May 2007

# GEAR TECHNOLOGY

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The Journal of Gear Manufacturing



*THE GEAR INDUSTRY'S INFORMATION SOURCE*

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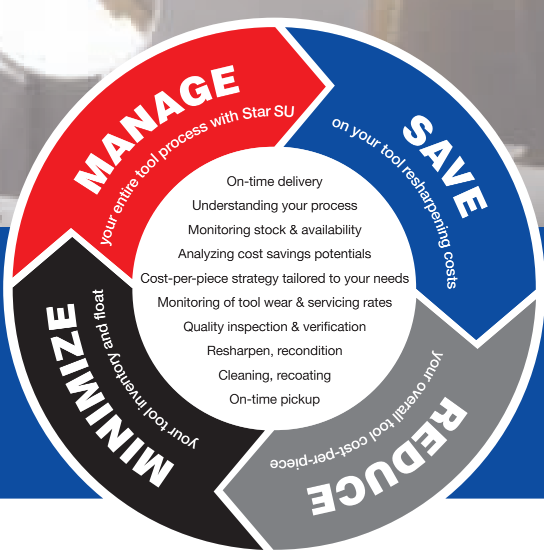


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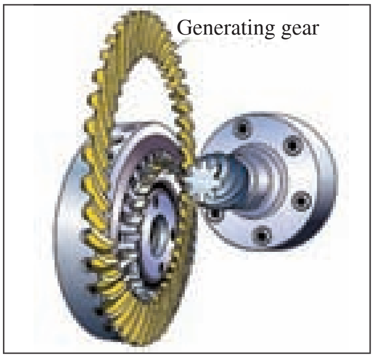




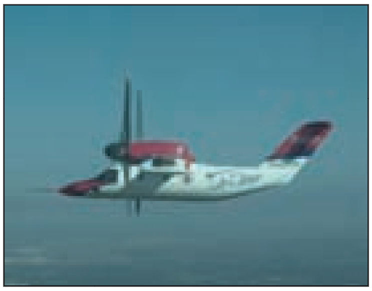

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May 2007

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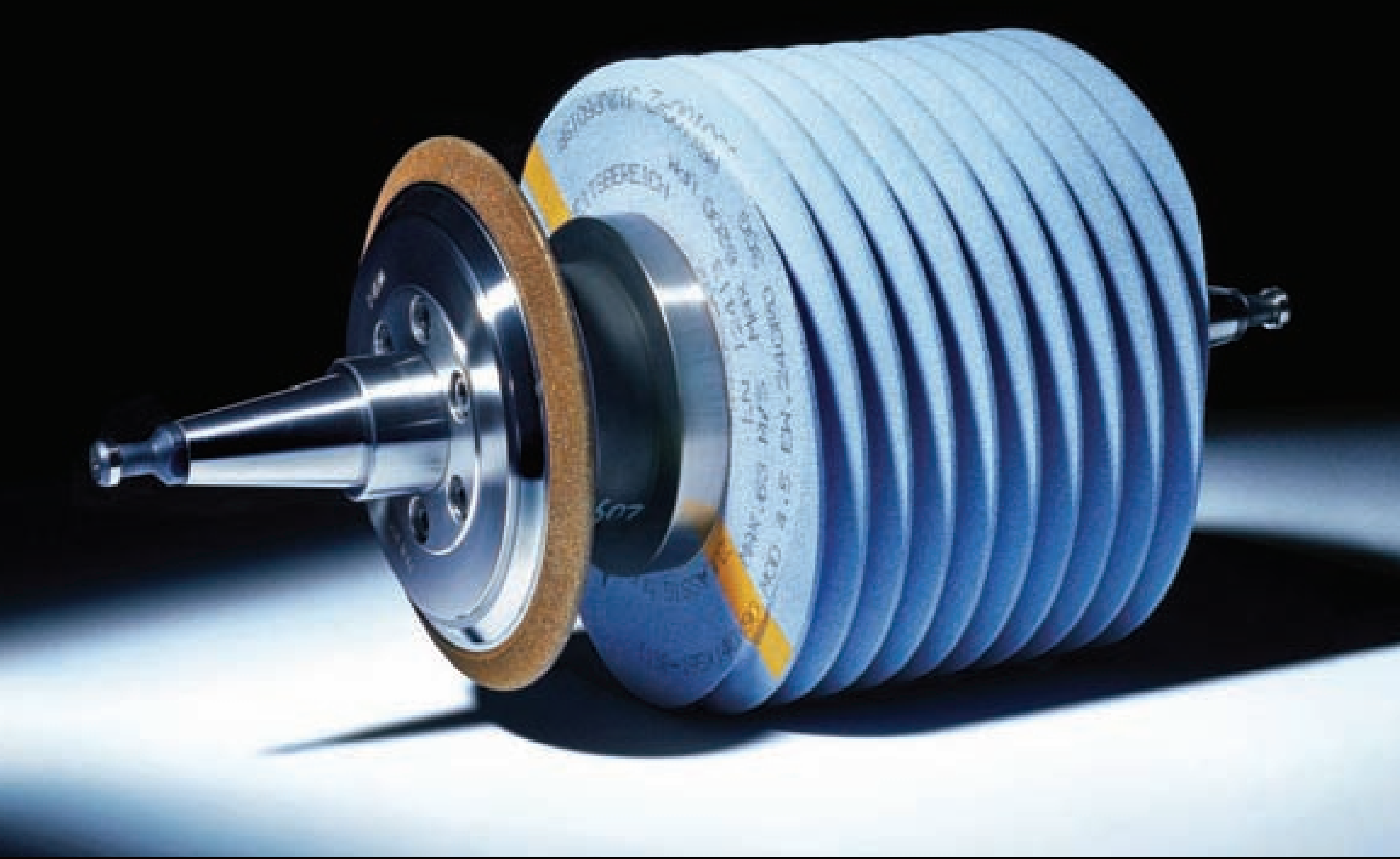

