and other future stop-start engines by protecting both the crankshaft and the bearing shells from damage where metal-to-metal contact would otherwise occur.

It is estimated that the IROX bearing overlay can help increase the life of crankshafts and bearing shells by more than five times in more extreme applications, such as direct-injected engines and engines with stop-start systems, according to the company.

"In order to meet the demands of hybrid and other start/stop engines, we wanted to come up with a wear resistant material," says Bob Sturk, chief application engineer for bearings at Federal-Mogul. "This has been a real problem in our industry—finding substitutes for lead materials because each material on the market has its own limitations. IROX gives our customers a better option. It enables them to do more with their engines."

"The drive for increased engine efficiency is placing demands on crankshaft bearings that require new designs and materials applications," adds Michel Prefot, Federal-Mogul's vice president, technology and innovation, bearings. "Satisfactory lubrication requires an adequate oil film between the bearing shell and the crankshaft to keep the surfaces apart. Efforts to reduce fuel consumption and CO_2 output are pushing engine design towards reducing oil film thickness and significantly increasing the number of starts, which is where bearings are most vulnerable. IROX technology overcomes many of the most challenging wear-related issues that will be faced by a majority of new generation engines."



IROX offers good sliding and anti-wear properties along with higher fatigue properties to enhance performance (courtesy of Federal-Mogul).

As engines are downsized but maintain their output through turbo-charging, the specific loads on the bearings increase. When hybrids operate in electric mode or when drivetrains using stop-start strategies switch off the engine, the crankshaft speed drops to zero. Without rotation, the crankshaft settles into contact with the bearing shells and the oil pump stops providing lubrication, allowing metal-to-metal contact and causing wear when the engine restarts.

The lubrication conditions at startup are very different from those that exist during high-speed, high-load operation. While solid lubricants or dry bearing materials are effective at preventing metal-to-metal contact at low running speeds, these conventional solutions are not suited to higher speeds that require journal bearings with a generous lubricant supply. Federal-Mogul's new system combines the features of both of these established technologies by introducing a polymer coating for traditional metallic bearing shells, integrated with solid lubricants and wear inhibitors to produce a production-ready solution. Extensive development has led to the identification and optimization of a number of key parameters, such as layer thicknesses, substrate material specification, resin binder properties, curing conditions and functional additive specifications, and a number of patents on the technology.

"Basically, we borrowed technologies from many of our other products for IROX," Sturk says. "The coating offers very good sliding and anti-wear properties, but there was also a benefit we didn't originally see coming; we were able to get higher fatigue properties to enhance the performance."

The IROX bearings have an overlay that is a polyamide-imide (PAI) polymer resin binder containing a number of additives dispersed throughout the matrix. These additives provide a variety of properties to the finished coating, such as wear resistance, mechanical strength, thermal conductivity and embeddability (the ability to safely envelop loose abrasive particles).

Test results have shown an improvement in life compared to both conventional shell materials and state-of-the-art competitors. "Typical bearings with aluminum overlays show significant wear after 100,000 stop-start cycles," Prefot says. "However, the new generation of engine systems require 250,000 to 300,000 cycles, so the durability challenge has been raised. Bearings with the IROX overlay can meet the demands of repeated starting; in comparison tests where conventional aluminum overlays showed 100 microns of wear and lead-free bronze showed up to 50 microns, our shells still looked like new with a measurable wear of just a few microns."

Another advantage of the new Federal-Mogul bearings is improved conformability, which has the effect of increasing the bearing surface area and hence increasing the load capacity. This means specific loading can be increased through the use of boosting, and low viscosity oils can be used by vehicle manufacturers (to improve fuel economy) without increasing risk of engine seizure, both important benefits in the development of low emission engines.

Because of IROX bearing overlay durability, vehicle manufacturers also can now consider utilizing cost-effective nodular iron crankshafts, thus mitigating the need for an expensive, forged steel crank. This compatibility also eliminates the need for hardening of the pins and journals on the crankshafts. As vehicle manufacturers struggle to offset the cost burden of increasingly sophisticated engine systems such as turbo-charging and direct injection, any reduction in base component specification is welcome.

IROX-overlay bearings are the latest addition to Federal-Mogul's portfolio of lead-free bearings products. "The IROX bearing overlay is an excellent example of how we're continuing to strengthen our position as the world's leading engine and transmission bearings manufacturer," says Gerard Chochoy, senior vice president, powertrain sealing and bearings. "We see excellent opportunities to displace conventional

continued

bearings in many automotive and other applications with the IROX overlay."

"Increasing fuel economy and reducing CO_2 emissions, while meeting the durability challenge of start-stop and hybrid applications, supports the trend of highly-loaded downsized engines while enabling the use of more cost-effective crankshaft materials," adds Prefot.

Pilot manufacture of the new shells has been underway since 2005, and full-scale production is scheduled for the first quarter of 2011. "The customer response has been unbelievable," Sturk says. "IROX enables them to do more with their engines, allowing our customers to get more power out of smaller parts."

For more information:

Federal-Mogul Corporation
26555 Northwestern Highway
Southfield, Michigan 48033
Phone: (248) 354-7700
www.federalmogul.com

Excel Gear

LAUNCHES GEAR/GEARBOX OPTIMIZATION SOFTWARE

Excel-Lent gear/gearbox design and analysis software has been developed by Excel Gear, Inc. and written in *Visual Basic .Net*. This software has been written by engineers who also design and manufacture gears for their own use, according to company president N.K. "Chinn" Chinnusamy. "Although commercial software has long been available in the gear industry, it has been too expensive or too complicated to be used by engineers without specialized gear design knowledge. Our software is specifically designed with a user-friendly interactive input screen providing defaults and options in accordance with the AGMA 2001 standard," Chinnusamy says.

The users of *Excel-Lent* can easily navigate through the input screens to edit, analyze and produce reports on the optimum gear and gearbox design for various industrial and other applications. "This software is not designed for any specific industry," continues Chinnusamy. "It can be used for machine tools, heavy materials handling equipment or even the wind turbine industry. For the wind turbine industry, for example, the designer needs a full understanding of all the operating loads on the gear members to arrive at the required power rating."

The key calculations performed are the AGMA power rating and load calculations, including bending strength geometry factor (J) and pitting resistance geometry factors (I). Output from the software is a single page of data printed in a format that is easy to read and interpret. Other commercial software typically prints five or six pages of information, which may be confusing to most design engineers unless they are gear experts, Chinnusamy further observed.

The users of *Excel-Lent* need not be familiar with AGMA standards to use this software. Those who are not gear engineers can also benefit from the gear engineering knowledge embedded in the software package.

Excel-Lent contains three sections—design, analysis and gear dimensions. Any of the sections can be used individually to run calculations. On a typical job, according to Excel Gear, hundreds of hours typically spent doing the calculations can be saved. The three sections are detailed below:

Design: This section calculates the size of gears, based on minimal input by the user. The user needs to specify only the input rotational speed, gear ratio, power to be transmitted and the material and heat treatments selected from the material tables of all commonly used materials in the industry. Key values calculated are the diameter and face width of the pinion required to achieve the surface fatigue power rating and optimized DP or module (based on the calculated diameter) required for the bending fatigue power rating. The data are automatically exported to the analysis program for detailed analysis. The results are the power ratings for 5,000–100,000 hours of B1 life (reliability factor of 1). If required, other values such as face width or center distance may be entered, but Excel Gear recommends leaving the face width and center distance values blank for optimized gear design. Design and analysis programs are used to design one gear stage in sequence on an external or internal spur and helical gear mesh.

Analysis: This program calculates the power rating of a gear set for 5,000, 10,000, 25,000, 50,000 and 100,000 hours of B1 life (reliability factor of 1). Reliability factor of 1, 1.25, or 1.5 can be selected, as required. The user needs to enter mesh type (spur, helical, internal and external), pressure angle, helix angle (if applicable), pinion speed, number of teeth in pinion and gear, material (from the list provided in the software), face width, DP or module and quality required. Crown and/or profile shift, if used, can also be entered. The program will calculate the power rating of the gear set and show hp or kW capability along with torque, tangential force and static capacity. Static capacity is based on yield strength and, if bending stress exceeds yield strength at any time, permanent deformation or even tooth breakage may occur. If the results are satisfactory, the user can print the single page results only or, optionally, also print all the AGMA factors used in making the calculations. *Excel-Lent* lists commonly used gear material for the user to select. If the results are not as required, the user can select another material or change other design criteria as required to achieve the desired results. If a special material is desired, its yield, bending and contact stress numbers can be easily entered. If any of the required input data are missing, the program will prompt the user to supply what is missing. Metric or inch units can also be selected with just one click.

Dimensions: *Excel-Lent* will calculate the manufacturing dimensions for a new pinion and gear or calculate the dimension of a pinion or gear to mate an existing pinion or gear. This can be done for external gears, internal gears or a gear rack. Users need only to enter the type of mesh (spur or helical, internal of external), pressure angle, helix angle (if helical gears), number of teeth in pinion and mating gear, DP or module and the quality of the gears. It will then calculate the center distance, dimension over pins, span measurement, form diameter, roll angles and all gear tolerances to match the quality required (AGMA, DIN, or ISO). The program will calculate the helix angle required to match a specified center distance if the user chooses that option.

The program displays plain English error messages when input is question-

continued

able or in error. For example, if the center distance is incorrect, the program will flash error messages such as, "Center distance specified is too large/small." The program calculates optimized profile shifts for pinion and gear operating at a non-standard center distance, if the operating center distance is specified. If the profile shift required to operate is large and makes the top land narrow, the program will flash warning messages and display the proper profile shift amount to avoid narrow top land. *Excel-Lent* further provides users the option to balance beam strength or specific sliding of gear and pinion, if desired. This is a key requirement for wind turbine gears. The program will also calculate gear blank tolerances to achieve the desired quality level, if shaft and bore diameters are entered.

For more information:

Excel Gear, Inc.
11865 Main Street
Roscoe, IL 61073
Phone: (815) 623-3414
Fax: (815) 623-3314
www.excelgear.com

B&R

ADDS PLANETARY GEARS TO SYNCHRONOUS AND STEPPER MOTOR LINE

B&R Industrial Automation recently announced the addition of precision planetary gears to its line of synchronous and stepper motors. The result is a high performance and economical drive program for all industrial fields that can be optimized to meet customers' needs and is provided from a single supplier. B&R developed a motor-gear building block principle together with German manufacturer Neugart. The planetary gears are delivered fully mounted on B&R's 8LSA, 8LVA, 8JSA and 80MP series motors. Gears in both straight and angled designs and with all conventional drive flange geometries were developed together with Neugart as the technology partner. The standard gears are single-stage for gear ratios of 3, 4, 5, 8 and 10 and have 8–15 arcmin backlash or less. The gears are also offered in two-stage or three-stage designs. At the top of the product line, the premium series provides backlash of less than 1 arcmin as an option paired with high-output torques.

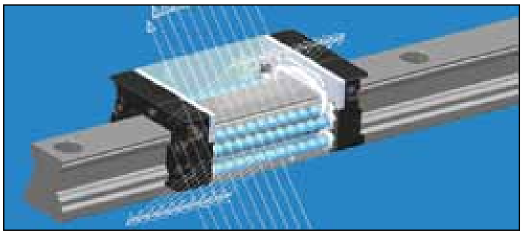
For more information:

B&R Industrial Automation
1250 Northmeadow Parkway S-100
Roswell, GA 30076
Phone: (770) 772-0400
www.br-automation.com

Rexroth

DELIVERS HIGH-PRECISION BALL RAIL SYSTEM

The highly optimized High-Precision Ball Rail linear guide system from Bosch Rexroth Corporation reduces rolling, pitching and yawing deviations in linear guideways due to ball recirculation. The result is smooth motion with virtually no deviation in the X, Y, or Z direction. The system is suitable for high-end machining, measuring and scanning devices requiring ultra-precise movement. The precision performance is achieved via technological enhancements to the bearing raceway geometry to minimize ball pulsations and reduce the influence of guideway bolts on the running smoothness of the runner block. Rexroth now includes High-Precision Ball Rail technology as a standard in SP and UP accuracies as well as the completely new XP accuracy class. The blocks can be run on standard Rexroth rails, or for additional accuracy and smoothness, on special high-precision rails. The High-Precision Ball



Rail System is available in preloaded sizes 15–45, with or without ball chain technology. Single-piece rail lengths up to six meters are available.

For more information:

Bosch Rexroth
5150 Prairie Stone Parkway
Hoffman Estates, IL 60192
Phone: (847) 645-3600
www.boschrexroth-us.com

Stafford

RELEASES DUAL-KEYED COUPLINGS

A new line of large bore couplings was recently introduced by Stafford Manufacturing Corp. Stafford

continued

Dual-Keyed couplings feature axial and annular keyways to transmit torque while restraining lateral motion in pumps and mixers that are driven by unsupported shafts. Offered in 1" to 5" I.D sizes, the keyways are machined to customer specifications. Available in steel, stainless steel, or aluminum, Stafford Dual-Keyed couplings come with straight- or stepped bores to join dissimilar shafts. Stafford Dual-Keyed couplings are priced according to material, size, and quantity. Price quotations are provided upon request.

For more information:

Stafford Manufacturing Corp.
256 Andover Street
Wilmington, MA 01887
Phone: (978) 657-8000
www.staffordmfg.com

PI Components

AVAILABLE FOR BIO-MEDICAL APPLICATIONS

Physik Instrumente (PI) recently exhibited its latest piezo motors, piezo positioners and six-axis hexapod robots at the Medical Design and Manufacturing (MDM) show in October. Due to their low power requirements, compactness, fast response and nonmagnetic features, these products are typically found in a wide variety of medical device applications. Piezo ceramics can be used in applications from nebulizers to positioning devices in MRI machines. The advantages of piezo motors and actuators over classical motion control components include sterile/high bake out temperatures, no lubrication required, lower power consumption, vacuum compatible, faster response and direct linear motion without conversion losses. PI features motors for micro liquid dispensing; ceramics for pumps, nebulizers and atomizers; non-magnetic piezo motors for imaging/OCT, MRI; scanning stages for bio-research microscopy and hexapod robots for computer-aided surgery.

For more information:

Physik Instrumente (PI)
16 Albert St.
Auburn, MA 01501
Phone: (508) 832-3456
www.pi-usa.us

igus

RELEASES HYBRID BEARING CONCEPT

The word ‘hybrid’ is used in engineering to describe a system where two technologies are combined together. Igus has now achieved this with a completely new type of cost-effective hybrid linear bearing that both rolls and slides. The new hybrid bearing, DryLin WJRM, was developed with the goal of reducing driving force, especially in applications involving the manual adjustment of machine-guard doors, partitions and adjustable locks, or for light handling tasks. For this purpose, igus took the advantages unique to sliding and rolling movements and combined them.

A self-lubricating, plastic, sliding sleeve bearing ensures the hybrid linear system is robust, dirt- and moisture-resistant, lightweight and low cost. Meanwhile, a maintenance-free polymer roller brings ease of use to applications where heavy machine doors up to 110 pounds have to be adjusted manually. The required driving force is reduced by a factor of four to five due to this roller bearing, which carries the main load. This makes manual operation much easier. The new hybrid bearing is the latest extension to the DryLin W linear guide range from igus. The extremely compact system was modeled by igus’ design engineers in such a way that the rollers fit inside the linear profile without increasing height, which remains at a low profile of 0.71 inches (18 mm). Standard linear guide profiles can be used, which are available in three styles for shaft diameters of 0.39 (10 mm): as individual rails for more flexibility and as double rails for fast installation without time-consuming alignment. The latter comes with a distance between rails of 1.57 inches (40 mm) or 3.15 inches (80 mm). The hybrid bearing housing is made from blue-chromed die-cast zinc. DryLin W is a flexible, modular linear guide system made from hard-anodized aluminum profiles, die-cast zinc housings, stainless steel or aluminum and plastic plain bearing materials. The wide variety of different combinations within this easy-to-install system allows users to optimize available design space.

DryLin W linear guides work without lubrication as dry-running systems and do not require maintenance during operation. They use plastic liners made from iglide J or iglide J200, both of which are low wear and have a very low coefficient of friction. They are also chemical resistant, vibration damping and moisture resistant.

For more information:

igus Inc.
PO Box 14349
East Providence, RI 02914
Phone: (401) 438-2200
www.igus.com

SplineRail Linear Actuator

SIMPLIFIES DRIVE AND GUIDANCE

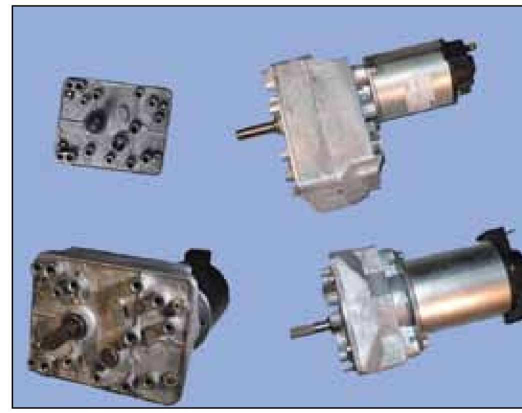
Haydon Kerk Motion Solutions, Inc., a manufacturer of engineered linear motion products, recently introduced the SAA06 Motorized SplineRail Linear Actuator. Linear motion has traditionally required separate components to handle both drive and guidance. The compact SplineRail simplifies this by combining both functions in a single, coaxial component. The Motorized SplineRail utilizes a Kerk precision rolled lead screw, supported by bearings and contained within a concentric aluminum spline, driving an integrated Kerkite composite polymer nut/bushing. The extruded aluminum spline offers excellent torsional stability. KerKote TFE coating and self-lubricating Kerkite nut/bushing material ensure long life and zero maintenance. The motorized version of the SplineRail uses the Haydon Size 17 single stack or double stack stepper motor. When mounted vertically, the SplineRail can also be used to simultaneously lift and rotate (Z-theta motion). With one motor driving the screw and a second rotating the rail, a compact, self-supporting pick and place mechanism can be created. Screw leads are available from 0.05" to 1.2" per revolution, providing a wide range of performance profiles, including self-locking threads that can support a load without external power or breaks. Typical applications include pick-and-place mechanisms and robotic assemblies in life sciences instrumentation, semiconductor equipment, business machines, packaging and assembly, and a wide range of factory automation applications. Combined with Haydon Kerk's offering of motion control components, the Motorized SplineRail can be used to create custom systems for many types of motion.

For more information:

Haydon Kerk Motion Solutions, Inc.
1500 Meriden Road
Waterbury, CT 06705
Phone: (203) 756-7441
www.haydonkerk.com

Crouzet

INTRODUCES SECOND GENERATION GEARBOXES



Crouzet North America, a company of Custom Sensors & Technologies, has introduced the new GDR1 and GDR2 Gearbox Series featuring quiet operation, versatile mounting and high torque. The new gearbox line is suitable for a variety of medical, commercial and industrial automation applications where smooth performance and continuous duty capability are required. The GDR1 and GDR2 gearboxes feature gear ratios from 25:1 up to 650:1, continuous torques up to 6 Nm, and speeds ranging from 4 to 100 rpm. Heavy-duty metal housings provide optimum durability and robust operation. Frame sizes measure 64.1 mm (2.52") wide x 81.6 mm (3.21") long, with thicknesses of 65 mm (2.56") for the GDR2 and 35 mm (1.38") for the GDR1. The new series is designed with several mounting holes and additional mounting plates for easy adaptability and mounting. The new gearboxes interface with Crouzet's line of DC brush, DC brushless and AC asynchronous motors. DC brush motors are available with 12, 24 and 48-96 volt windings while DC brushless motors feature 9-56 volt windings. AC asynchronous motors are available in up to 40 watts with winding options from 24, 115 and 220 volts at 50 or 60 Hz. Crouzet's Custom Adaptation

continued

Center can customize products to meet specific application requirements, such as adding custom shafts or connectors. Gearboxes can be supplied with flying leads, cables and connectors to suit individual requirements and are RoHS compliant. DC motors can also be supplied with encoders and EMI filters. "Crouzet's new GDR1 and GDR2 provide an excellent value for a midrange gear motor," says Jim McNamara, Crouzet application engineer. "Customers are finding that the new gearboxes provide a quieter and smoother performance than others on the market," he adds. "With this product addition, Crouzet has increased our spur gearbox torque range by 20 percent."