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EDITORIAL

| | |
|---|---|
| **Publisher & Editor-in-Chief** | Michael Goldstein<br>*publisher@geartechnology.com* |
| **Managing Editor** | William R. Stott<br>*wrs@geartechnology.com* |
| **Senior Editor** | Jack McGuinn<br>*jmcguinn@geartechnology.com* |
| **Assistant Editor** | Robin Wright<br>*robin@geartechnology.com* |
| **Editorial Consultant** | Paul R. Goldstein |
| **Technical Editors** | Robert Errichello, Don McVittie,<br>Robert E. Smith, Dan Thurman |

ART

| | |
|---|---|
| **Art Director** | Kathleen O'Hara<br>*kathyohara@geartechnology.com* |

ADVERTISING

| | |
|---|---|
| **Advertising** | RK Media, Inc.<br>Ryan King<br>*ryanking@geartechnology.com* |

CIRCULATION

| | |
|---|---|
| **Circulation Manager** | Carol Tratar<br>*subscribe@geartechnology.com* |

INTERNET

| | |
|---|---|
| **Web Developer** | Dan MacKenzie<br>*webmaster@geartechnology.com* |

RANDALL PUBLISHING STAFF

| | |
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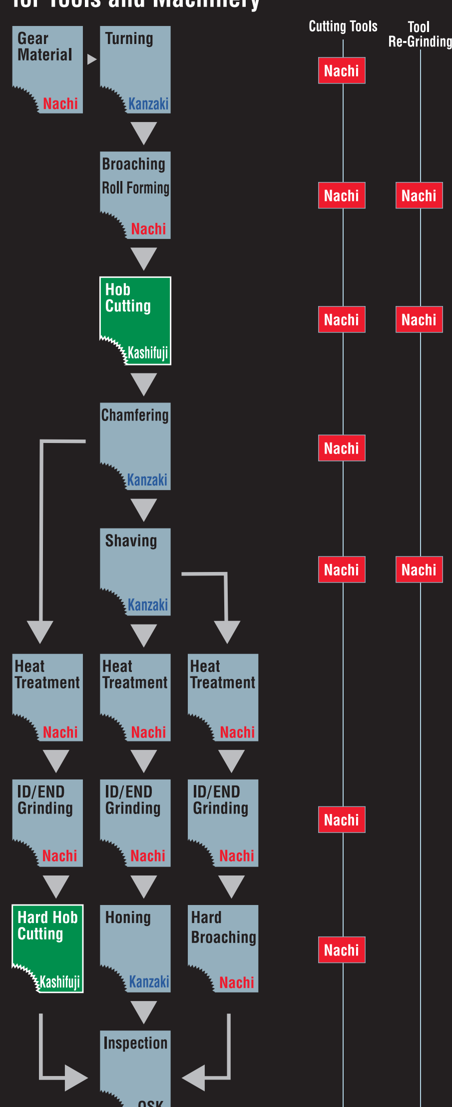
Gear Production Alliance