For more information:

Crouzet North America,
2470 Coral Street, Bldg. D
Vista, CA 92081
Phone: (760) 597-6322;
Fax: (760) 597-6320;
mcnamaj@us.crouzet.com
www.crouzet.com

Brushless DC Servo Motors

EXPAND CAPABILITIES

The BX4 family of brushless DC servo motors from Faulhaber recently welcomed a new member. With a 22 mm module, the 2232/2250 BX4 CSD/CCD is the world's smallest brushless motor with integrated motion controller in uniform-diameter construction, according to the company. It combines all the advantages of BX4 technology in a tiny package: long service life, high non-cogging torque and freedom from adhesives. This makes them suitable for use in demanding application areas such as robotics, automation, medical technology, specialty machinery and the aerospace industry. The drives are based on Faulhaber motion control systems. With their compact, uniform-diameter construction and suitable gearing combinations, they provide the drive solution for a wide variety of applications. The drives have serial RS232 or CAN interfaces and can be configured using *Faulhaber Motion Manager 4.4* software.

Additional features of the new drives further expand their scope of use: a wide temperature range of –25 to +85 degrees C, thermally allowable continuous current up to 0.69 A, and a configurable speed in the range of five to 8000 rpm. The units are also available with customer-specific software on request. All products with integrated electronics have automatic peak and continuous current limitation to protect the motor and the electronics. Operation of the motor and the electronics from separate supply voltages is possible as an option. The new drives are available in two motor lengths (32 and 50 mm) with a rated voltage of 24 V DC.

For more information:

Faulhaber Worldwide
Distributed by Micromo
14881 Evergreen Avenue
Clearwater, FL 33762
Phone: (727) 572-0131
www.micromo.com

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no lubrication or maintenance
US 7,421,929 B2 patent granted, other patents pending worldwide
EXAMPLE
MGT planetary magnetic gear box

A Present State and Futuristic Vision

OF MOTOR DRIVE TECHNOLOGY

Mahesh Swamy and Tsuneo Kume

Management Summary

One of the driving forces behind the industrial revolution was the invention—more than a century ago—of the electric motor. Its widespread use for all kinds of mechanical motion has made life simpler and has ultimately aided the advancement of humankind.

And the advent of the inverter that facilitated speed and torque control of AC motors has propelled the use of electric motors to new realms that were inconceivable just a mere 30 years ago. Advances in power semiconductors—along with digital controls—have enabled realization of motor drives that are robust and can control position and speed to a high degree of precision. The use of AC motor drives has also resulted in energy savings and improved system efficiency.

This paper reviews the development and application of inverter technology to AC motor drives and presents a vision for motor drive technology.

Introduction

The electric motor control has advanced considerably in recent years. This can be attributed to significant progress in the field of power electronics enabled by unprecedented progress in semiconductor technology. The benefit of improvement in the motor drive industry has touched varied applications—from heavy and large industrial equipment, such as rolling mills in steel making plants, paper mills, etc.—to the mechatronics equipment used in machine tools and semiconductor fabrication machines. The AC motor controller is comprised of the induction motor controller and the permanent-magnet motor controller, both of which have played a key role in the overall progress of the motor drive industry. Figure 1 shows a current inverter (induction motor controller) and AC servo drives (permanent-magnet AC motor and their controllers). The controllers shown in Figure 1 employ the latest that industrial technology has to offer (Ref. 1) in power semiconductors, using the most advanced motor drive control algorithms in the form of vector control. Such controllers are ubiquitous in today's varied industrial and commercial applications. As the use of AC motor drives becomes more widespread, it is difficult to ignore an important fact—i.e., the electric power used by electromechanical energy conversion equipment, of which electric motors form the bulk, exceeds 70% of the total industrial electric power produced. Given that future residential applications will soon be using motor drives in, for example, washing machines and HVAC applications, it is important to concentrate R&D efforts on achieving higher efficiency and smaller-sized products that use less raw material, are less toxic to the environment, have a long MTBF (mean time between failures) and are easy to recycle.

The concepts, ideas and equipment used in the motor drives industry are easily applicable to harnessing energy from alternate sources, including solar and wind energy. It therefore is not surprising to find that power electronics play an important role in these applications. The motor drives industry can thus become a key player in solving the future energy crisis and simultaneously contribute significantly to environmental preservation.

AC Motor Drives

The present-day industry categorizes AC motor drives in two distinct categories: induction motor drives and permanent-magnet AC motor drives. The basic difference between the two types of drives is performance and cost. Induction motors are still the workhorse of today's industry. Applications that use induction motors may not need high-precision positioning and velocity control. Such applications typically use what is known in the industry as general-purpose AC motor drives. However, the machine tool, semiconductor manufacturing and other sophisticated industries require highly precise and controlled motion. Permanent-magnet motors are the motor of choice because of their smaller size, higher efficiency, lower inertia and therefore higher controllability. Such motors are grouped in the servo motor category, are controlled by permanent-magnet AC motor (PMAC) drives and are typically more expensive than their induction-motor counterparts.

General-purpose AC motor drives—V/f control. The power structure of the general-purpose AC motor drives is similar to the PMAC motor drives. Both of these drives are referred to as voltage source inverters, a term that will soon be clear. Since the power topology includes a large DC bus capacitor as a filter—and since it is the voltage that is modulated to provide variable voltage—variable frequency to the AC motor, such as an inverter topology, is called a voltage source inverter and forms the integral part of most present-day AC motor drives. A typical schematic of today's AC motor drive is shown in Figure 2.

The general-purpose AC motor drives typically provide constant flux into the induction motor. Since the motor flux is the ratio of the voltage to the frequency (V/f) applied to the motor, this ratio is held constant to achieve constant flux operation. The motor current increases almost linearly with load. Conveyor belts and other frictional loads require such profiles.

For centrifugal loads like fans and pumps, the flux in the motor can be altered to follow a square function. By doing this, the power consumed by the motor becomes a cubic function of speed ($P \propto f^3$) enabling significant energy savings. Even if the V/f is held constant in these types of applications, there is still significant energy savings compared to constant-speed drives, where relatively large losses are associated with valve or damper control. Thanks to the square-type torque characteristics of the load, a voltage reduction at lower speed range is possible that further improves efficiency. The resulting improvement in efficiency is so significant that even the member countries that ratified the Kyoto agreement in the year 2000 agreed to convert fans and pumps from being operated directly across the line to operation via AC motor drives to save energy and reduce the overall carbon footprint of a given plant. It is significant not only for those countries but for all people using centrifugal loads to convert the fixed-speed fans and pumps to variable speed.

High-performance AC motor drives—vector control. Though the majority of industrial applications require unsophisticated V/f control, there are quite a few that require higher performance. Such applications include machine tool spindle drives, paper-making machines, winders and pinch rolls in the iron and steel industries, elevators, top drives for oil drilling, winders/unwinders, pick-and-place operations, printing, rolling mills and other applications requiring high torque at low speed. Such performance was achievable in the past using DC motors—that are now being replaced by vector-controlled AC motors. The term "vector control" refers to techniques where the torque component of the input current is directed orthogonally to the magnetic field in the induction motor to result in optimal torque production. Such orientation-based control is called field-oriented control. Similar to a DC machine, it is now possible to independently control the field flux and motor torque to achieve high performance from AC motors.

The basic idea of field-oriented control is to transform the input time-varying current flowing into the motor from three-phase to time-varying, two-phase components called α and β components. These α and β components are then transformed into two axes (d-axis and q-axis) that rotate synchronously with the air-gap magnetic field of the motor, thereby making them stationary with respect to the rotating magnetic field of the AC motor (Fig. 3a). By maintaining the orthogonal relationship between the d-axis and q-axis components and by controlling the q-axis component, optimal torque is produced even at standstill condition. The transformation of the motor current from three-phase to d-q axis requires instantaneous position and speed of the rotor, which is achieved using pulse encoders mounted on the shaft of the AC motor.

There are two fundamental approaches to field-oriented control. They are:

- Direct field-oriented control
- Indirect field-oriented control (Ref. 2).

In the direct field-oriented control method, the posi-

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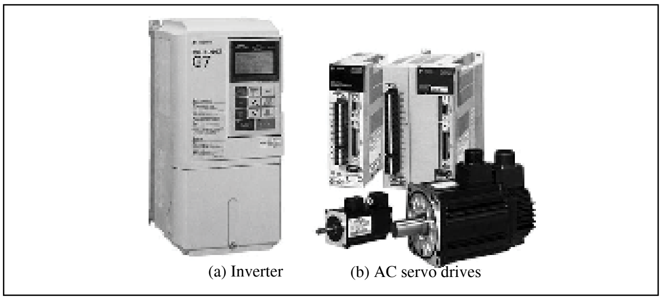

Figure 1—Typical AC motor drives: (a) three-level induction motor controller; (b) AC servo drives and servo motors.

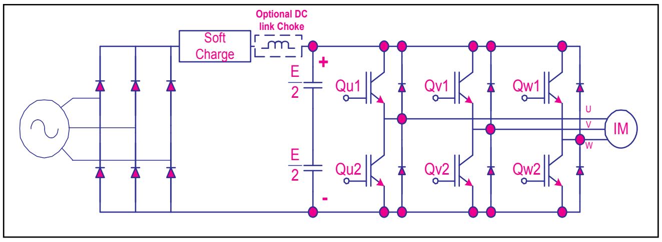

Figure 2—Schematic of a typical voltage-source, inverter-based AC motor drive.

tion and magnitude of the air-gap flux in the AC motor are derived from measurement of motor input voltage and current. The measured flux is compared with a steady reference flux and is fed into a flux regulator that forces the q-axis flux to go to zero to achieve complete decoupling between the two orthogonal axes. The d-axis value of the measured flux is also used to compute the measured electromechanical torque being produced by the motor, which is then compared with the reference torque. The torque regulator controls the torque-producing component of the current to achieve desired torque at desired speed. The angle information from

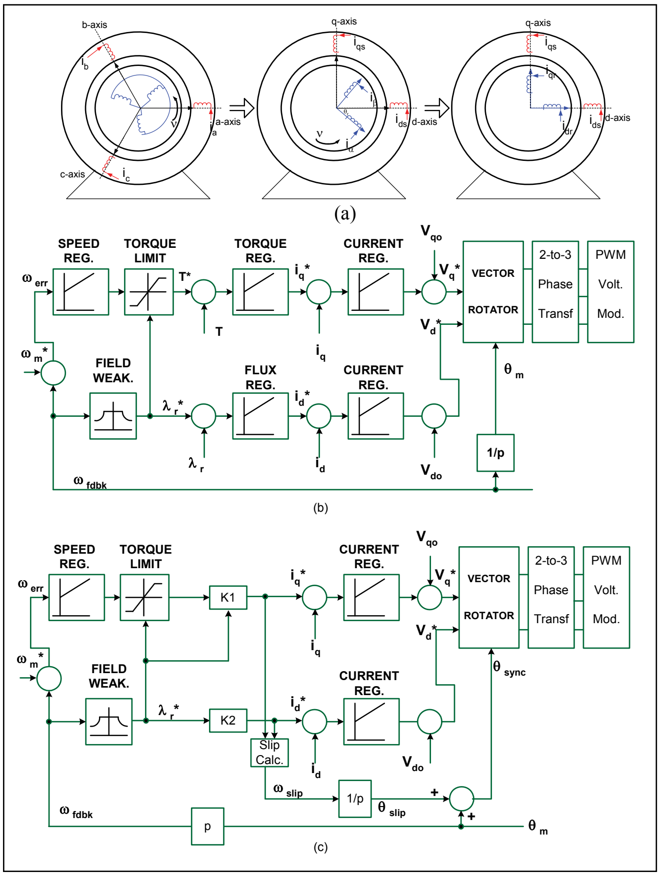

Figure 3—Schematic of typical induction motor control in modern AC drives: (a) three-phase to two-phase to two-axis transformation; (b) direct field-oriented control and (b) indirect field-oriented control.

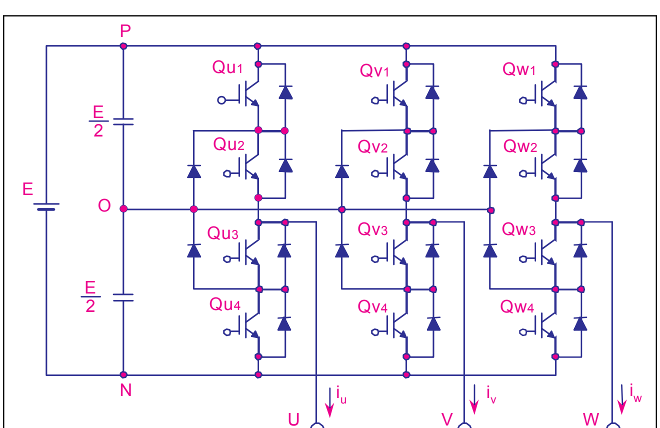

Figure 4—The neutral point clamped three-level inverter circuit topology.

the encoder is directly used to perform the transformation from three-phase to two-axis and vice-versa.

The control philosophy in the indirect field-oriented control is quite different from direct field-oriented control. Air-gap flux is not explicitly calculated in the case of indirect field-oriented control. The motor slip is calculated based on measured current parameters. The calculated slip is used to calculate the slip angle, which is then added to the angle information from the encoder to achieve the correct position of the air-gap flux. The newly estimated angle is used for the transformations so that the d-axis motor current is aligned correctly with the air gap flux to achieve high-performance torque control, even at standstill. This is clearly a significant advantage of the indirect field-oriented control over the direct field-oriented control. However, the calculation of the motor slip angle requires information about the rotor parameters that is sensitive to temperature and other operating conditions. This sensitivity is more pronounced in higher-power motors. At higher speeds, the resolution of the encoder and the computation time available for the microprocessor to compute the slip angle are typical limitations with the indirect field-oriented control method. This limitation does not exist with the direct field-oriented control method and/or the use of both types of this control—i.e., indirect field-oriented control for standstill and low-speed range, and direct field-oriented control for high-speed range is a classical way of modern control, given the fact that present-day microprocessors are robust enough to do computations for both methods and switch over, from one to the other, depending on the state of a flag that is settable based on motor speed. A typical schematic for the two types of control along with the concept of coordinate transformation is shown in Figure 3 (Ref. 2).

High-performance AC motor drives—sensorless control. In the control schemes discussed above and shown in Figure 3, the encoder feedback forms an integral part. Unfortunately, in many industrial applications there is fear that either the signal wires carrying the encoder signal could break or the encoder itself could be rendered inoperative due to a hostile environment like heat and humidity at the motor.

In other cases, the mounting of the encoder on the shaft may present an expense that the consumer is not prepared to bear. In either case, there is a need to achieve high performance from AC motors without the use of encoder signal.

The situation described above leads to a new breed of controllers called sensorless control. Some drive manufacturers call this type of control "open-loop control." The advent of sophisticated microprocessors with the capability of performing real-time, highly intense calculations has made this field of study very interesting and challenging.

Many researchers have worked on this topic, and it remains an important research and development discussion at many major motor drive manufacturers. Two methods are gaining popularity. They are:

- Using the motor itself as a sensor by injecting a high-frequency signal into the motor to reveal saliencies due to the slot and teeth of the stator structure
- Flux observer based on a machine model that is updated as the motor temperature changes

In the latter case, operation at zero input frequency is not possible, while the exploitation of motor saliencies to identify the rotor position has been shown to be effective in controlling the motor, even at zero input frequency (Ref. 3).

Realistically, zero shaft speed is adequate in many high-performance applications like winders and top drives, where the drill bit is typically tightened and loosened when the bit needs to be changed. Hence, the flux observer, employed in direct torque-controlled (DTC) drives is more than adequate for such applications. Other flux observers that use standard PWM techniques are also sufficient, provided the internal microprocessor used is fast enough to perform the needed calculations for the flux observer. Many researchers have worked in this area and quite a few motor drive manufacturers are introducing sophisticated sensorless algorithms that push the boundaries consistently.

Advances in Power Topology

Significant progress in semiconductor technology has facilitated higher switching frequency of PWM-based voltage source inverters—the workhorse of the modern-day AC motor drive. Carrier or switching frequencies in the range of 10-kHz to 15-kHz are quite common. This significantly contributes to improved controllability of voltage, current and torque. It also helps in the reduction of acoustic noise. However, high-speed switching of IGBTs increases high-frequency leakage currents, bearing currents and shaft voltage. It also contributes to voltage reflection issues that result in high voltage at the motor terminals, especially when the motor is at distances farther than 20 m from the drive. Researchers and engineers in the area of power electronics and AC motor drives have long recognized this and have developed many tools that are inserted between the drive and the motor to handle such application issues.

Three-level, neutral-point clamped inverter. Instead of adding a component between the drive and the motor, modifying the power topology to reduce the problems described above is a much more prudent approach. Yaskawa Electric Corporation was the first drive manufacturer to introduce a three-level drive structure for general-purpose, low-voltage applications (Ref. 4). The three-level drive topology employed by Yaskawa is called the neutral-point, clamped three-level inverter.

The neutral-point clamped (NPC) three-level inverter was first introduced by A. Nabae, I. Takahashi and H. Akagi in 1980 and published in 1981 (Ref. 5). With this circuit configuration, the voltage stress on its power switching devices is half that for the conventional two-level inverter (Fig. 2). Because of this, it was applied to medium- and high-voltage drives. Early applications included the steel industry and railroad traction areas in Europe (Refs. 6–7) and Japan (Ref. 8).

In addition to the capability to handle high voltage, the NPC inverter has favorable features—lower line-to-line and common-mode voltage steps; more frequent voltage steps in one carrier cycle; and lower ripple component in the output current for the same carrier frequency. These features lead to significant advantages for motor drives over the conventional two-level inverters in the form of lower stresses to the motor windings and bearings, less influence of noise to the adjacent equipment, etc. Combined with a sophisticated PWM strategy, it also makes it possible to improve the dynamic performance employing the dual observer method.

In order to benefit from the above features, general-purpose pulse-width-modulated (PWM) NPC inverters have been developed for low-voltage drive applications (Refs. 9–10). In this product, a unique technology is used to achieve balancing of the DC bus capacitor voltages (Ref. 11). Details are described in the following sections.

Figure 4 shows the circuit diagram of the NPC three-level inverter (Ref. 4). Each phase has four switching devices (IGBTs) connected in series. Taking phase U as an example, the circuit behaves in the following manner:

- When IGBTs QU1 and QU2 are turned on, output U is connected to the positive rail (P) of the DC bus.
- When QU2 and QU3 are on, it is connected to the mid-point (O) of the DC bus, and when QU3 and QU4 are on, it is connected to the negative rail (N).

Thus, the output can take three voltage values compared to two values for the conventional two-level topology. The relation between the switching states of IGBTs and the resulting output voltage with respect to the DC mid-point is summarized in Table 1.

DC bus capacitors need to be connected in series to get the mid-point that provides the zero voltage at the output. This is not a drawback since series connection of the DC capacitors is a common practice in general-purpose inverters rated at 400–480 V range due to the unavailability of high-voltage electrolytic capacitors. The current from the inverter bridge into the capacitor mid-point is the only new issue for this topology, and maintaining the voltage balance between the capacitors is important and influences the control strategy.

In order to illustrate the output voltage waveforms, consider PWM reference signal for phases U, V and W as:

$$e_U = A \sin (\omega t) \quad (1)$$

$$e_V = A \sin (\omega t - 120^\circ) \quad (2)$$

$$e_W = A \sin (\omega t - 240^\circ) \quad (3)$$

A is the modulation index. It is assumed that no third harmonic component is used to improve utilization of the DC bus voltage (Ref. 4).

Waveforms of the output voltages vary by the modulation index and the phase angle. To illustrate the behavior of the output voltage, let the modulation index *A* be equal to 1.0, meaning that full voltage command is applied, and let the phase angle ωt be 75° for phase U. This condition is shown in

continued

Table 1: Relation between switching-states and output voltage.

	Q_{u1}	Q_{u2}	Q_{u3}	Q_{u4}	V_u
Switching State	ON	ON	OFF	OFF	+E/2
	OFF	OFF	ON	ON	-E/2
	OFF	ON	ON	OFF	0

Figure 5, where the phase voltages in per-unit are expressed as:

$$e_U = 1.0 \sin 75^\circ = 0.966 \quad (4)$$

$$e_V = 1.0 \sin (75^\circ - 120^\circ) = -0.707 \quad (5)$$

$$e_W = 1.0 \sin (75^\circ - 240^\circ) = -0.259 \quad (6)$$

For the condition shown above, waveforms of the phase voltage with respect to the DC mid-point, the line-to-line voltage and the common-mode voltage are obtained for one

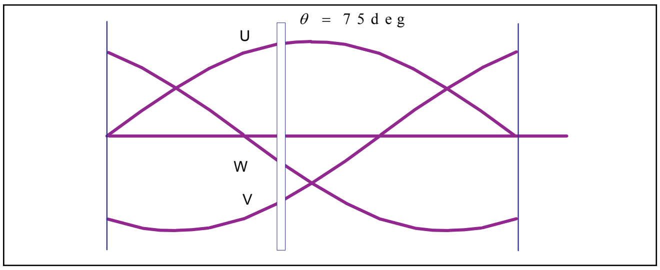

Figure 5—Phase angle chosen for waveform illustration.

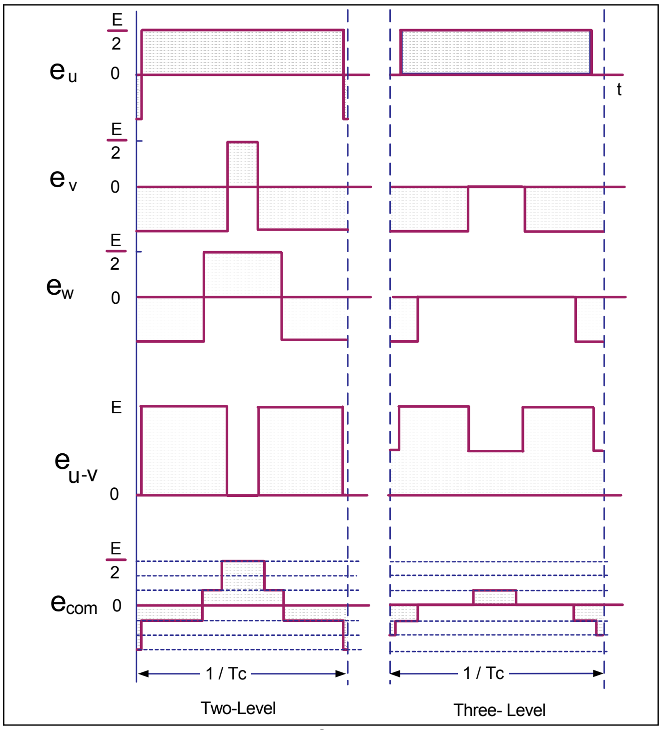

Figure 6—Voltage waveform comparison between two-level and three-level configurations.

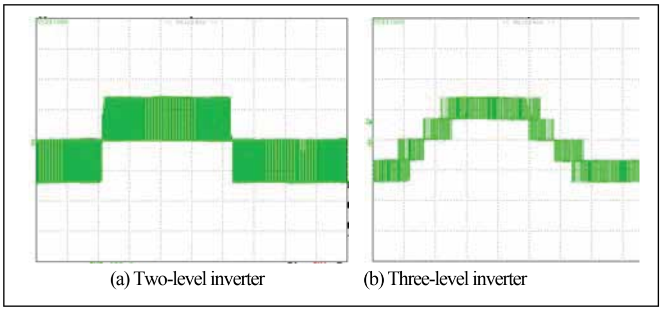

Figure 7—Measured line-to-line waveforms—V:500 V/div; T: 2 ms/div.

cycle of the PWM carrier signal, as shown in Figure 6.

In Figure 6, *Tc* is the period of the PWM carrier signal. Line-to-line voltage e_{u-v} is defined as:

$$e_{u-v} = e_u - e_v \quad (7)$$

It is the actual voltage applied to the motor terminals. Common-mode voltage e_{com} is defined as:

$$e_{com} = (e_u + e_v + e_w) / 3 \quad (8)$$

The common-mode voltage affects the leakage current, shaft voltage and bearing current.

Measured line-to-line voltage waveforms for two-level and three-level inverters are shown in Figure 7 and measured common-mode voltages are compared in Figure 8. The waveforms in Figures 7 and 8 are for a 460 V, 7.5 kW motor drive system. As shown in Figures 6–8, the three-level inverter has smaller voltage steps than the two-level inverter—in both the line-to–line and common-mode voltages. In addition, the common-mode voltage amplitude of the three-level is lower than that of the two-level in some phase angle ranges. These characteristics bring significant benefits to drive applications.

Features and Advantages of Three-Level Inverter

This section compares surge voltage at the motor terminals, leakage current, shaft voltage and bearing current for two-level and three-level inverters.

Current waveforms. First, the ripple current component in the three-level inverter is lower for the same PWM carrier frequency due to the smaller and more frequent voltage steps. In other words, the carrier frequency can be lower for the same current quality compared to the two-level inverter, thereby reducing switching losses in the IGBTs.

Surge voltage at motor terminal. When the cable between the inverter and motor is long, voltages at the motor terminals are higher than those at the inverter terminals due to the steep voltage transient and distributed inductance-capacitance combination of the cable. High voltage appearing across the motor terminals may damage the insulation material of the windings. A high rate of voltage change also creates irregular voltage distribution among winding turns, affecting the life of insulation material.

Since the voltage step of the three-level inverter is half that of two-level inverter, the peak voltage at the motor terminal is significantly lower than that of the two-level inverter. Waveforms in Figure 9 are based on the concept that the voltage can swing up to twice the input voltage when a step voltage is applied to an L-C resonant circuit. In Figure 9a, the overshoot magnitude of *E* is added to the original voltage *E*, making the peak value as high as 2*E*. In Figure 9b, the voltage jump is 0.5*E*, which is added to the original voltage of *E*, resulting in the peak value of 1.5*E*.

Figure 10 shows measured motor voltage waveforms when the cable is 100 m long. These waveforms clearly show the difference in the peak voltages. High-frequency ringing caused by the distributed parameters is also visible in these waveforms.

Leakage current. The high rate of the common-mode voltage causes leakage currents to flow from the conductors of the cable and motor windings to the ground through the parasitic capacitance in these components. This leakage current creates noise problems in equipment installed nearby the inverter. It is also strongly related to the EMI noise level.

Because of the smaller-voltage steps of the common-mode voltage, the leakage current of the three-level inverter is much smaller than that of the two-level version.

Figure 11 shows a significant reduction in the peak-leakage current level in the three-level case. The measurement was conducted with a 460 V, 7.5 kW motor and 100 m cable.

Shaft voltage, bearing current. Bearing damages of motors driven by inverters have been reported in cases where the shaft is not grounded. These problems are caused by the shaft voltage and bearing current created by the common-mode voltage and its sharp edges.

When the rotor of a motor is rotating with the bearings insulated by film grease, there exists capacitance between the rotor and the frame (ground). This capacitance is charged by the common-mode voltage through the capacitance between the stator winding and the rotor. Hence, the shape of the shaft voltage is similar to that of the common-mode voltage. Voltage edges of the shaft voltage cause current to flow through the bearing insulation. It leads to the breakdown of the insulation and discharge of the shaft voltage.

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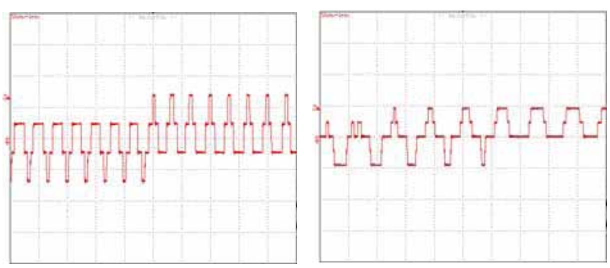
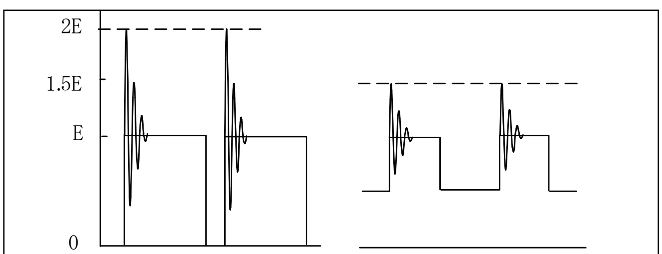

(a) Two-level inverter (b) Three-level inverter

Figure 8—Measured common-mode voltage waveforms—V: 250 V/div; T: 100 μs/div.



(a) Two-level (b) Three-level

Figure 9—Voltage overshoot at motor terminals.

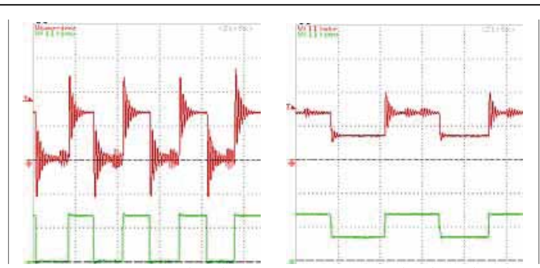

(a) Two-level (b)Three-level

Figure 10—Measured surge voltage at motor terminals—V: 500 V/div; T: 50 μs/div.

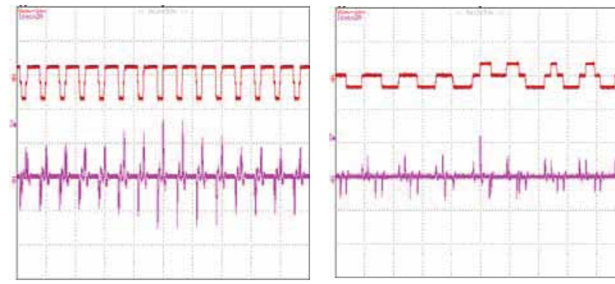
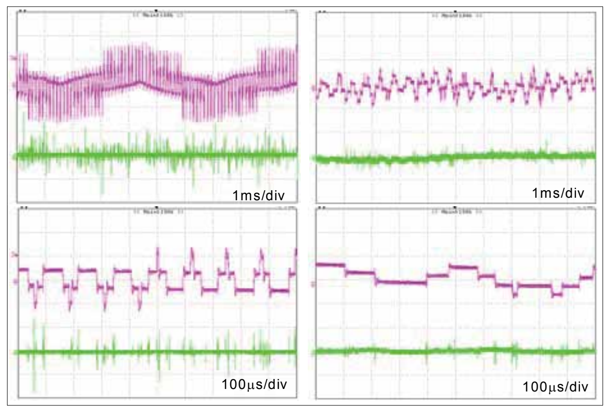

(a) Two-Level (b) Three-level

Figure 11—Leakage current—upper scale: common-mode voltage, 500 V/div; lower scale: leakage current, 2 A/div; T: 100 μs/div.



(a) Two-level (b) Three-level

Figure 12—Shaft voltage and bearing current—upper in each frame: shaft voltage, 10 V/div; lower in each frame: bearing current, 20 mA/div.

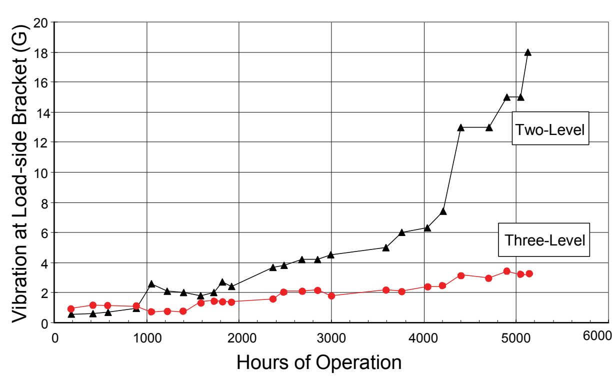


Figure 13—Result of bearing life tests—0.7 kW, 2,100 rpm.

Figure 14—Varispeed G7, 400 V, 1.5 kW.

Since the change of the common-mode voltage is smaller in the three-level inverter, it has a significant advantage over the two-level model with regards to shaft voltage and bearing currents. Figure 12 shows the test results of shaft voltage and bearing current for two-level and three-level inverters. In these tests, insulation material was inserted between the bearing and its housing to facilitate observation of bearing current.

Although Figure 12 shows that the bearing current in the three-level inverter case is significantly smaller, it is difficult to estimate the difference in the bearing lives. Actual long-period tests were conducted to verify the superiority of the three-level inverter. Figure 13 shows that the use of three-level topology can result in significantly longer bearing life.

Extreme conditions including temperature, type of grease and motor speed were employed to perform the bearing life test of Figure 13. It should be pointed out that in practice, the normal bearing life would be longer than that shown here.

Figure 14 shows a 400 V, 1.5 kW unit. The units from 18.5 kW up to 300 kW have as standard a built-in DC reactor. This reduces the input harmonic-current distortion. In addition, the units come equipped with a second rectifier bridge to facilitate twelve-pulse rectification. This can be achieved using a delta-delta-star isolation transformer for phase shifting. The input current THD can be reduced to about 12% using the twelve-pulse method.

The matrix converter. The voltage source PWM inverter has been established as the major controller of motor drive systems. However, it is associated with issues pertaining to the input side or the AC power system side as well as the output side or the motor side as described in the preceding sections. Typical problems in two-level voltage-source PWM inverters include the following:

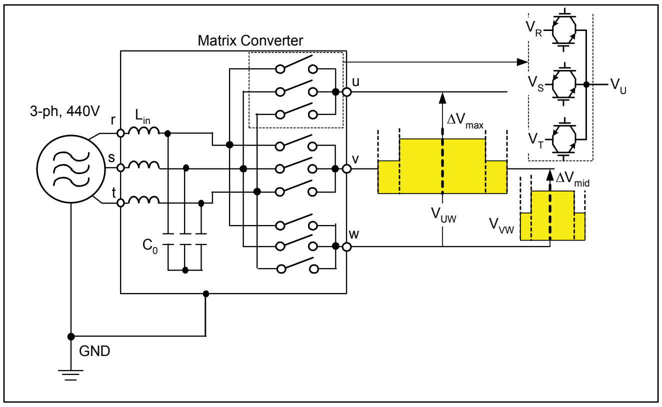


Figure 15—Schematic of a matrix converter with representative output line-to-line voltage patterns; sizes up to 22 kW use reverse-blocking IGBTs.

Table 2— Comparison: two-level inverter vs matrix converter		
Performance parameter	Two-level Inverter	Matrix Converter
Input Current THD	high	low
Common-mode voltage step	large	small
Common-mode current	high	low
Shaft voltage step	large	small
Bearing current	high	low

- High levels of input current harmonics that have an unfavorable influence on the electrical system
- Interference with other equipment due to large common-mode current, conducted and radiated EMI
- Potential for motor insulation failure caused by surge voltage at the motor end
- Premature bearing failure in motors due to shaft voltage and bearing current

In spite of the various advances made in addressing input and output power pollution caused by voltage-source PWM inverters, there remains a need for a converter that addresses both the input and output power pollution problems in an easier way, without the need for large, external, peripheral equipment. Such a drive would then be able to achieve an environmentally harmonious system. One converter topology that shows promise in realizing this goal is the matrix converter (MC) (Ref. 12).

The MC is a direct-frequency conversion device (AC-to-AC converter) that can generate variable magnitude/variable frequency output voltage from the AC utility line. It is fully regenerative and has sinusoidal input current with unity power factor. Figure 15 shows the basic topology of a matrix converter.

The concept of a matrix converter was first presented by Venturini (Ref. 13). Since then, it has always been topology that merited more attention. Lack of low-cost, high-performance semiconductors prevented the complete adoption of this topology. But owing to recent advances, it has been shown to be a very viable product. Yaskawa is one of the first companies to commercialize this product. Three-phase MC consists of genuine, bi-directional switches that allow PWM control of both input and output currents. It does not require the intermediate DC link and the associated large capacitive filter that is typical of voltage-source inverters.

In practical implementation, understanding commutation procedure from one switch to another is very important. The commutation of current between switches should adhere to the following two constraints:

- Avoid input line-to-line short circuit
- Avoid output open circuits

Several multi-step commutation strategies were introduced that adhere to the above two constraints (Ref. 14). The four-step commutation technique is perhaps the most popular and widely used. However, in all techniques, the applied gating signals and real turn on/off of the bi-directional switch are different because the real turn-on/off time of each switch is affected by the direction of the output current and the amplitude of the input voltage. Thus, during the commutation sequence, unwanted voltage distortion can occur in the output voltage of a matrix converter, similar to voltage distortion caused by dead-time between the upper and lower switches of a conventional voltage-source inverter.

Many researchers have worked on this topic and have proposed various reliable software/hardware implementation techniques (Ref. 15). In all techniques, the only possibility to deal with the distortion problem at low speed is to apply some means of compensation to accommodate for the loss of output voltage due to the delay in commutation.

The input to the matrix converter is an AC voltage source, while the load on the matrix converter is an induction motor that is inductive in nature. Since the current into the inductive load is switched from one phase to another, it can create interference and stress the input AC source. To prevent this, AC capacitors are used at the input of the matrix converter, which then absorb the switching ripple-current component. In order to prevent import of harmonics from external sources into the input capacitor, an inductor is used, the addition of which forms a low-pass input filter. The components of the input LC filter are chosen to filter the carrier frequency components of the matrix converter. The operation of the matrix converter in conjunction with the low-pass input LC filter results in a sinusoidal input AC current. The presence of an input LC filter provides a stable neutral point and facilitates further filter integration (Ref. 12). A summary of the advantages of a matrix converter over two-level voltage source inverter is given in Table 2.

The output phase voltage in a matrix converter has three levels, since it is constructed using the three available input phase voltages. Since the output voltage levels transit through the mid-level of the three available input voltages, the step change in the output voltage as well as in the common mode voltage is generally lower than in conventional two-level voltage source PWM inverters. The matrix converter exhibits lower-voltage step size in the common-mode voltage waveform, thus allowing easier filtering.

Figure 16 compares the common-mode voltage in a matrix converter with that in a conventional two-level inverter (Ref. 12). The common-mode voltage steps are much smaller in the matrix converter, resulting in potentially lower common-mode current, shaft voltage and bearing current. Integration of different filters to achieve a low noise drive that has lower ground current and a higher safety margin is the thrust of this paper.