## Gear Cutting Process Task Assignments for Tools and Machinery

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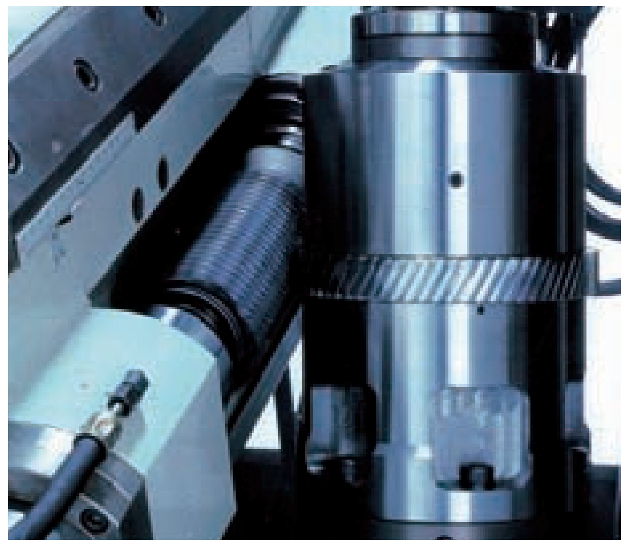
Kashifuji

# Environmentally friendly hobbing machine



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**NACHI AMERICA INC.**
17500 Twenty-Three Mile Rd., Macomb, MI 48044
Tel:586-226-5151 Fax:586-263-4571
E-mail:machinetools@nachi-ind.com

Coming in Next Issue OSK Display!

# The Gear Industry's GLOBAL Information Source

Have you ever been to Malaysia? How about Indonesia, Brazil, Slovakia or Russia? Well, we have. We go there every issue. *Gear Technology* has subscribers all around the world, so we go to a lot of places. Heck, we even have a subscriber in Ethiopia. Really, Ethiopia. He's responsible for making replacement parts, including gears, at a major cement manufacturer. (Hello, Daniel!)

All over the world, people are hungry for the type of information *Gear Technology* provides. People like Daniel seek us out to subscribe.

And we're looking for them, too. When we identify new gear companies—no matter where they are—we send them free sample copies of the magazine. In return, they send back subscription forms.

Today, *Gear Technology* has paid or qualified subscribers in 70 countries. In January, we mailed an extra 1,000 copies of the magazine to gear manufacturers in China. This issue, we've done the same thing by mailing to potential subscribers in India.

We embrace the globalization of the gear industry. In today's world, you almost have to. Many of you work for companies who have established joint ventures, partnerships, sales and marketing agreements or other arrangements with companies in other parts of the world. You, too, embrace the globalization of the gear industry.

But I know what some of you are thinking. Why is *Gear Technology* helping to educate my potential competitors around the world? Does *Gear Technology* want my foreign competitors to take away my business?

Nothing could be further from the truth.

The fact is, the gear industry is already quite global. How many of you have customer lists that look like our subscriber list? Do you have more overseas customers than you had 10 years ago? I thought so. Now, ask yourself: Are you better off if those customers actually understand gear manufacturing? Or are you just better off if they want the lowest price? *Gear Technology* helps spread the knowledge of what goes into quality gear manufacturing. We teach and reach the global gear industry.