From the explanations provided thus far on the operation of the matrix converter, it can be said that its performance is similar to that of a three-level inverter. Since the matrix converter is an inherently regenerative drive, it is fair to compare it with a back-to-back, three-level voltage-source inverter. Salient comparison points are:

- Matrix converter uses nine reverse-blocking semiconductor switching devices, while a comparable three-level, back-to-back voltage-source inverter employs 24 devices.
- A matrix converter does not need a smoothing DC bus capacitor and the associated soft-charge circuit.
- In the case of a back-to-back voltage-source inverter, two or three of the input phases are always connected together, resulting in large amplitude of the switching frequency component at the input terminals. In order to reduce its influence on the power system, large smoothing inductors along with some passive components are needed. In the case of a matrix converter, a given input phase is either connected to the motor or is left floating (turned-off). The switching frequency component amplitude that needs to be attenuated thus is much smaller and results in a much smaller input filter.
- The control scheme of a matrix converter is complex because of the absence of the DC bus capacitor that is instrumental in separating the front-end PWM rectifier from the motor-side inverter in the case of a voltage source inverter. However, recent progress in control concepts has reduced the severity

continued

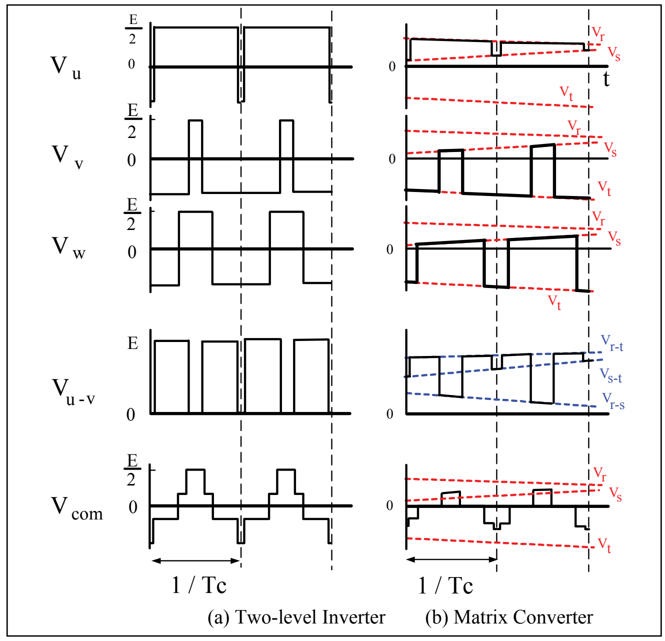


Figure 16—Common-mode voltage in two different types of motor controllers, both employing three-phase modulation.

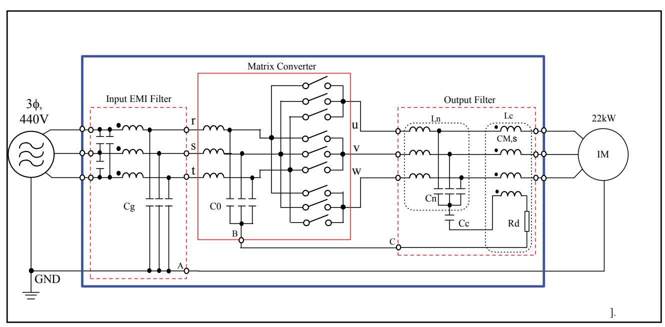


Figure 17—Schematic of a matrix converter with input and output filters to achieve environmentally harmonious drive system (Ref. 12).

Figure 18—400 V, 22 kW environmentally harmonious matrix converter.

of this drawback significantly.

Various additional filters that are required to achieve a low-noise motor drive system can be easily integrated with the matrix converter. Figure 17 shows a matrix converter with input- and output-filter configurations. In addition to the standard-input, low-pass LC filter, a small-sized input EMI filter is added to provide filtering for conducted EMI.

The output section consists of a normal-mode filter (NMF) to provide sinusoidal output voltage waveform at the motor terminals. A common-mode filter (CMF) is also employed at the output in order to attenuate the common-mode voltage and hence the common-mode current. Shaft voltage, which mimics the common-mode voltage, also reduces; this helps reduce the bearing current.

Figure 18 shows the actual unit of an environmentally harmonious power converter—a complete system that consists of the integrated filter and a matrix converter. The dimensions of the matrix converter integrated with the filters (Fig. 18) are: Width: 530 mm; Height: 700 mm; and Depth: 290 mm. An equivalent back-to-back voltage-source inverter with similar integrated filter would have occupied 37% more volume than the matrix converter.

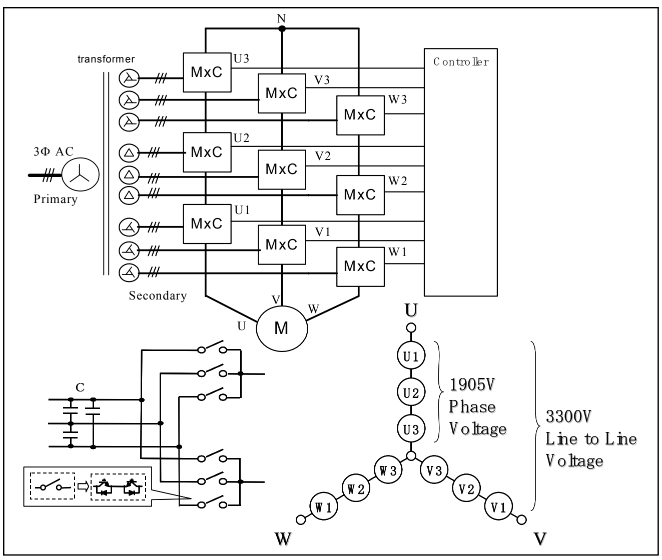


Figure 19—Schematic of medium-voltage matrix converter drive with its associated vector representation (Ref. 16).

(a) (b)

Figure 20—Developed "RoboPorter": (a) transporter for human; (b) automatic transporter for objects.

Medium-voltage matrix converter (Ref. 16). An interesting application of the matrix converter is its use in medium-voltage drives. Matrix converters can be used to create appropriate voltage on a cell-by-cell basis. By intelligently phase shifting the carrier of each cell and combining them in the motor winding, multi-step medium-voltage levels are achievable. By keeping the carrier frequency high enough, the phase-shifted carrier-voltage waveforms are seen to yield almost sinusoidal-output voltage waveforms. Engineers at Yaskawa Electric have developed one such method that has gained popularity. The scheme and its associated vector diagram are shown in Figure 19. The salient features of the medium-voltage matrix converter are:

- Four-quadrant operation
- Excellent input-current waveform because of multiple phase-shifting winding of input transformer
- Flexible design—
  * Three cells in series yields 3.3 kV, 200 to 3,000 kVA system
  * Six cells in series yields 6.6 kV, 200 to 6,000 kVA system
- Excellent output-voltage waveform due to multi-step configuration attainable by phase-shifting carrier frequency

Future of Motor Drives

The progress made by the power semiconductor industry starting from 1960s onward has directly influenced the progress of the motor drives industry. Following this direct link, one can confidently say that the research and experimentation are going on with newer switching semiconductors like GaAs (gallium arsenide), SiC (silicon carbide), and GaN (gallium nitride) devices will soon dominate the motor drives industry. Higher switching speeds at lower power loss will be achievable. Major changes to the cooling system are expected to revolutionize the motor drive industry.

SiC devices—advantages and challenges. A silicon carbide device can be operated at extremely high temperature without paying the penalty of increased losses and deteriorating performance typical of traditional silicon-based devices. SiC devices have been reported to operate easily at 150°C and higher. Some researchers have pushed it to operate even at 250°C (Ref. 17). Higher operating temperature definitely reduces the volume and cost of the cooling system. The other player in the SiC market is the PFC (Power Factor Correcting Equipment) industry. Most electronic gadgets use power supplies and by using SiC devices, the overall efficiency can be greatly improved. And because of its ability to operate at high frequencies and high temperature, the size of the cooling system can be greatly reduced. Higher operating frequency would mean smaller passive components that interact with the switch. The switch-mode power supply transformer can be reduced in size and the overall cost of equipment lowered.

In spite of the advantages that SiC devices provide, there are some important issues that still need to be addressed. First and foremost is the cost. The yield of defect-free parts is very low and the cost of the material itself is about 75% of the cost of the entire product for an SiC-based Schottky barrier diode (Ref. 17). This is much different from traditional Si-based devices, where the cost of the material is in the 10% to 20% range of the total product cost. The next important fact that needs to be addressed is the difficulty of achieving a stable oxide layer. This prevents its use as a controlled switch. MOSFETs and IGBTs need this oxide layer to control the bulk of the transistor. Since there have been manufacturing problems associated with the oxide layer, SiC-based IGBTs or MOSFETs are still being developed. However, JFETs and bipolar transistors (BJTs) do not need the oxide layer and there are some manufacturers that are planning to introduce JFETs and BJTs that use SiC devices. A typical amplification factor (β) of 20 is achievable in cases of power BJTs that use SiC devices (Ref. 18).

GaN devices—advantages and challenges. Gallium nitride (GaN) devices can withstand high voltages without showing degradation (Ref. 19). These devices have been shown to be able to be switched at high frequencies and high voltage—making them very attractive in power systems engineering and large-power motor drives. GaN has recently been grown on silicon-based wafers, both 4" and 6"type. This is a remarkable improvement because it reduces defects and allows widespread use in power electronics. Given the fact that the power density of GaN devices is typically six or more times that of Silicon devices, it a very promising high-power switching device. GaN devices can be operated at high temperature as well. Hence, prevailing opinion among researchers is that GaN devices may be better suited for both high-voltage and high-power applications. This holds promise for the power generation and distribution industry. And, the cost of GaN devices is not expected to be much more than that of currently used silicon-based power devices. This, too, is a positive point for GaN devices. But it is too early to understand how the devices will be adapted to power electronics and motor drives; GaN-based hetero-structure FETs are being developed, but mainly for the RF industry. It may take a few more years before the details are worked out for use in motor drives.

Though both SiC and GaN devices can be operated at high temperature and high frequencies, it is important to not forget that the ancillary circuits that are needed to turn these devices on and off also need to be able to handle the high-temperature environment. Hence, further progress in these areas needs to happen.

Permanent-magnet motor drives. Permanent-magnet (PM) motors are becoming very popular in many industrial applications, including elevators and pumps. The residential market will soon be using motor drives for sump pumps, well water, HVAC, etc. All these applications are ideally suited for PM motors. Many of these applications do not need tight control-of-position or servo-type performance. The main intention of using these motors in residential and other unsophisticated applications is primarily to reduce size and achieve higher efficiency. Most of these applications will require sensorless control capability. Drive manufacturers, including Yaskawa, have products that can operate PM motors in open-loop fashion (Ref. 20). To achieve acceptable performance, the motor parameters need to be known with a fair degree of accuracy. In the absence of such information the drives will need to be equipped with "auto-tune" features that are sophisticated enough to determine the needed values of d and q axis inductances, motor resistances, etc. Given the advances in microprocessors now used in general-purpose drives, this task is relatively easy. But the challenge is in performing such tasks without employing high-end processors. The future research is currently focused on such areas.

High-performance PM motor drives that use encoders can benefit immensely if similar performance is achievable without the use of encoders. The IPM (interior permanent-magnet) motor is better suited for sensorless control. A saliency-based, sensorless drive of an adequately designed IPM motor for a robot vehicle was demonstrated by Yaskawa at Kitakyushu international airport in April 2006 (Ref. 21). The motor is deliberately designed to meet the requirements of robot applications and lends itself more to saliency-based sensorless control. The speed and position of multiple-wheel motors are synchronously controlled by the drive amplifiers and a single motion controller over the speed range—from zero to maximum speed for the robot vehicle application. Two types of robot vehicles—one a two-wheeled differential drive, the other an omni-directional drive, were demonstrated to transport humans and objects. The sensorless technique used in the robot vehicles injects high-frequency signals into the motor to detect the initial magnetic pole position and then to track the poles as they rotate. The intended use is to help security personnel in airports, malls, etc., and also to assist in transporting bags within the airport premises. A photo of such a cart is shown in Figure 20 and the actual motor that is included within the wheel is shown in Figure 21. In the demonstration at Kitakyushu airport, the two-wheel differential drive type was human-driven, and the omni-directional drive type was automatically controlled on trajectory from a distance of 25 m. The absolute position of the robot could be corrected by the laser rangefinder attached to the robot (omni-direction drive). This was introduced as an afterthought because of the tire slippage on the polished surface of the airport and the need to achieve precise position information for transporting bags.

Linear motors. An efficient wafer-transportation technique is key to achieving higher throughput in the ever-growing semiconductor manufacturing industry. Automatic wafer-handling systems that reduce the risk of dust contamination invariably use linear motors. The modern semiconductor fabrication machines are large and require linear motors with relatively long stroke length to accomplish efficient wafer transportation.

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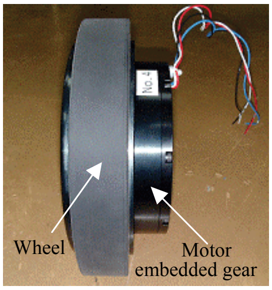

Figure 21—Photo of the proposed motor installed in wheel.

There are two types of permanent-magnet synchronous linear motors: a moving-magnet (MM) type and moving-coil (MC). The MM type has magnets on the moving table, whereas the MC type has windings on the moving table. In the moving-magnet type, the losses in the windings increase as the length of the stroke increases and so are not preferred for applications requiring long travel. On the other hand, in the moving-coil type linear motor system, there is a need for a large number of high-cost magnets that must be distributed all along the guiding track of the entire stoke length, making it an expensive system.

Recently, there have been some development activities in moving-magnet type, linear motor drive systems for use in long stroke applications. In one such development effort, the stationary body is divided into multiple sub-sections. Each section is driven by an independent (dedicated) servo-amplifier. In this configuration, the losses in the coil are reduced because only the section that provides thrust need be powered. However, the need for multiple dedicated servo-amplifiers makes the system expensive. In addition, there is need to have a total system controller that can coordinate the excitation of various sections, thereby making the system complicated and expensive.

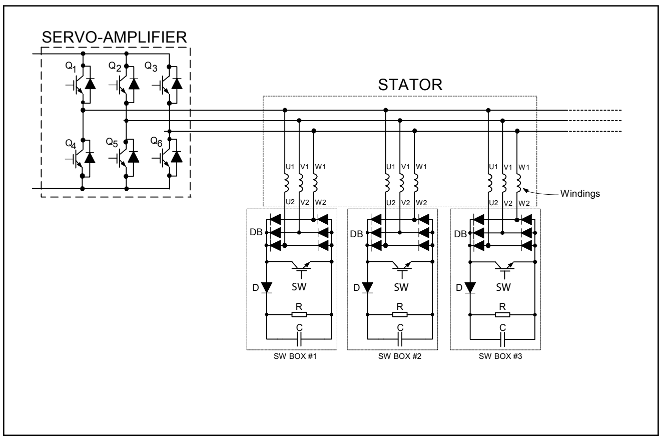

Figure 22—Circuit configuration for winding change technique.

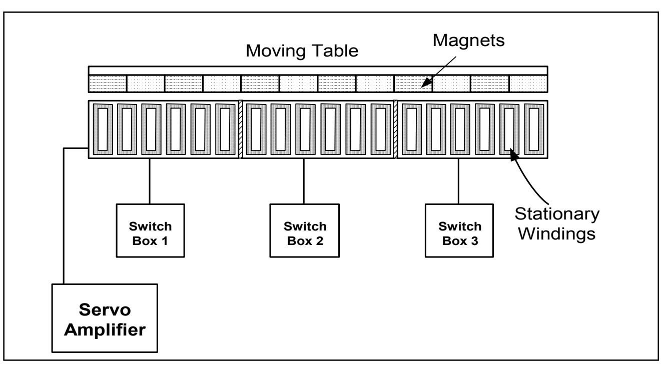

Figure 23—Structure of Yaskawa's moving-magnet-type linear motor.

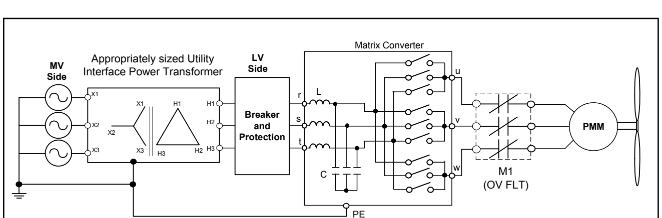

Figure 24—Schematic of possible use of a matrix converter in a wind turbine application.

Engineers at Yaskawa have developed a novel method that uses a moving-magnet-type linear motor for long stroke applications equipped with a method of electronic winding change used for rotating motors, shown in Figs. 22 and 23 (Ref. 22). This technique was also used to extend speed control range of induction motors and permanent-magnet motors (Ref. 23).

Segmented core structure is used by Yaskawa and others for fabricating the high performance servo motors. This improves the winding density and improves the space factor by at least 2 compared to traditional laminations. Further, the use of Neodymium-iron-boron (Ni-Fe-B) high performance magnets resulted in size and weight reduction of almost 25% and higher torque per amp capability.

The future of servo motors and drives is very bright. However, it is closely tied with the availability of higher performance rare-earth magnets that can operate at alleviated temperatures without deteriorating in performance. Cost of these rare-earth magnets is also important and typically the cost comes down when the usage increases. Higher-power motors typically adopt the buried interior permanent-magnet (IPM) structure because of higher mechanical stability compared to the surface permanent-magnet (SPM) structure. IPM motors up to 400 kW have already been developed and tested. These are primarily used in wind power applications and other high power pumping applications.

Renewable energy sources and power electronics. Power electronics plays a major role in the efficient conversion of mechanical energy to usable electrical energy when it is used in a wind turbine system. Advances in wind-turbine technology have made the wind energy a feasible alternative to the traditional coal and hydro energy. However, it is still more expensive than coal or hydro power. By connecting multiple wind turbines to a common grid, the efficiency of large scale production is achieved. Such facilities are called wind farms and they are gaining in popularity, due to the urgent need for environmentally friendly sources of energy.

The matrix converter may perhaps be an ideal drive for use in wind turbines. A permanent-magnet motor can be employed as the main generator, which would feed electrical energy to the matrix converter, which would then transform the voltage and channel the energy back to the electrical grid with little or no harmonic distortion. As mentioned earlier, large power permanent-magnet motors are available, and these can be used in conjunction with a matrix converter to connect to the grid.

Since wind turbines are not considered as emergency power supplies, the ride-through capability of PWM inverters with large DC link capacitors is not required in matrix converter based turbine systems. The speed range of such a system also does not have to be wide. Typically 20% speed range (around the base speed) is more than satisfactory for meeting the maximum energy capture requirement and for suppressing the turbulence due to wind gusts. Lower power permanent-magnet-matrix converter combination is also feasible and should be given serious thought. A possible arrangement is shown in Fig. 24. A transformer may be necessary to connect to the grid.

For MW power rated turbines, the matrix converter can be used in the rotor circuit of a doubly fed induction motor. This will enable a lower power matrix converter to be used for harnessing large amounts of wind energy. The three-level inverter would also be a good candidate for such an application.

Conclusions

In this paper, the present status of the motor drives industry is presented. All aspects of the motor drives industry have not been covered because the topic is too involved and too vast to be covered here. Salient products and their features have been discussed in broad terms. It is emphasized that providing an efficient means of converting electrical energy to mechanical motion may perhaps have the key to reducing our energy dependency. Alternately, efficient means of converting mechanical energy to electrical energy by the use of power electronics in wind turbines is another area in which humankind can benefit.

The challenge to present engineers and the motivation to future engineers lies in developing techniques, topologies and control methods that will result in more efficient conversion processes, both electrical energy to mechanical energy and vice versa.

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Medical Modifications

MAXON UPGRADES TISSUE REMOVAL SYSTEM FOR INTERLACE

Contributed by Maxon Precision Motors

Medical engineers are consistently looking for ways to provide devices to physicians that offer smaller incision requirements, a more accurate procedure and the opportunity for a quicker recovery. According to the Jones Institute of Reproductive Medicine at Eastern Virginia Medical School, located in Norfolk, Virginia, fibroids affect more than 30 percent of women in the United States. Uterine fibroids are noncancerous growths of the uterus that often appear during child-bearing years. The Mayo Clinic states that as many as three out of four women have uterine fibroids sometime during their lives, but most are unaware of them because they often cause no symptoms.

In the past, monopole loop electrodes that scraped tissue from uterine walls slowed and impacted the accuracy of these operations. For years, physicians requested that these devices be replaced with less intrusive equipment. Interlace Medical, located in Framingham, Massachusetts, in cooperation with its motor supplier, Maxon Precision Motors, recently came up with a solution.

The five-man engineering team at Interlace worked on their latest tissue removal system for about two and a half years. Fast turnaround of new devices is always a valuable asset for a company, but it's all about finding and implementing the right components for the results you're looking to achieve.

Interlace's MyoSure Tissue Removal System was designed to remove fibroids found on the uterine wall. The MyoSure device was designed to eliminate the challenges posed by the currently marketed devices. Since the design of the new system was performed largely in-house, the Interlace Medical team was able to get together regularly and go over the pros and cons in each design step. The team was also very sensitive about the way the device went together to hold down manufacturing costs, which could be passed along directly to the customer.

The challenge in developing the company's device was the need to upgrade the present method so that it was fast enough and accurate enough to compete. Interlace's first version used an autoclavable motor manufactured by Maxon. The device used a single motor mounted inside the handle, with all the electrical connections transferred through a tiny cable.

"Interlace contacted Maxon initially looking for a high-performance autoclavable motor, gearbox and control solution for their prototype design," says Joe Martino, northeast sales and applications engineer. After several design tests, the latest version of the MyoSure system had the motor housed inside the controller chassis instead of the probe, eliminating the need for an autoclavable motor. An integral rotary encoder is used for closed-loop control of the motor. Still, because the enclosure for the MyoSure had already been designed, the company had to find a compact motor with the highest performance per size that they could get.

The MyoSure operates from a foot pedal and only turns in one direction, which made motor selection easier. The RE40 motor used in the device is fitted with rare earth magnets to provide its high performance while maintaining a compact size. These motors use a patented rhombic moving coil design to deliver long life, low electrical noise, fast acceleration, and high efficiency. Plus the component's ironless rotor allows for zero cogging and simple, accurate control. Motor efficiency is 86 percent depending on the winding.

Interlace designed a unidirectional flexible shaft into the system that interconnects with the remotely located Maxon RE40 motor. This approach meant that they could go to a single-use, totally disposable probe system, which helped with certification. The MyoSure has obtained FDA 510[K] clearance and expects CE Mark certification to sell in Europe in the next year.

The device and its optical scope are 6.25 mm in diameter. This means that patients require less anesthesia during the operation. Overall, the device can provide a clear operative field, fewer device insertions, reduced perforation risk, and shorter procedure time—which was the primary design goal.

The MyoSure incorporates Maxon's EPOS 24/5 position controller as the driver for the device. According to Albert Chin, vice president of R&D at Interlace, "Maxon worked closely with us from day one. Their application engineers helped us to select the right motor and controller for the

continued

The RE40 motor used for the MyoSure provides high performance while maintaining a compact size.

The EPOS controller uses simple logic and control functions for monitoring the motor.

The MyoSure Tissue Removal System was upgraded with Maxon's RE40 motor and EPOS controller.

job. This prevented us from over designing the device, which would have increased our production costs."

EPOS 24/5 is a digital motion controller capable of being used in position, velocity and current mode. It communicates through RS-232 or CANopen, with complimentary software for CANopen and Windows DLL. The controller only requires an 11 to 24 VDC input to be capable of operating at 5 amp max continuous current and 10 amp peak current. The 50 kHz switching frequency and built-in choke insure compatibility with most low inductance motors, while the sinusoidal commutation for brushless motors insures minimal torque ripple and low noise.

The EPOS controller uses simple logic and control functions for monitoring the motor's operation, including acceleration and deceleration, as well as speed. The motor control logic is a software program that is burned into firmware at the factory. With Maxon's guidance, the MyoSure control box passed all the electrical safety testing necessary for Class B office use.

"As the design changed through many iterations of development, testing various motion control solutions, Interlace eventually needed a powerful, efficient and high power solution for the final design," Martino says. "The RE40 plus encoder plus customized EPOS 2 controller was able to meet all of Interlace's final design requirements."

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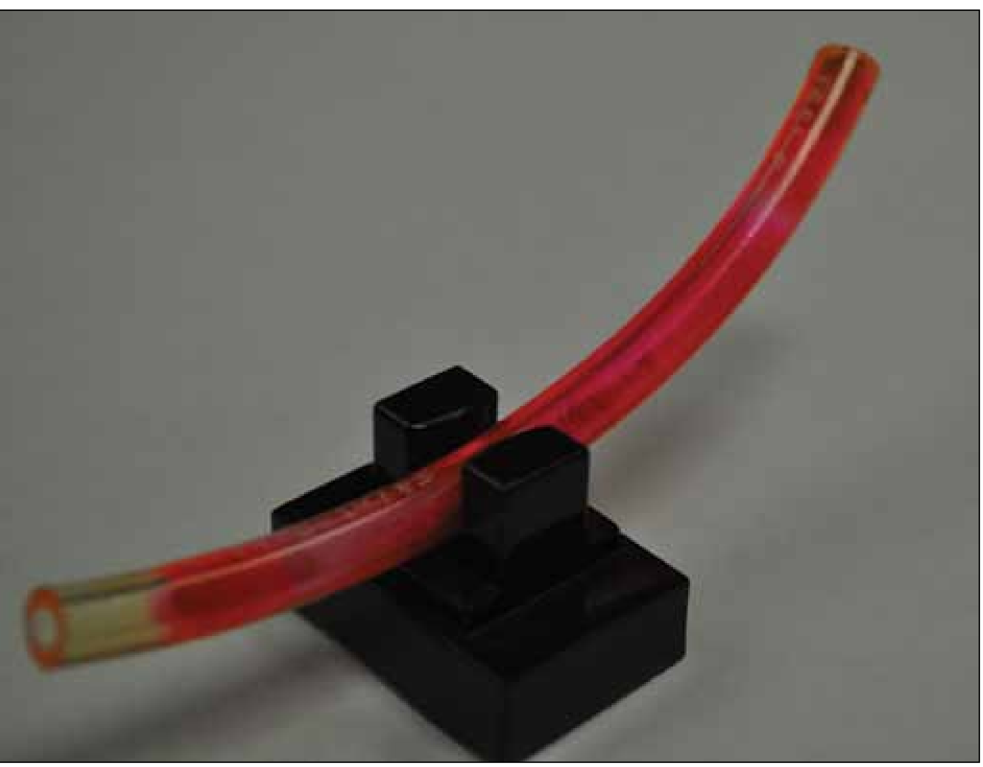
Medical Pumps with Uncommon Sens(ors)

NEW-GENERATION SENSORS IMPROVING OUR QUALITY OF LIFE

Jack McGuinn, Senior Editor



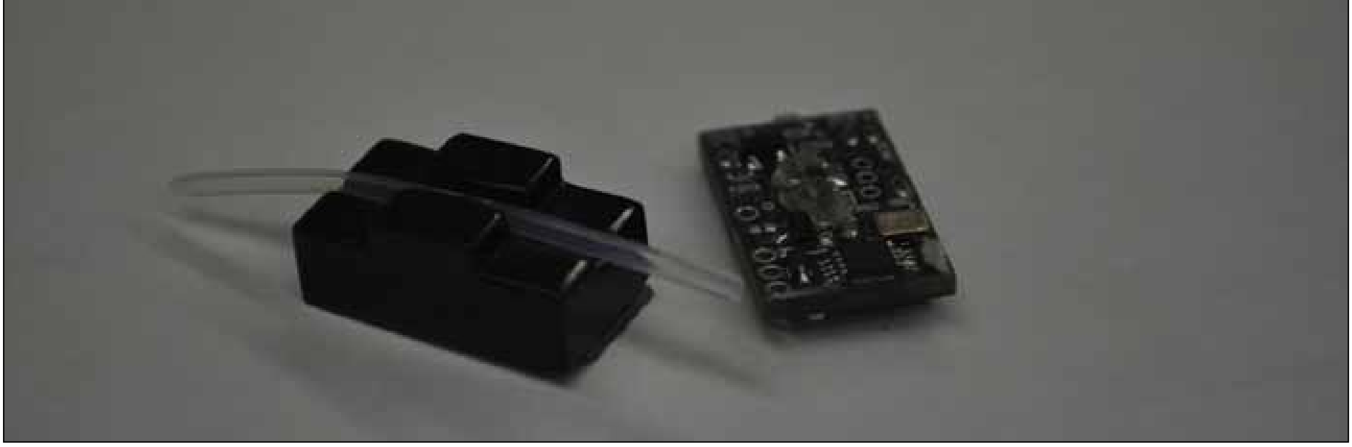
A series of ultrasonic, non-invasive air bubble and particle detectors (above and top, next page) from Cosense has a wide range of applications for the detection of air bubbles and particles in fluid-lines in the wafer etching process as well as in coolant lines. Standard sensors can detect air bubbles as small as 500 microns in size in tubing from 1 mm to 12 mm. Custom sensors for OEM customers can be designed to measure air bubbles down to 100 microns in size (photos courtesy Cosense).

Pumps and pumping applications have been around for millennia—longer, if you include those found in the breasts of most living creatures—great and small.

But the sensors that usually serve as the "brain" within today's pump systems are a much more recent technological advance.

The first known pump device is attributed to—who else?—the Greeks. Archimedes, a Renaissance man before there was a Renaissance, is credited with inventing the screw pump—a device used to remove a sailing vessel's bilge water. Its 21st century iteration is still used today in the coal and grain industries.

As for sensors, pressure and pressure management of some form have existed and been recognized since the 16th century, when Italian physicist and full-fledged Renaissance man, mathematician, astronomer and philosopher Galileo—secured a patent—who knew?—in Pisa to create a machine



for pumping (extracting) river water for irrigation use. But it was in 1967—according to most accounts—that what we know as the "modern" sensor was developed by the Honeywell Research Center via a patent awarded to Art R. Zias and John Egan for an "edge-constrained silicon diaphragm."

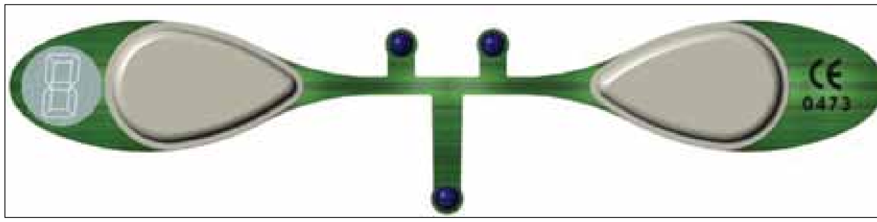
Today, dollar estimates of the U.S. market for sensors in general vary, with medical sensor applications pegged at around $5 billion and an annual growth rate of perhaps 10–15 percent through 2014. The overall sensors market is estimated to be around $12 billion per year, with an annual growth rate of about 5 percent.

Medical application sensor types include pressure, temperature, flow and level. In fact, according to a Freedonia Group study, "(Process variable) sensors will continue to be among the two largest product segments, given the numerous applications for these products."

But for now, let's concentrate on one niche in the medical sensor universe—pumps; more specifically, pumps with sensors.

Pete Smith, senior applications specialist for Hampton, VA-based Measurement Specialties, Inc. (MSI), provides a bit more background on sensor/pump applications.

"Medical equipment has always contained some degree of sensing technology, although often it has been rudimentary and fairly basic. For example, old-style blood pressure equipment used dial gauges to indicate the reading to the clinician. The dial gauge itself was a crude pressure sensor. Over the past couple decades, more and more sensors have found their way into medical machines. These sensors have added



This MSI sensor is embedded in a sleep apnea patch used for monitoring airway flow during sleep. It features strain gage sensing of chest movement, contact microphone-sensing for snoring and pyroelectric sensing for exhalation monitoring (photo courtesy MSI).

utility, new features, better indicators, more reliability and more patient safety to the equipment.

"As an example, flow sensors in infusion pumps monitor for proper dosing and operation of the pump. If anything isn't working properly, the pump stops and alerts the nurse of the problem."

And beyond that, says Smith, sensor technology is improving patients' quality of life while shortening hospital stays, allowing for much less stressful home recovery time.

"In the past few years, there has been a move in the medical equipment industry to redesign machines so they will function well in 'home healthcare' applications. Rather than keeping patients in the hospital, they are sent home, but with sophisticated monitors that can continuously check on the patient's condition and quickly alert the doctor via a cell phone link, or over the internet. These 'home healthcare' machines are filled with sensors to add intelligence and safety, and make them foolproof."

As one might expect, with an industry dedicated to making small things even smaller—as specified by its OEMs and end-users—challenges abound.

Says U.S.-based HSI Sensing president David Posey, "The sensor has evolved by making them smaller, (but) the reduction in size cannot give up any performance in magnetic sensitivity. (Our customers) require high quality, customer service (audits, reports, visits). Nothing new to us; we welcome their challenges and opportunities."

Mustansir Faizullabhoy, director of business development for Hauppauge, NY-based Cosense, offers his take.

"There are challenges on multi-

continued

HSI manufactures what is claimed to be the world's smallest and most sensitive magnetically operated reed switch. At more than 50 percent smaller than the smallest reed switch currently on the market, this new switch was designed to address the need for smaller electronic components in the medical and healthcare industry, including hearing aids, pacemakers and other implantable devices, defibrillators, surgical instruments and test/ diagnostic equipment (photo courtesy HSI).

ple fronts—from sourcing the crystal material, manufacturing, meeting each specific customer's critical functional requirements and while still providing a cost-effective solution."

And back at MSI, Smith comments on perhaps the greatest challenge of all—time—or the lack of it.

"One challenge is the time and investment needed to be part of a medical product development project. Often, a new medical product takes several years from concept to a running production line.

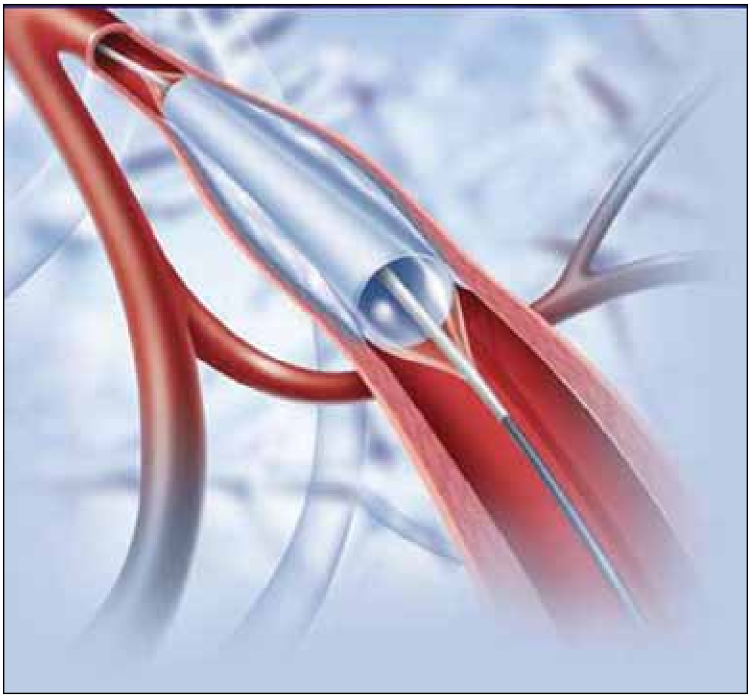
"Another challenge is that once in production, making changes, even very minor ones, is a significant effort. The effects of the change must be evaluated and studied to be certain there are no unintended consequences." As in, one might well assume, accidental injury or death.

But of course it doesn't stop there.

"The medical equipment industry spends a lot of resources implementing and operating quality control programs," says Smith. "Unlike most other types of customers, medical companies conduct periodic audits of their supply chain. These audits are highly detailed and rigorous. They occur at our facilities and can sometimes take a few days. In addition, there are any number of governmental and oversight groups that scrutinize the industry, and each of them have their own set of auditors. We have the FDA in the USA, and most other countries have an equivalent agency, but often with different standards. If a company wants to sell products in many countries, the regulatory maze is very complex."

Adds Cosense's Faizullabhoy, "We try to achieve the Six Sigma quality standard. Each customer has their own set of criteria. Testing specifications are mutually agreed upon prior to production launch so that customer expectations are met. Also, conforming to ISO9001 standards for design and manufacturing are a must. Sensors must be 100 percent-tested and offer fail-safe functionality."

"Fail-safe" means if a sensor malfunctions then it raises an alarm to the subsystem which automatically shuts down the system to prevent any unsafe conditions.



MSI's proprietary Microfused silicon strain gage pressure sensor measures pressure levels of cryogenic gases used in novel angioplasty procedures (photo courtesy MSI).

All three of the companies discussed in this article are OEM suppliers, and are involved in all of the things that such status incurs.

"Our medical customers work closely with us during the development of a sensor solution, says MSI's Smith. "They do extensive qualification and validation—not only of the sensor device we plan to sell them, but also of the factory and processes we plan to use to make them. Once in production, our customers perform regular audits of our entire company to insure we are maintaining quality standards that were outlined at the beginning of development.

"Our customers also make sure we conform to the Code of Federal Regulations, Title 21, which outlines requirements for medical products."

At Cosense, "We are an OEM manufacturer of sensors that are tailored to each customer's specifications," says Faizullabhoy. "The typical conditions that OEMs impose on manufacturers include meeting cost constraints while maintaining quality of components."

And says Posey at HSI, "Many OEM's require customization for their application; with the benefits of cell manufacturing they want the part 'ready to go'. They do not want to modify it for any reason. We welcome the opportunity to build different versions of the 'same' device (e.g.—longer wires, connectors, customization for specific application)."

As one might expect with one complex industry (sensors) working with others (device makers, medicine, etc.) equally complex, R&D is important. That means one's engineers working with the other's engineers, for example, in making something work to everyone's benefit.

But as Posey points out, R&D is a customer-to-customer dance.

"It (R&D) depends on the company," he says. "Some manufacturers design and build what are called 'standard products,' which are sold to everyone from a catalog, and everyone buys the same components. We not only have standard products, but we also work with a customer to develop and build custom products specifically designed to meet the customer's specifications. Custom products are typically not sold to anyone except the customer for whom they were designed."

Adds Faizullabhoy, "On all our special sensor development programs we work together in the R&D phase very closely with our customers, and this is typical in this industry."

HSI's Posey concurs, but points out that "(R&D) is not industry wide. Some manufacturers are not set up for low-volume customization like we are. We have a (department) called Product Development specifically dedicated to work with our customer engineers."

Getting back to specifics, i.e.—sensors for pumps. Is one type of sensor more difficult to produce than another? That probably depends on the sensor application. Remember, we're talking life-and-death here.