Besides all that, you can't stop your overseas competitors from learning. Companies in China and India are buying technology at an astounding rate. You need to stop thinking of them as countries that compete on low-cost labor. In some cases, their machine tools and processes may be more modern than yours.

In April, many of the world's leading gear machine tool manufacturers exhibited at the CIMT machine tool show in Beijing (see our article on p. 55). CIMT is the Chinese version of IMTS or EMO. Virtually every company that makes equipment for manufacturing gears wants a piece of that market. Many of them are unveiling new machine models for the first time at this show.

Most of you are still very busy. Your order books are probably filled through the end of next year, and you're getting prices that actually allow you to make a profit. So right now, you're probably not too worried about foreign competition.

My sense is that gear manufacturers in other countries are just as busy. Right now, countries like India and China have a huge demand for gears within their own borders. Their growing middle classes want automobiles, appliances, good roads, electricity and safe housing. Building the infrastructure alone requires massive amounts of machinery. Even in Ethiopia, you can't make cement without gears.

But someday there'll be a recession. When it comes, look out! Right now, China and India are building up their capacity. What will they do with that capacity when things get tight in their home markets? Maybe they'll look to sell more gears in your backyard.

When they do, will you be ready? Will you look to these foreign companies as potential partners, as many have begun to do already?

The gear industry is already global, and it will grow more global with each passing year. *Gear Technology* is making every effort to be at the center of this globalization. How about you?

Michael Goldstein,
Publisher & Editor-in-Chief

P.S. *Gear Technology*'s circulation has been audited annually by BPA International since 1996. You can view our current circulation statement by visiting *http://www.geartechnology.com/bpai_statement.pdf*. The statement shows that we had qualified subscribers in 62 countries as of the November/December 2006 issue. Because our subscriber list is constantly changing, all the circulation data included in this editorial is based on our most current publisher's data.

# Letters to Editor

## Name That Beachfront

While reading through the January/February 2007 issue of *Gear Technology*, a question arose around the location of a picture that appears on page 80. The picture in question is at the top of the page and has the caption "Beachfront Gear Manufacturing" running through it. One believes the location to be Harrison Hot Springs in British Columbia. It looks very close, but I am not sure. Could you shed some light on this for us?


ADDENDUM

Beachfront Gear Manufacturing

Lots of us became interested in gears while taking drafting classes in high school. Kirk Rademaker got hooked on orthographic projection as a teenager, but went about pursuing his passion for gears in a unique way.

Rademaker became an interactive environmental artist and makes his living creating gears, transmission, nuts and bolts, turbines and various other industrial machinery out of sand. He's based in Santa Cruz, CA, and travels the world participating in corporate team-building events and creating customized sand sculptures for parties. Gears are a favorite of the artist's because of their sharp lines and abstract shapes.

"I just love doing gears because they're a sign of movement. My abstracts always have a lot of movement. I looked at some of the sculptures and decided they looked mechanical and went mechanical," he says.

It takes from three to five days for Rademaker to construct a sculpture. He compares the sand's consistency to working with stale mashed potatoes and, upon completion, sprays the sculpture with glue for adhesion.

Sand gears don't come cheap and Rademaker says he was recently paid $1,000 per sculpture per day, plus airfare and lodging at the Ritz-Carlton San Juan for a gas turbine he created for a conference.

"This isn't a job that I'll ever get rich doing, but I've been able to travel to Europe and all over the world making sand sculptures, and I love the creativity and working with people on the beach," he says.

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Or call (847) 437-6604 to talk to one of our editors!

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Thanks for looking into this for us.

Regards,
Gordon Kisser, purchasing
Vancouver Gear Works Ltd.

*Editors' Reply: Good call! The picture is indeed from Harrison Hot Springs, B.C. For additional information on the gear sand sculptures, visit the artist's website at* www.sandguy.com.

## Overseas Outsourcing Hurts Our Industry

*(Editor's Note: The following letter was in response to our online Voices question, "Is OEM Outsourcing Good or Bad for the Gear Industry?")*

OEM outsourcing [outside the United States] is in no way any good for any industry, let alone the gear industry. Gear manufacturing is one of the most difficult types of machining, and it takes training to do it right.

A lot of the companies that have begun outsourcing their gears now had to let a lot of good machinists go. Now those machinists are working (if they are lucky) in a machine shop atmosphere that is not challenging their knowledge in gear manufacturing. In many cases, that is because it was the only job they could find close to home.

I travel through all of North America and see plants from New York to Detroit to Mexico, and you cannot prove to me that outsourcing gears overseas or even to Mexico can be cheaper. There are a couple of plants in the Carolinas that are the most state-of-the-art gear manufacturing plants around, and you can't tell me that outsourcing to lower labor cost countries is cheaper. The larger OEM companies that outsource their gears now do it only because they don't what to invest in the equipment needed to be competitive.

You can walk in a gear plant in Detroit and there will be one guy operating one machine. In other parts of the country, it might be one guy for four machines, but at the plants in the Carolinas, it's more like one guy for six or eight machines—and he's not working as hard as the one guy in Detroit.

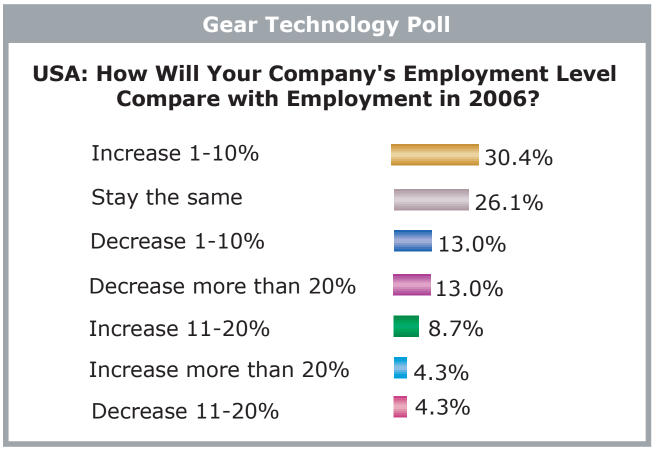
Anyway, when we close another plant, there are just that many more gear machinists to go on to other industries. There's a bevel gear plant closing in Missouri soon. It had about 200 employees at the plant with about 75 working in the gear cutting area. Almost all will soon be working outside the gear industry and more than likely not in manufacturing at all. That's not good for the gear industry, much less manufacturing.

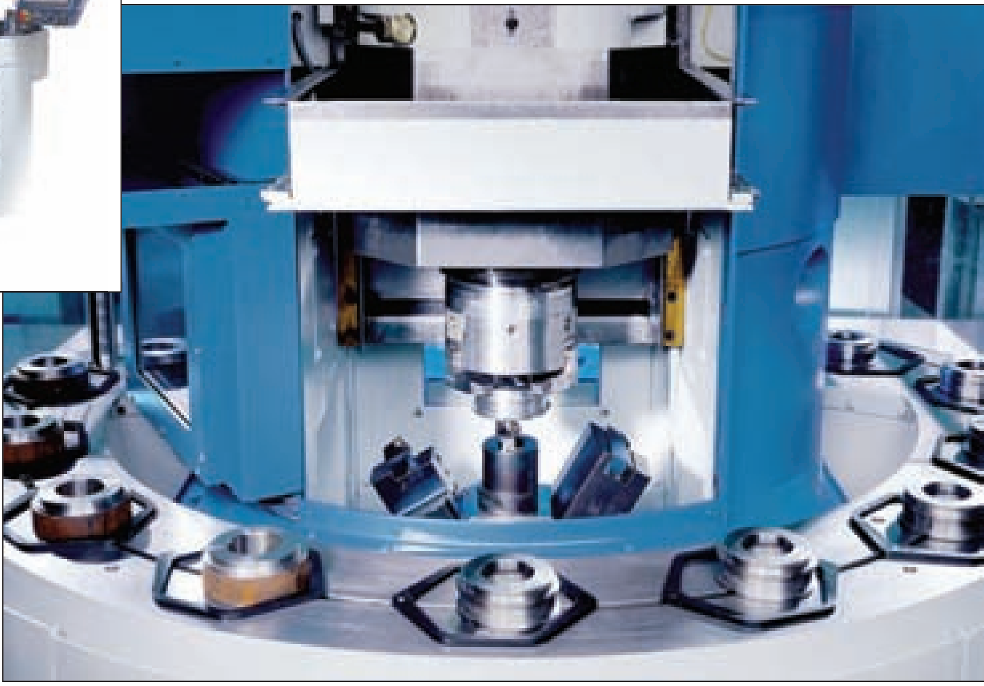
Maybe we need to have a job fair for gear manufacturers in cities that are losing gear making plants?