"In many applications, our customer is looking for a high level of performance from the sensors," says MSI's Smith. "Typically, they want sensors with good accuracy, repeatability, long term stability, etc. Basically, the pressure sensor that goes into a kidney dialysis machine needs to perform better than the one that goes into a refrigerator or irrigation pump."

Adds Faizullabhoy, "A medical-related sensor has to have much greater MTBF (mean time between failure) requirements, meet stringent regulatory approvals and is typically integrated in customer-designed pumps. Each has their own set of challenges of packaging and integration."

So what's next for sensors? Sure, we just *know* that they will get even smaller as the technology advances. But what else?

"There are a couple-dozen frontiers for sensors in medical applications," says Smith. "To name a few—sensors will be finding their way into implantable applications; more sensors in monitoring the home healthcare patients; sensors in providing well person monitoring to give very early indications of an impending medical problem. Also, very low power sensors that will operate for years from small batteries or from electrical power generated inside your body using biochemical cells."

At Cosense, Faizullabhoy says the Next Big Thing will be "Integrating other functions for monitoring as part of the ultrasonic sensor. For example, flow control and temperature. (There will be) demands for sensors to become smaller, more sensitive, multifunctional. Also, many devices are now employing Bluetooth technology, i.e.—no magnetic sensor involved in operation of the device. I hope the Bluetooth technology proves 'too costly' in regards to power consumption within the device. This will, over time, return (makers) to magnetic sensing devices."

Today's various sensor-pump combinations have taken medical device capabilities and applications beyond the unimaginable. Better health, longer life and shorter hospital stays are just a few of the benefits (photo courtesy MSI).

And while the sensor industry is not experiencing any acute problems, it's not all clear sailing, according to MSI's Smith.

"The biggest problems confronting medical equipment manufacturers in general are meeting and keeping current with FDA requirements; managing their supply chain to maintain the high quality levels expected; avoiding and mitigating litigation from customers and patients; and trying to figure out how to navigate the health insurance maze, government-sponsored care and the evolution of patient care toward new paradigms in the next decade."

But all of this aside, one paramount truth is that medical sensors are playing a revolutionary role in our improving quality of life and extended lifespan.

For example, "Portable infusion pumps for drug and pain therapy that can be worn by the patient on the hip are a good example of improving the quality of life," says Cosense's Faizullabhoy.

And at MSI: "Our sensors are being used in wearable insulin infusion pumps," says Smith. "They give patients freedom to conduct normal lives and avoid the periodic insulin injections that were used a decade ago. We've also been involved in wearable pumps that provide medication infusion to control chronic pain and even provide low-dose, continuous chemotherapy."

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Development of an Actuator

FOR AMBIENT TO CRYO APPLICATION

Karen Menzel, Hans Jürgen Jung and Jörg Schmidt

(Proceedings of the 40th Aerospace Mechanisms Symposium, NASA Kennedy Space Center, May 12–14, 2010)

Management Summary

During the qualification campaign of the NIRSpec (near-infrared spectrometer) instrument mechanism, the actuator could not achieve the expected lifetime that had been extended during the development phase. The initial design could not be adapted to the requested number of revolutions during that phase.

Consequently the actuator needed to be modified so that the function of the mechanism would not be endangered or, by extension, the overall function of the NIRSpec instrument. The modification included a change of the overall actuator design—internal dimensions, tolerances, materials, lubrication and assembly process—while keeping the interface to the mechanism, mass and function.

The lessons learned from the inspection of the failed actuator have been implemented in order to ensure the development and qualification success. The initially available time for this activity was in the range of six months to meet the overall program schedule.

Introduction

The actuator consists of a three-stage gearbox flanged to a stepper motor. A lever connected to the actuator by an eccentric mechanism moves the upper sled of the refocusing mechanism assembly (RMA)—an optical NIRSpec sub-unit carrying highly sensitive mirrors (Fig. 1).

The high non-operational temperature range of 296K—as well as the low operational temperature of 30K—require a special design considering the great thermal expansions between 27K and 323K, as well as a proper material selection that deals with the change of mechanical properties at cryogenic temperatures. Both the new material concept and the molybdenum disulfide (MoS_2) lubrication coating confronted the engineers with unexpected effects.

In order to keep the development risk (both technically and regarding the schedule) low, two different breadboard models and one qualification model have been built and tested; two flight models and one flight spare will be delivered to the customer.

Key Equipment Design and Performance Requirements

The refocusing mechanism of the NIRSpec instrument provides the focusing function by means of two corner mirrors changing the optical path length by movement of the mirrors.

Three titanium blades guide the RMA upper sled, which is driven by an eccentric drive requiring a maximum torque of about 0.55 Nm. Considering ECSS (*Ed.'s note: a space environment standard; i.e., a standard for calculation of radiation effects and a policy for design margins*), margins, the actuator has to generate a worst-case torque of 1.21 Nm at ambient and 1.4 Nm at 30K, driven with a rated current of 120 mA. This is realized by a stepper motor attached to a planetary gear with a gear ratio of 184:1 distributed to three stages.

The most important requirement is the wide operational temperature range from 30K to 323K. The observations at the first actuator demonstrate the high importance of both the selection of a proper dry lubrication as well as a CTE (coefficient of thermal expansion)-consistent design, ensuring constant tolerances within the operational temperatures for both the bearings and gears.

According to the expected in-orbit cycles, as well as the flight model test campaign, the qualification model has to be loaded in different cycles from the mid-stroke position, resulting in a total of about 400,000 motor revolutions (including ECSS margins) without significant performance reduction. As learned from the first actuator, special attention has to be paid to the metal-to-metal contact due to coating wear between sliding parts. Therefore, a redundant lubrication design should be considered, especially taking into account the RMA being a single-failure object; that means a breakdown of the sub-unit results in the inability to re-focus the NIRSpec instrument.

The actuator's operation in an environment close to contamination-critical optical equipment rules out lubrication systems with particulate or molecular contamination, and yet requires solid lubrication.

Initial Design of First Actuator and Lessons Learned

The first RMA actuator consisted of a material mix of six different sorts of steel with an estimated COE (common operating environment) at 30K, varying between 7.5 x 10^{-6} 1/K (ball bearings) and 15 x 10^{-6} 1/K (gearbox housing). This design was based on experience in gearbox development for usual applications—every single material has its specific strength playing on the individual function. But this cryogenic application cannot be called usual, and different strategies must be pursued.

The shrinking at cryo is likely to have caused increased friction and therefore affected the lifetime significantly. The lubricant used—Dicronite—showed significant signs of abrasion after life testing (about 330,000 motor revolutions), resulting in metal-to-metal contact as well as a major increase in necessary current; according to ECSS, a clear failure of life test.

Motor current measurements during the life test demonstrated that the actuator lubrication would have survived the nominal lifetime but, due to lifetime extension, the results as described above have been obtained.

Similar actuators have been successfully used in ground-based cryo applications, but in areas where an exchange of a failed actuator can be performed at any time.

Design of the New Actuator

Figure 4 represents the new actuator in cross-section; the main design was kept, in general, but the rear motor bearing was substituted by larger duplex bearings. The rotor axial pre-load spring was moved from the front duplex to the rear bearing. Ideally the front duplex bearings of the motor should have been arranged in 0-orientation to allow a limited rotation of the rotor axis (isostatic support conditions). Due to assembly constraints, an X-arrangement had to be selected in combination with an increased play of the rotor axis rear bearing. The planetary gear with three stages still has a gear ratio of 184:1.

The material concept was changed significantly to a CTE-consistent design as increased friction and raised bearing loads are supposed to be at least part of the reason for the first actuator's failure.

As Figure 5 illustrates, all motor and gearbox parts—except the screws—are manufactured of either hardened Cronidur (X30) or titanium; the higher CTE of the screws only results in behavior comparable to extension bolts, and the machining of well known material for these critical functional components minimizes risks.

Coating for Solid Lubrication

After the failure of the Dicronite coating during life test, a solid lubricant concept had to be selected that is well known

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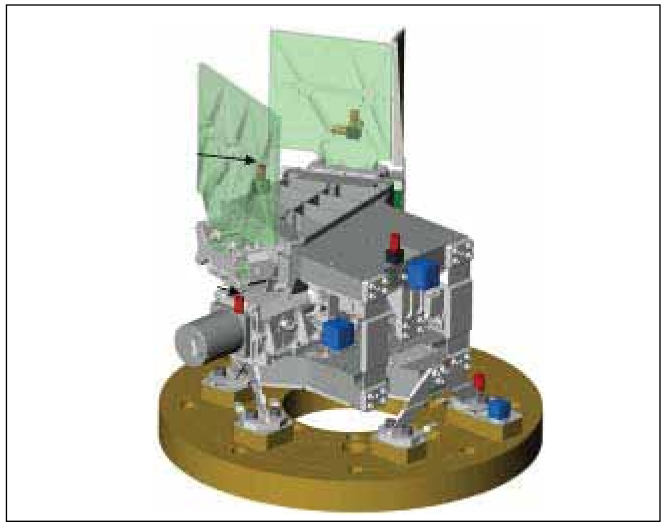
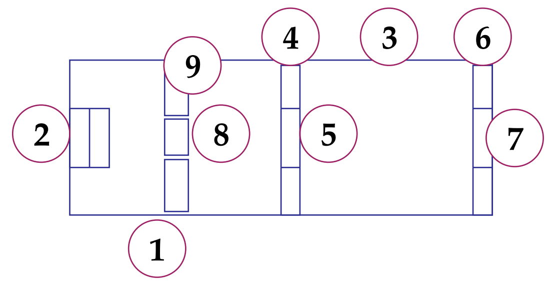


Figure 1—Refocusing mechanism assembly.



No	Nomination	DIN	Common Name	CTE (20°C)	Est. CTE (30K)
1	Gearbox housing	1.4305	X10	17	15
2	Gearbox bearings	1.4108	X30	9.9	7.5
3	Motor housing	1.4301	X5	17	15
4	Front motor flange	1.4305	X10	17	15
5	Front motor bearing	1.4108	X30	9.9	7.5
6	Rear motor flange	1.4305	X10	17	15
7	Rear motor bearing	1.4037	X65	10.8	8.5
8	Sun wheel	1.4112	X90	10.4	8.3
9	Planetary wheel	1.4034	X46	10.5	8.3

Figure 2—Material concept of first actuator.

Figure 3—Lubrication failure of first actuator after life test. Visible corrosion results from the exposure of the blank metal to air after disassembly of the actuator.

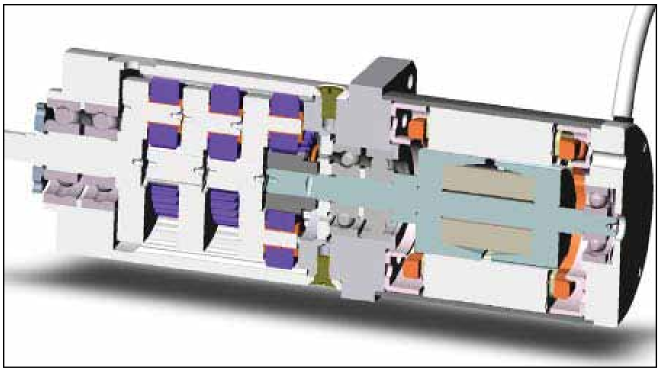


Figure 4—New design RMA actuator.

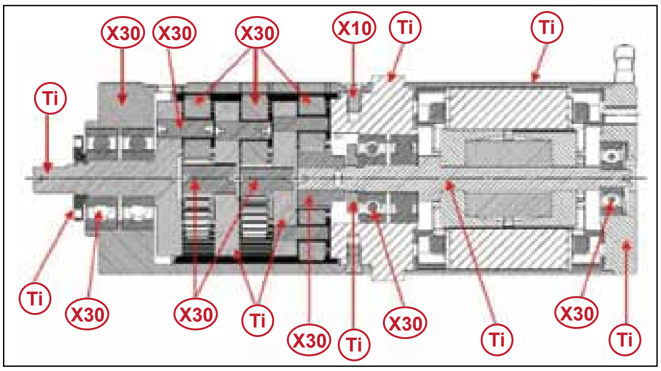


Figure 5—New material concept.

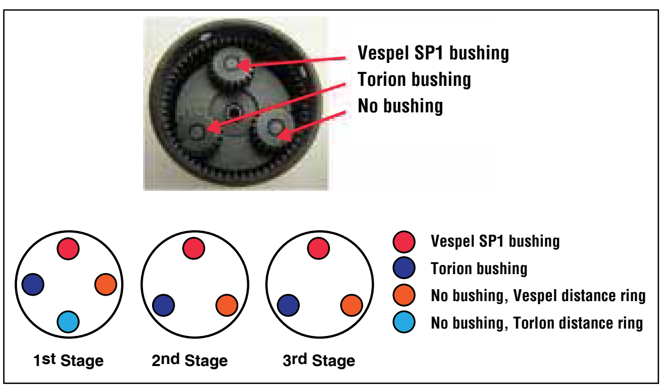


Figure 6—Pre-QM1 design (MoS_2–lubricated).

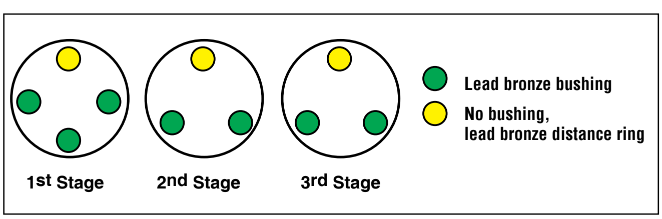


Figure 7—Pre-QM2 design (lead-lubricated).

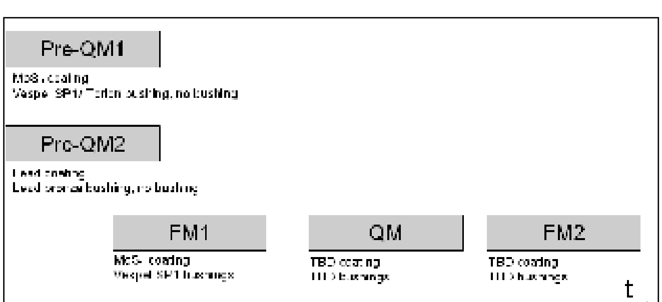


Figure 8—Development concept and success-oriented approach.

for space applications due to the short time frame of development. Sputtered molybdenum disulphide (MoS_2) seemed to be the most suitable lubricant, as it has proven its reliability in numerous space applications. In order to have a back-up solution during the development program, a lead-lubricated breadboard model was set up, tested and compared to the MoS_2-coated model before starting the qualification program. This development approach is explained later on.

Plain Bearing Bushings

Sputtered MoS_2 is well known as a solid lubricant for ball bearings where the predominant relative movement is a combination of sliding and rolling friction. However, this experience cannot be found in a gearbox lubrication application. The planetary wheels are rotating around the pins pressed into the planet carriers. This journal bearing was one of the critical areas where the Dicronite coating wore off. Therefore a redundancy was requested for this function. Plain bearing bushings made of plastics have been found to fulfill this requirement for increased safety against abrasion. In case of local lubrication failure, these bushings fulfill journal bearing functions and prevent direct metal-to-metal contact.

The bushings were toleranced in such a way that they shrink onto the planet axis in cryo in order to gain a defined sliding surface. That requires a small low-temperature embrittlement at temperatures down to –246°C, relatively low CTE and good sliding properties in cryo—all not self-evident for organic plastics.

Different materials have been considered in this application:

- Vespel SP1/Vespel SP3. Vespel is a well known plastic material used in space applications; type SP3 is self-lubricating by containing small particles of MoS_2 while SP1 represents the unfilled material.
- Copper metal matrix composite (Cu-MMC). The self-lubricated Cu-MMC has been developed by Austrian Research Centers for use in tribological sliding contacts under vacuum. It is based on a copper matrix with inclusions of solid-lubricant particles, and one of its highest advantages compared to plastics is its low CTE.
- Victrex PEEK 450G is supposed to be applicable especially for cryogenic applications.
- Torlon 4203 PAI stands out due to its high ductility—even at cryogenic temperatures.
- Sintimid 15M/30M is a sintered polyimide designed for cryogenic applications and filled with either 15% MoS_2 or 30%, respectively.
- PGM-HT contains of PTFE filled with glass fibers (15%) and MoS_2 particles (5%) and is often used for ball bearing cages.

Bushings have been manufactured of all the materials as well as sliding samples for friction coefficient comparison. Friction tests under ambient in combination with MoS_2 powder should give a first impression of the tribological behavior. While Vespel SP1, Victrex and Torlon showed good machinability, Sintimid, Cu-MMC and Vespel SP3 were very brittle during manufacturing (the higher the filling percentage or the bigger the particles, the worse was the machinability) and some of the bushings broke during machining. It turned out that filled material is not suitable for this application as the marginal wall thickness and particle size are in the same range.

The bushings were assembled onto the planet axes and exposed to a liquid nitrogen dip test. Sintimid bushings cracked or indeed broke during the test and therefore failed. Victrex material was undamaged, in principle, but showed slight white marks after removal of the bushings that are suspected to be material degradations.

Based on the experiences with Vespel in an Astrium space application, this material has been selected for the FM1 model, but Torlon has been considered for one of the breadboard models in order to allocate a back-up solution.

Development Concept and Success-Oriented Approach

A success-oriented approach has been chosen due to programmatic reasons: i.e., the FM1 was produced and tested with the design described above without the qualification program having started yet. In order to gain confidence, two breadboard models—or pre-qualification models—have been set up. As every stage of the planetary gear has three (1st stage four, respectively) planet axes that are equally loaded, different bushings could be assembled and their behavior during life test can be compared.

Pre-QM1 is MoS_2-lubricated and contains bushings of Vespel SP1, Torlon and planet axes without bushings (Fig. 6). Pre-QM2 is lead-lubricated with bushings of lead bronze assembled or no bushings, respectively (Fig. 7). If no bushing is assembled on one of the planet axes, a distance ring is necessary to prevent the appropriate planet gear from moving along the axis.

These breadboard models have been manufactured first and the FM1 production has been started during their test campaign, as displayed in Figure 8. Indeed the FM1 has been assembled into the sub-unit at a time for which the actuator has not been fully qualified; as the pre-QM1 and FM1 are not assembled completely identical and the pre-QM life test was in some ways simplified but equivalent at best.

Life Test Pre-QMs

As the pre-QMs had to be life-tested without being integrated into the RMA, an equivalent test set-up had to be designed in order to load the actuators correctly.

Springs connected to a disc (Fig. 9) load the actuators with the torque corresponding to the load the real blades are generating in the RMA mechanism. Figure 9 illustrates that the maximum torque at 120° from launch position and the load represented by the spring set-up are very accurate.

The cryogenic temperature during pre-QM life test was not 30K (liquid helium) but 80K (liquid nitrogen) due to facility reasons. This temperature is justified by the fact that neither the shrinking or the change in material properties between these two temperatures are high compared to their absolute values.

The expected lifetime of the RMA actuator is about 400,000 motor revolutions, including ECSS margins. As Figure 10 illustrates, in the case of pre-QM1 the so-called success current—indicating the friction—does decrease during lifetime up to the end of life test at about 430,000 motor revolutions. The MoS_2 coating seems to be properly run in at this time. Lead-coated pre-QM2 showed some degradation starting between 320,000 and 380,000 motor revolutions, but is still within the ECSS success criteria at end of life. The detailed visual inspection of the bushings (Figs. 12–13) did not show significant differences in abrasion on bushings

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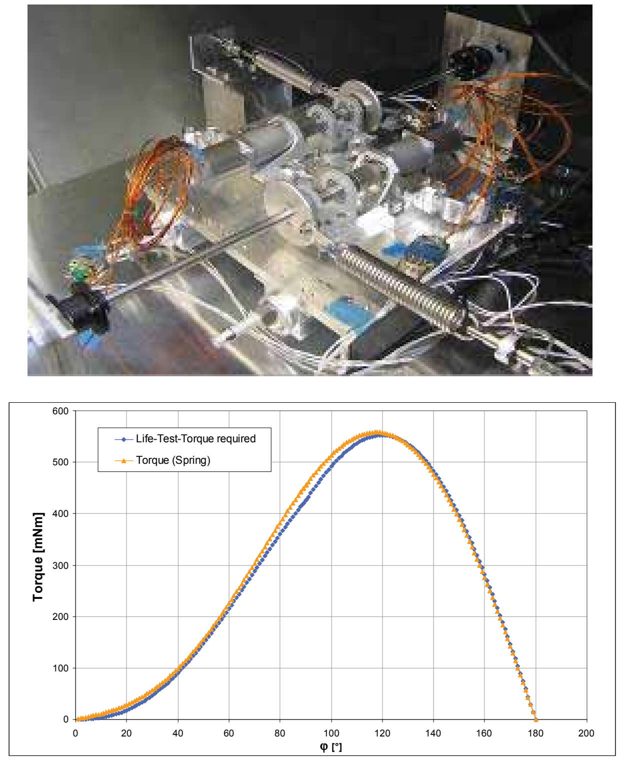

Figure 9—Pre-QM life test (top); load application during life test by spring assembly (bottom).

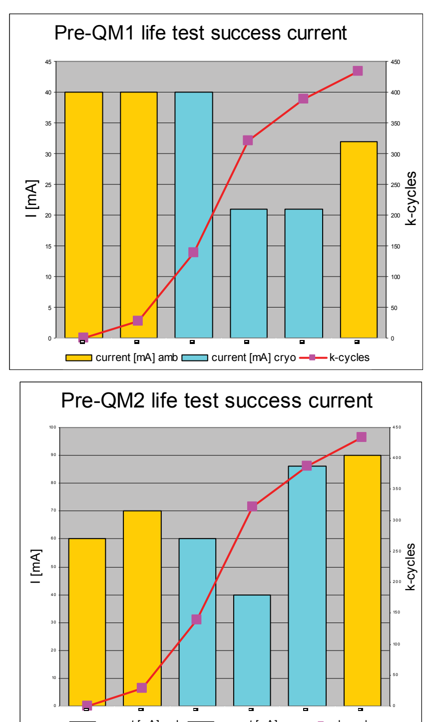

Figure 10: Results of Pre-QM life test.

made of Vespel SP1 and Torlon.

These test results provide high confidence in the selected material combination. Flakes of coating have been delaminated during vibration (this issue is explained later in detail) from gear teeth on planets, suns and hollow wheel. This damage did not affect the gearbox's performance, and the surfaces look smooth and properly run in after life testing (Fig. 11), and XRF (X-ray fluorescence) measurement at ESTL (NASA Electronic Systems Test Laboratory) revealed a remaining MoS_2 layer of at least 0.14 microns.

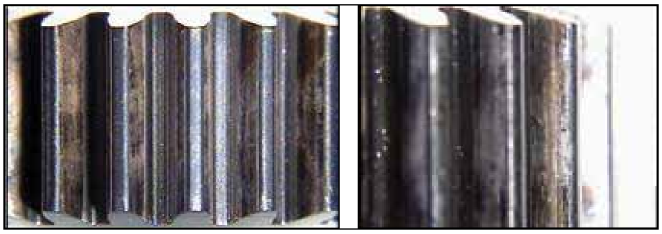

Figure 11—MoS_2 gearbox inspection after life test.

Figure 12—Pre-QM1 Vespel SP1 bushing and distance washer after life test.

Figure 13: Pre-QM1 Torlon bushing and distance washer after life test.

Figure 14—Lead-coated gearbox and lead-bronze bushing after life test.

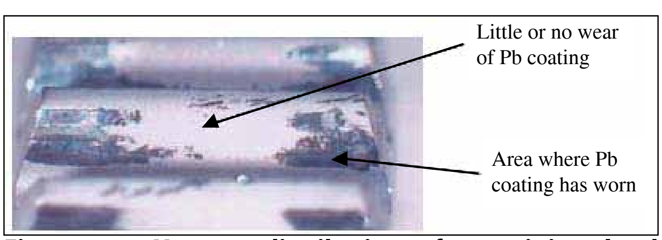

Figure 15—Uneven distribution of remaining lead coating on the planet teeth.

Figure 16—Failed pressing trial results.

In addition, a visual inspection of the lead-coated pre-QM2 gearbox found it in good condition with no evidence of metallic wear of the steel surfaces. XRF measurements confirmed that lead remained on the gear teeth, but that in several areas it was extremely thin. Examination of the thickness values shows that in all but one case the minimum thickness was less than 0.1 µm, and as low as 0.03 µm in one instance.

However, it should be stressed that very little lead is required—especially on polished-steel surfaces—to provide effective lubrication.

As with the MoS_2-lubricated gears, wear of the lead coatings was uneven across the teeth. This is illustrated in Figure 15 for a planetary gear from stage 3; note that the lead coating in the center of the tooth is virtually unworn, but elsewhere lubricant wear has clearly taken place.

It was also apparent that lead had transferred during tooth-to-tooth contact, leaving patches where the thickness of the lead was greater than the thickness of the coating, as initially applied. This effect accounts for the relatively large patch width (>2 mm) occasionally observed. It should be noted that lead transfers more efficiently than MoS_2—a fact consistent with the observation that no anomalously high coating thicknesses were observed for the MoS_2–lubricated gears.

Technical Difficulties and Challenges

Planet carriers and gearbox housing. The initial approach was a design containing a number of parts made of unhardened Cronidur—i.e., the planet carriers and the gearbox housing. It is impossible to shrink-fit hardened pins onto hardened carriers; the risk of deformation due to hardening of the hollow wheel (→ ovalization) was considered unacceptable. But Cronidur is not corrosion-resistant in the unhardened condition, so a substitution of the material—or heat treatment—had to be considered.

To replace the Cronidur, the planet carriers have been manufactured from titanium. Extensive trials have been performed to identify the necessary oversize for press fit. By doing so, the required torque loading is transmitted to the sun wheel on the one hand—but not to exceed the ultimate strain of about 7% of titanium (Figs. 16–17). As for the gearbox housing, a material substitution has been widely discussed with many experts, but the number of materials in the same CTE range of Cronidur is very limited.

Using titanium for the gearbox housing is out of the question as the gear supplier is not able to cut the internal gear from titanium. The steel 17-4PH has been deemed an alternative but, due to its sensitivity against stress-corrosion cracking, its usage would have required advanced fatigue analyses.

Nevertheless, adhering to the previous concepts offers two distinct opportunities:

- Hardening the entire gearbox housing (Fig. 18, right)
- Manufacture a hollow-wheel ring from Cronidur (Fig. 18, left), harden it and assemble it in an

integrated design to a titanium housing (Fig. 18, middle)

Both methods have been tested; the entire gearbox and hollow-wheel ring have been subsequently hardened and 3-D-measured with this result: the hollow wheel was ovalized but the gearbox remained *stable*.

Influence of surface quality on coating adhesion. As indicated previously, both pre-QM1 and FM1 showed signs of coating delamination on the gear teeth of planets, sun wheel and gearbox housing after vibration testing, which was detected during subsequent inspection (Fig. 19). This finding raised three main questions:

1. Does a remaining layer of MoS_2 still exist on the gear teeth?
2. Is the lubrication sufficient?
3. How can the generated particles be prevented from emerging from the gearbox and possibly contaminating optical equipment on the instrument?

Investigations at ESTL revealed a minimum MoS_2 layer of 0.14 micron-thickness existing on the affected surfaces, and the successful pre-QM1 life tests justify confidence in the coating quality. Nevertheless, an investigation has begun to find out whether the chosen pre-treatment electro-polishing and defined surface roughness do in fact represent the ideal parameters.

Samples have been manufactured with varying surface qualities between 0.1 micron and 0.5 micron, as well as electro-polished/not electro-polished. The deflating conclusion of the pin-on-disc test following the coating process was that surface roughness does not significantly influence the quality of the coating adhesion, but electro-polishing treatment reduces the endurable revolutions in pin-to-disc testing down to 20%–30% of those samples that were not electro-polished.

Influence of proper run-in on friction/torque. Molybdenum disulphide is, to an extremely high degree—hygroscopic. When exposed to ambient atmosphere/humidity, it absorbs water and binds it molecularly, which alters the coating's microscopic structure, and friction increases. Because the process is not completely reversible by simply drying MoS_2 in a vacuum, mechanical pressure via a run-in must be applied in order to overcome this initial peak-torque in the gearbox and ball bearings. Evacuating throughout the weekend resulted in better torque value than evacuating only overnight; a proper run-in even increased the torque margins.

While this effect is not unknown in the technical world, many experts are of a very different opinion on how to deal with a MoS_2-coated actuator, and that good communication with all suppliers is essential in sensitizing every employee to this issue.

Conclusions and Lessons Learned

The first flight model with the MoS_2 dry lubrication and Vespel SP1 bushing has been successfully implemented into the flight model RMA. The RMA has performed its acceptance program and is currently mounted onto the NIRSpec optical bench. We are confident of having supplied an actuator that will safely provide the required functionality throughout the lifetime of the NIRSpec instrument.

During the very short time frame of the execution of this seven-month development program, we have learned a great deal about not only development programmatic, but material and lubrication technologies as well. Some key lessons learned are outlined here, not all of them new.

Programmatic lessons learned:

- Do not change too many technical parameters at the same time; it may become impossible to identify the reason for both improvement and deterioration.
- Postponing tests and planning to combine them with other tests due to programmatic reasons may be a shortsighted decision. Both technical and programmatic reasons might eliminate the possibility of performing a particular test at a later time. Certain measurement results can be generated at only one specific time; once this time frame is closed, the opportunity for measurement might be missed forever.
- Ensure that your suppliers are fully aware of their contribution to the development success. This key success factor ensures that the suppliers provide their utmost technical capabilities and are extremely flexible with the necessary modifications that are normal in such a development program. Access to the supplier's expertise can only be acquired if they feel part of the team and understand the final application of their contributed part. As an example, Gysin (gear box) should be mentioned as they succeeded in providing a gear tooth surface quality far beyond standard industrial needs by the proper setting of the standard machinery.
- A success-oriented approach initially has the allure of saving time and money, but always contains high risk of failure, such as doubling the cost at the end as

continued

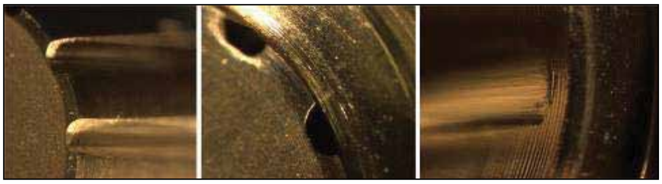

Figure 17—Passed pressing trial results with 40 μm oversize.

Figure 18—Hollow-wheel ring and integrated design versus gearbox housing made entirely of Cronidur.

Figure 19—Coating damage after vibration.

the work had to be done twice. We must confess that we had good luck that the selected combination of materials for the FM1 was the right choice, as this combination was found to be the best as a result of the pre-QM life test. In many other development programs similar results could not be achieved.

Technical lessons learned:

- MoS_2 lubrication might be seen as a state-of-the-art dry lubrication. We learned that the processes applied to the materials prior to coating do in fact have a relevant influence on the sputtering process; even the sequence of processes seems to be of importance. The initial loss of sections of dry lubricant on the gear wheels—as observed after vibration testing (Fig. 19)—is still not understood and will be further investigated (see last section, "Outlook").
- When we initially saw those areas of lubrication loss on the gear wheels (Fig. 11), we were sure that this was the end of the story. But thanks to ESTL's confidence in their sputtering process and the measurements performed showing sufficient MoS_2 on the teeth to survive the life test, we decided to continue. The life test was a success. Those observed areas increased, but the residual MoS_2 layer survived. It is the intention to continue the life test on the pre-QM (see last section, "Outlook").
- Witness samples for process control for any kind of surface layer generation; they should be of the same material and should have been exposed to the same processes and sequence of processes as the units to be treated. In some cases where geometry also impacts the surface treatment, the witness sample should also have a similar geometry.
- Keeping MoS_2 surfaces in either a dry environment or, ideally, in a vacuum or constant N_2 atmosphere, requires specific knowledge of how to prevent moisture absorption of the MoS_2. Permanent purging of mechanism elements like bearings is one of the methods applied if the outer environment is not adequate. In the vicinity of optical surfaces at temperatures below those of the mechanism (cold traps), purging or even open venting holes might allow particles from the MoS_2 to escape from the mechanism and pollute the optical surfaces. As seen from the life test, particle generation cannot be avoided. Consequently the purging process, purging direction and venting-hole definition need to be properly planned at the beginning of the project to prevent pollution effects.

Outlook

In a very short time frame of seven months, a dry-lubricated actuator for ambient and cryo application was developed with a complete combination of new materials. Though the development was a success, some questions are still open and require further investigation.

As outlined in the "lessons learned," the material treatment process does have an important impact on the success of the sputtering process. The observed partial loss of lubricant on the gear wheels remains unexplained. From the pin-on-disc test results we do have clear indications that the electropolishing is of negative influence, but the physical or chemical nature of such an effect is still not completely understood. Other effects like the order of hardening and polishing might be also of influence. These effects need to also be assessed for different standard gearbox or bearing materials. Astrium hopes to initiate a program with ESA, ESTL and technical surface coating experts to further investigate this issue.

Though we did initially lose some lubricant on the gear surfaces, they survived the life test and it would be of interest to determine the final life of such surfaces in the gearbox. Therefore, Astrium will continue the life test on the prequalification models (both the MoS_2 and the lead-lubricated ones). Life test stop criteria will be a certain current threshold (TBD) that would be equivalent to a certain increase of the friction torque of the unit (e.g., 50%). A dedicated inspection program of the units will follow the life test, and results will be reported at the next ESMATS to be held at Astrium in Friedrichshafen, September 2011.

Acknowledgment

Astrium would like to thank their partners in this development program for their utmost efforts provided in terms of technical quality, adherence to the very tight schedule and their expertise and support at every phase of this project.

- Phytron GmbH—motor development and the overall assembly and functional testing
- (Swiss-based) Gysin AG—gearbox components
- (German-based) GRW—bearing manufacturing and Cronidur hardening
- (UK-based) ESR—MoS_2 and lead lubrication

PTE
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Has Moved

In September 2010, publisher/editor-in-chief, Michael Goldstein and the Randall Publications staff moved into their new office located at

1840 Jarvis Avenue in
Elk Grove Village, IL 60007

The furniture is officially broken in and we're ready to continue to provide the most comprehensive trade journals to/for the gear and power transmission industries. Call us at (847) 437-6604, fax us at (847) 437-6618 or simply drop by the office if you're in or around the Chicago area. Thanks again for your continued support of *Gear Technology* and *Power Transmission Engineering (PTE)*.

Randall Publications LLC Staff. Front row left to right, Dave Friedman, Carol Tratar, Dorothy Fiandaca, Kathy O'Hara, Luann Harrold, Michael Goldstein, Marsha Goldstein and Randy Stott. Back row, left to right, Janusz Lewandowski, Matthew Jaster and Jack McGuinn.

AWEA to Wind Supporters—

DON'T PANIC

Despite posting its slowest quarter since early 2007, AWEA remains optimistic that the wind industry can and will work successfully with the revolving doors in Washington. Denise Bode, CEO of AWEA, addressed the mid-term elections and 2010 third-quarter results in a recent wind industry webcast in November.

"After years of strong growth for wind energy in this country, our numbers are slowing because Washington gridlock has stalled any progress on solid and certain investment policies," Bode said. "The 85,000 Americans in the wind energy industry hope the new Congress will act to include more renewable energy as part of America's future."

During the webcast, Bode discussed the dramatic shift of power in Washington and what it means for the future of wind energy in America.

"The U.S. wind energy industry looks forward to working with John Boehner, the next Speaker of the House. Like us, he wants to 'reduce our dependence on foreign sources of energy, protect us against blackmail by foreign dictators, create American jobs and grow our economy,' as Rep. Boehner says on his website. He says he wants to roll up his sleeves and get to work creating jobs. The market-based policies that drive renewable energy—tax credits and resource portfolio standards—are perfectly compatible with Rep. Boehner's agenda, and have been supported on a bipartisan basis at the state and federal level for over a decade," Bode said.

AWEA will continue to discuss renewable policies with government officials including Sen. Mark Kirk (Illinois), Sen. Michael Bennet (Colorado), Rep. Jerry Moran (Kansas), Sen. Chris Coons (Delaware) and Sen. Richard Blumenthal (Connecticut), in the hopes of adding jobs and spurring economic development in both red and blue states.

A wind farm in Evanston, Wyoming features Vestas turbines (courtesy of Vestas Wind Systems).

Bode said new Republican and Democratic representatives need to learn that wind energy can keep costs down for consumers and provide an opportunity for in-sourcing and bringing investments from abroad back to the United States.

The growth of wind energy in the last five years has been aided by the production tax credit, support of a refundable tax credit under the American Recovery and Reinvestment Act and state requirements for renewable energy. "We're still the fastest growing manufacturing sector in the United States with nearly 400 facilities supplying components to the industry," Bode added.

Members of Congress have supported the U.S. wind energy sector for many years according to the AWEA because they know it creates jobs for Americans and investment in the economy, as well as homegrown clean energy made in the United States.

"Public opinion is still strongly behind wind energy and our job is to provide factual information and show the American people that wind remains an engine for growth," Bode said.

It's long-term legislation from Washington that will prove both Republicans and Democrats are ready to make the commitment. Elizabeth Salerno, director of industry data and analysis at AWEA, discussed the third quarter results during the webcast.

Only 395 MW of capacity were installed in the third quarter of 2010, and industry installations were down 72 percent from 2009, according to Salerno. She also compared statistics here in the United States with the global wind community. Currently, the United States lags far behind both Europe as well as China in new wind installations. It's not from lack of effort, as approximately 4,700 MW of projects have started construction in the past six months, more than 10 new requests for proposals for utility-scale wind projects were issued in the third quarter and at least nine new wind projects signed long-term power purchase agreements.

Data from the U.S. Energy Information Administration and other third-party sources show that wind accounted for 39 percent of new installed capacity in 2009, versus 13 percent from coal. In the first nine months of 2010, the ratio has flipped, and wind accounted for only 14 percent versus 39 percent from coal.

"We're increasing our dependence on fossil fuels, impacting our national security, instead of diversifying our portfolio to include more renewable," Bode said.

"The post-2010 world of wind energy is filled with question marks because we don't know where the economy or policies are going to land," Salerno said. "All of these factors really push around the growth in wind."

February 1–2—Offshore Wind Power 2011. Boston. Following the success of this year's Offshore Wind Power USA event in Philadelphia, Green Power Conferences would like to announce the 2nd annual event taking place in February 2011. Offshore wind energy is the new growth industry in North America, with wind resources off the U.S. coasts offering a vast, yet largely untapped energy potential. Offshore development promises to be a significant domestic renewable energy source, especially for coastal energy loads with limited access to interstate grid transmission. For more information, visit *www2.greenpowerconferences.co.uk*.

February 15–17—Gear Materials: Selection, Metallurgy, Heat Treatment and Quality Control. Clearwater, FL. Discover how both the gear design engineer and the gear metallurgist can better grasp their related, critical roles in the world of gear processing, heat treatment and inspection. The gear design engineer is responsible for the initial selection of material and heat treatment, but the finalization of both material and thermal processing must be a joint effort. This seminar shows how the gear design engineer first approaches the problem of material selection and heat treatment technology, as influenced by the performance and life requirements of the gear set. It also shows how the gear metallurgist can participate in and thereby optimize the finalized gear manufacturing process. Interspersed in the course are examples of gear-related problems, failures and improved processing procedures. Analyses and comments on a number of relevant failures are given. For more information, contact Jan Alfieri at *alfieri@agma.org*.

March 1–3—Expo Manufactura. Cintermex, Monterrey, Mexico. The largest event in Mexico for the processing and manufacturing industries boasts more than 350 companies representing more than 600 national and international brands. Expo Manufactura brings professionals together with technological solutions in aerospace, medical devices, automotive, metallurgical, aeronautics and electrical appliances. More than 9,000 industry professionals will visit the show looking for industry insights, new technologies and networking opportunities. For more information, visit *www.expomanufactura.com.mx*.

March 15–18—Gear Dynamics and Gear Noise Course. The Ohio State University. The Gear Dynamics and Gear Noise Short Course has been offered for more than 30 years and is considered extremely valuable for gear designers and noise specialists who encounter gear noise and transmission design problems. Attendees will learn how to design gears to minimize the major excitations of gear noise: transmission error, dynamic friction forces and shuttling forces. Fundamentals of gear noise generation and gear noise measurement will be covered along with topics on gear rattle, transmission dynamics and housing acoustics. This course includes extensive demonstrations of specialized gear analysis software in addition to the demonstrations of many Ohio State gear test rigs. A unique feature of the course is the interactive workshop session that invites attendees to discuss their specific gear and transmission noise concerns. The round table discussions are intended to foster interactive problem solving discussions on a variety of topics. Cost is $1,950. For more information, contact Jonny Harianto at *harianto.1@osu.edu*.

March 21–24 2011—Automate 2011. McCormick Place, Chicago. Automation technologies such as robotics, machine vision and motion control help companies in every industry become stronger global competitors. Automate 2011 brings together a broad range of integrated solutions while examining the latest technology advances in these fields. Formerly the International Robots, Vision and Motion Control Show held once every two years, Automate 2011 has partnered up with ProMat 2011, a leading trade show for the material handling and logistics industries, to bring guests new ideas that can be put to use immediately. One badge gets you into both shows. For more information, visit *www.automate2011.com*.

March 22–26—IFPE 2011. Las Vegas Convention Center, Las Vegas. IFPE is the leading international exposition and technical conference dedicated to the integration of fluid power with other technologies for power transmission and motion control applications. Held every three years, the exposition showcases the newest innovations and expertise in fluid power, power transmission and motion control. More than 100 education sessions focus on the newest technologies, best practices and the latest research and developments including: The National Conference on Fluid Power, Innovations Theater and college-level courses in hydraulics and pneumatics. For more information, visit *www.ifpe.com*.

May 6–8—Gears, Motors and Controls Expo. Bombay Exhibition Centre, Mumbai, India. GMC 2011 is a showcase of gears, motors, controls and allied products scheduled to be organized from the 6th to 8th May 2011. The 3rd edition of the event builds on the success of the earlier editions held in Chennai & Mumbai. It will be held in conjunction with Pumps, Valves & Compressors Expo 2011. The three-day event will be promoted extensively across India and the region, and visitors will comprise key decision makers from nearly every industry segment. With customer satisfaction at the heart of the trade show's strategy, GMC 2011 hopes to build on previous efforts and deliver maximum rewards to the participants. Bonfiglioli and Elecon are industry partners for the 2011 event.

Bullock

PRESENTED LIFETIME ACHIEVEMENT AWARD

Ron Bullock

At its 2010 Manufacturing and Wholesale Distribution Executive Summit in Rosemont, Illinois, RSM McGladrey presented its Lifetime Achievement Award to Ron Bullock, chairman of electric motor and gearmotor manufacturer Bison Gear & Engineering Corp. In presenting the award, Karen Kurek, Managing Director of RSM McGladrey, noted that "Ron Bullock exemplifies the ideal of the executive who serves both his business and his community, in equal and exemplary fashion. His leadership in the power transmission industry is equaled by his vision for the quality of secondary education."

"We are still the world's biggest manufacturing economy with 12 million highly productive workers—50 percent more productive than the next 11 leading manufacturing economies," said Bullock. "Manufacturing also accounts for one-half of all research and development in the United States."

In outlining Bullock's industry leader qualifications for the award, it was noted that he currently serves as chairman of Bison Gear & Engineering Corp. in St. Charles, Illinois, where he made significant strides in product innovation and market expansion after his acquisition of the company in 1987. In addition, Bullock has played a leadership role in numerous industry associations, having served on the Industry Advisory Council on Electric Motors at Underwriters Laboratories and as a past director of the American Gear Manufacturers Association (AGMA). He was a founding member of SMMA, the Motors & Motion Association, as well as the Electric Motor Education & Research Foundation (EMERF). Bullock has served as vice chairman of the National Association of Manufacturers (NAM) and chairman of the Illinois Manufacturers Association, the oldest and largest state manufacturer's organization in the United States. In addition, he is a director of NAM and vice chair of its think-tank, The Manufacturing Institute.

Addressing his community participation, Bullock related, "As a life-long learner, I benefited from a great public school education, but I'm discouraged by our current inability to provide the necessary skill sets for young people to qualify for entry level positions in today's high tech manufacturing. I've been engaged over the past several decades working with educators to improve the system. What really works is applied learning that students can use in their day-to-day lives."

As an example of his applied learning philosophy, Bullock and Bison Gear developed numerous pilot programs with high schools as a model of cooperation between industry and local school systems. In 2007, Bison Gear implemented its Skilled Workforce Initiative in cooperation with the College of DuPage, bringing manufacturing leaders, educational institutions, economic and workplace development organizations together to create a talent pool of better-qualified employees with plans to offer long-term stable employment.

The Illinois Department of Commerce and Economic Opportunity recognized the Skilled Workforce Initiative by presenting Bison Gear its Business Leadership Award. Testimony Bullock delivered before the National Science Board on K-16 Science, Technology, Engineering and Mathematics (STEM) education in 2005 led to an invitation to serve on NSB's Commission on 21st Century Education in Science, Technology, Engineering and Mathematics. In 2009, Bullock was appointed by the governor to the State of Illinois' P-20 Council to help align and improve education throughout the statewide system.

"Through the NAM Manufacturing Institute, we have developed a system of stackable, portable credentials that young people can obtain in secondary education, and qualify for highly paid manufacturing jobs at companies that will encourage their continuing education," Bullock said.

After relating the saying, "A dream is just a dream if you are dreaming it alone," Bullock thanked the audience and enlisted their support with the challenge, "I would ask all of you to join me as we effect meaningful change in our educational system by supporting IMA's Education Foundation and the NAM's Manufacturing Institute. Together, we can make those dreams come true!"

Parker Hannifin

INVESTS IN WIND TURBINE SAFETY COURSES

Parker Hannifin has been providing hands-on support for hydraulic systems in wind turbines, to ensure they stay in top condition during extreme weather conditions. As the fastest growing energy sector, the wind energy market demands a specific type of technical support. Operating in some of the most severe weather and technical environments,

continued

Matt Fielder

wind turbines are running 24/7 and experiencing extremes of temperature and vibration. Parker's hydraulic filtration and fluid condition monitoring equipment is helping maintain fluid cleanliness in the turbines and ensuring extended life with real time contamination data.

For Matt Fielder, hydraulic filter division-Europe's industrial business development manager, this has meant a commitment to learning a new skill of ascending wind turbines safely that entailed attending a Wind Turbine Climbing Course run by the National Access & Rescue Centre (NARC). The two-day course was held in the Lake District in England, near the town of Kendal.

"It was a demanding but exhilarating two days that involved the correct use of equipment, a set of which I now have ready to ensure access to any wind turbine across the U.K.," explained Fielder. "The course also covered working at height, setting up working stations with the use of lanyards, evacuation from a turbine, rescue of injured workers and correct use of emergency evacuation equipment."

The qualification is a mandatory requirement for anyone needing to climb a wind turbine in the U.K. and Fielder's focus is developing new and existing power generation business, a view Parker fully supports and views as being a worthy investment for the company.

Hansen Transmissions

GETS BID FROM SUMITOMO

Sumitomo Heavy Industries, Ltd. has submitted an offer to Hansen Transmission International to acquire the shares of Hansen Industrial Transmissions NV, a manufacturer and distributor of industrial gearboxes based in Belgium. Hansen representatives have evaluated the proposed transaction in detail and believe it presents a great opportunity for both its industrial and wind gearbox businesses. Sumitomo will disclose details on the offer early 2011.

EPTDA

HOSTS SUCCESSFUL SUMMIT IN MALTA

The European Power Transmission Distributors Association (EPTDA), an association for the industrial distribution channel in Europe, hosted another successful industry summit in Malta, welcoming more than 280 participants from around the world. The leading association continues to grow at a promising pace as it welcomed almost 63 first timers, nine non-member companies and 30 international guests from the United States, Canada, South Africa, Egypt, Japan, etc.

EPTDA's Manufacturer Distributors Idea Exchange (MD-IDEX) sessions facilitated more than 750 individual meetings between manufacturers and distributors, highest ever in its history.

The association also hosted its first ever, "Next Generation" event at the convention, welcoming more than 40 young business potentials aiming to attract the future talent to invest, engage and get involved in the PT/MC industry.

EPTDA's newly elected president, David Harrow, managing director of Godiva Bearings, says "We are extremely proud of the success of our association and the annual convention in Malta. The positive energy amongst the members, a strong belief in the benefits that we offer to them, and growing interest from other industry leaders to join us, signals that we are moving ahead on the road to recovery, and helping PT/MC leaders to grow profitably."

One of the most successful highlights of this year's convention was the "Company Visits" organized in cooperation with Malta Enterprise. The executive chairman of Malta Enterprise, Alan Camilleri, served as the guest of honor at the Annual Business Meeting and welcomed participants to explore the trade and economic strengths of Malta, a small but promising business hub which is already home to several multinational enterprises like Lufthansa Technik Malta Ltd, Trelleborg Sealing Solutions, Methode Electronics, Hetronic Malta, Vodafone and many more.

"Our aim is to add value to our members' business and help them succeed," says Hans Hanegreefs, executive vice president of EPTDA. "Malta boasts many achievements across numerous sectors including pharmaceuticals, mechanical engineering, electronics, maritime products, yacht services, biomedical equipment, aircraft maintenance and many other industries that are directly or indirectly related to the PT/MC industry. The "Company Visits" is another innovative initiative by EPTDA to share information and knowledge that can be vital to our members' business growth," Hanegreefs adds.

Taraman

NAMED SME EDUCATION BOARD PRESIDENT


Khalil S. Taraman

Khalil S. Taraman, Ph.D, FSME, PE and D.I.T. chair of manufacturing engineering, Lawrence Technological University (LTU), Southfield, Michigan, has been named president of the SME Education Foundation board of directors for 2011, his second term in this position. Taraman's commitment to manufacturing engineering education which spans more than 40 years includes mentoring young men and women and encouraging them to pursue viable careers in manufacturing, engineering, science and technology. An incumbent officer and SME member since 1970, Taraman joined the SME Education Foundation in 1992 serving as

continued

chair of its nominating committee for a number of years before being elected vice president in 2008. His many awards include being named SME Educator of the Year—SME Region VII, California in 1988; SME Fellow in 1991, receiving the SME International Siegel Award in 1998, and being given the Outstanding Leadership Award in 1999 and 2000.

A graduate of Ain Shams University in Egypt, Taraman earned a BSME in 1964 and a MSME in 1967. He secured a MSME in 1969 from the University of Wisconsin and his Ph.D. in 1971 from Texas Tech University. Prior to joining LTU, Taraman was a professor at the University of Detroit for 16 years, where he was director of the Manufacturing Engineering Institute and ME Chairman. He served as senior technical consultant to many companies, the most notable being Bendix, Ford Motor Company and General Electric. In 1986, Taraman joined LTU to serve as dean and associate dean of engineering. Today, he is the DIT Chair of Manufacturing Engineering and Director of Manufacturing Systems Graduate Programs (DEMS and MEMS). He has supervised more than 100 graduate students who obtained their master and doctorate of engineering under his direction at GM, Ford, Bendix, Chrysler, Westinghouse, GE and Daimler-Chrysler.

Joining Taraman on the SME Education board of directors are: vice president/secretary: Brian A. Ruestow, operations manager, F. W. Roberts Manufacturing Co., Inc., Lockport, NY; treasurer/chair of finance: Peter F. Mackie, senior vice president - investments, Wells Fargo Advisors LLC, St. Louis, MO, and assistant treasurer/vice chair of finance: Edward Swallow, vice president, Business Development, Civil Systems Division, Northrop Grumman Information Systems, McLean, VA.

Whiteside

PROMOTED TO SALES MANAGER AT MAXCESS


Darrell Whiteside

Maxcess International, a provider of engineered components for the web handling industry, recently announced the promotion of Darrell Whiteside to sales manager, North America. Whiteside will manage one of the largest networks of factory-trained salespeople and enhance local sales efforts for Fife, Magpowr and Tidland products.

Whiteside joined Magpowr in 1999, assuming responsibilities for international sales. In 2001 he was promoted to the position of product manager for tension control; and, in 2007 became sales and channel manager for Magpowr products. Prior to joining Magpowr, Whiteside worked for Watlow Process Systems as a design engineer and Magnetek in International Sales. He has a bachelor's degree in industrial science with an emphasis on electronics and robotics from NE Missouri State University.

"Darrell's technical experience and understanding of our customer's unique needs have made him an invaluable member of the Maxcess team," says Tom Herold, vice president of sales – North America. "I'm confident he will hit the ground running as we work to further develop a customer-focused sales program that adds value while making it even easier to improve efficiency with Fife, Magpowr and Tidland equipment."

NFPA

RELEASES NEW TECHNICAL STANDARDS

The National Fluid Power Association (NFPA) has recently released seven new technical documents that are available for purchase including: ISO 10041-1:2010: "Pneumatic Fluid Power—Electro-Pneumatic Continuous Flow Control Valves—Part 1: Main characteristics to include in the supplier's literature"; ISO 10041-2:2010: "Pneumatic Fluid Power—Electro-Pneumatic Continuous Flow Control Valves—Part 2: Test methods to determine main characteristics to include in the supplier's literature"; ISO 10094-1:2010: "Pneumatic Fluid Power—Electro-pneumatic pressure control valves—Part 1: Main characteristics to include in the supplier's literature."; ISO 10094-2:2010: "Pneumatic Fluid Power—Electro-pneumatic pressure control valves—Part 2: Test methods to determine main characteristics to include in the supplier's literature"; ISO 19879:2010: "Metallic tube connections for fluid power and general use—Test methods for hydraulic fluid power connectors."; NFPA/T3.6.8 R3-2010: "Fluid Power Systems—Cylinders—Dimensions for accessories for cataloged square head industrial types"; NFPA/T3.6.37 R1-2010: "Hydraulic Fluid Power—Cylinders—Methods for determining the buckling load."

Sandvik, Haas and ABB Robotics

CELEBRATE TECH CENTER

Sandvik Coromant recently participated in the grand opening ceremony of the Haas Technical Education Center (HTEC) at Vincennes University's Indiana Center for Applied Technology (ICAT). Held in late October, the event celebrated the dedication of the facility and was attended by more than 250 educators, manufacturers, students and government officials. Brian Norris, vice president of marketing at Sandvik Coromant, spoke at the ceremony, along with representatives from Haas, ABB Robotics, CNC Software and various government, educational and trade organizations. The day's events focused on the current shortage of skilled workers and the need to apply innovative solutions to the issue. Sandvik Coromant has been an ongoing supporter of HTEC for many years and has been a key partner to the 1,000+ HTECs in the United States since the beginning of the HTEC program. The HTEC facility housed at ICAT is one of the largest in the nation, housing 35 Haas machines using Sandvik Coromant tooling. "Educational initiatives are important to every individual and company working in American manufacturing, as well as the country as a whole," Norris said. "The ICAT facility at Vincennes University provides an exceptional example of what can be accomplished when providers of manufacturing products work together with educators and government. Sandvik Coromant is proud to support such efforts." ICAT contributes to workforce development by offering college-level manufacturing courses, along with providing training and curriculum development assistance to educators and the industry.

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Urban Mobility—

REINVENTING THE WHEEL

Suggesting a bicycle is environmentally friendly is stating the obvious. But the Copenhagen Wheel, unveiled at the 2009 COP15 United Nations Climate Conference, is taking green technology and cycling in a new direction. Scheduled for release in June 2011, the Wheel was conceived and developed by the SENSEable City Lab, a research initiative at the Massachusetts Institute of Technology (MIT).

The smart/responsive Wheel allows the rider to capture the energy dissipated while cycling and braking and store it for later use. The "hybrid E-Bike" also maps pollution levels, traffic congestion and road conditions in real-time. Riders hook up to the Wheel through their smart phones and can lock/unlock the bike, change gears or select how much assistance they need from the motor.

"Our goal with the Copenhagen Wheel is to promote cycling by expanding the range of distance people can cover and by making the riding experience smoother," says Assaf Biderman, associate director at the SENSEable City Lab. "When long distance and steep hills are no longer barriers to comfortable cycling, many cities can become more bicycle-friendly."

The Copenhagen Wheel differs from other electric bikes in that all components are elegantly packaged into one hub. There is no external wiring or bulky battery packs, making it retrofittable into any bike. Inside the hub, City Lab has arranged a motor, three-speed internal hub gear, batteries, a torque sensor, general packet radio service (GPRS) and a sensor kit. In the future, riders will be able to spec out their bikes according to their personal riding habits and needs.

The Wheel's sensing unit collects information on road conditions, carbon monoxide, noise, ambient temperature and relative humidity. The rider can access this information through his or her phone or the Web and use it to plan healthier bike routes. It will also track the rider's exercise goals.

"Bicycles are very efficient machines," Biderman says. "Rather than reinventing them, we're introducing a simple technological enhancement that allows any bike to become a smart and responsive hybrid."

Cyclists utilizing the Wheel can also make bigger contributions through their daily commute. Sharing the information collected with the city allows city planners to cross-analyze different types of environmental data on a scale that has never before been achieved. It can also build a more detailed understanding of the impact of transportation on a city infrastructure or study dynamic phenomena like urban heat islands. Ultimately, this type of crowd sourcing can influence how a city allocates its resources, how it responds to environmental conditions in real-time or how it structures and implements environmental and transportation policies.

"Over the past few years we have seen a kind of 'biking renaissance,' which started in Copenhagen and is now transforming the urban experience in many cities from Paris to Barcelona or Montreal," says Professor Carlo Ratti, director at SENSEable City Lab. "We could also call it a 'Biking 2.0' revolution, whereby cheap electronics allow us to augment bikes and convert them into a more flexible, on-demand system."

While the navigation, health reporting and smart phone functions are fairly snazzy, one of the Wheel's greatest technological achievements may be its smart security system.

"If someone rides away with it, the Wheel goes into a mode where the brake regenerates the maximum amount of power and sends you a text message with its location," Biderman says. "So in the worst case, the thief will have fully charged your batteries before you get back your bike."

For more information on the Copenhagen Wheel, contact *senseable-cph@mit.edu* or visit *www.senseable.mit.edu/copenhagenwheel/*.