Ned Hoermann, sales manager
Engineered Tools Corp.

## American Gear Industry Still Optimistic About Growth in 2007

According to the results of our online poll, 43.4% believe their companies will employ more people in 2007 than in 2006.



# Emag's Newest Vertical Turning Centers

## OFFER QUICKER AUTOMATIC WORKPIECE CHANGEOVER

The VL series vertical standard turning machines from Emag are universal production tools with a small footprint and automatic workholding included.

A recirculating belt conveys the workpieces to the pick-up station in carrier prisms that require no resetting. The pick-up station is located behind the machining area, which allows for removal of finished raw components and the insertion of new raw parts at the front and when desired. The workpiece can be inserted directly into the carrier prism or into special workpiece receptors located in the prism. Therefore, the automated system provides a fixed production cycle when a new part is ready as soon as the old part had been machined. Where asymmetrical or long and thin workpieces have to be machined or where components have to be specially aligned, workpiece receptors and pallets of simple design can be inserted into the carrier prism. This allows for fully automated loading and unloading of a variety of workpieces.

The VL series is equipped with a chip conveyor, fume extractor, fluid-cooling systems for spindle motor and turret and automated workhandling solution.

With less than 400 mm travel between loading and machining position on the turret on the smaller and only 550 on the larger, the VL offers shorter speeds for a workpiece changeover. According to the company's press release, chip-to-chip times are shorter, which ultimately yields better output rates.

All guideways are protected from chips and dirt, as they are located above and outside the machining area. Telescopic covers are not used on the VL.

**For more information:**
EMAG LLC
38800 Grand River Ave.
Farmington Hills, MI 48335
Phone: (248) 477-7440
E-mail: *info@usa.emag.com*
Internet: *www.emag.com*

# Sunnen's Vertical CNC

## CLOSES LOOP ON AUTOMATED BORE SIZING

Sunnen's SV-1005 series vertical CNC honing system is now available with an integrated air gaging system to provide closed-loop control of tool size, along with downloadable SPC data. Matched with Sunnen's diamond-plated CGT Krossgrinding® tools or MMT Turbo-Hone multi-stone mandrels, the air-gage-equipped machine can automatically control hole size to accuracies of 0.25µm (0.000001") without operator intervention, working in a size range of 3–65 mm (0.120-2.56") diameter.

According to the company's press release, it is suitable for automated, high-Cpk production of small engines, hydraulic valves/bodies, fuel injectors, gears, compressor parts, turbocharger housings and gun barrels, in medium and high volumes.

Dolph Schallenberg, sales manager, says that by combining the new air gaging system with the machine's patent-pending tool-feed control, the SV-1005 eliminates the need for an experienced honing operator to tweak the process. The new Etamic air gaging system controls bore diameter and geography by

continued

taking post-process measurements of the parts while they are still fixtured on the machine's rotary table. He says that feedback from the air gage provides the highest possible accuracy for tool-feed control.

The SV-1005 matches an ultra-precise tool feed system with CNC control to allow any CNC-experienced machinist to master honing quickly. Setup is simple with a three-axis hand wheel for fine tuning the tool feed and the servo-controlled stroke system and rotary table. The control includes a switchable auto-correct feature for bore shape.

Using measurements from the air-gage system, it allows the operator to select from a library of "problem" bore images (taper, barrel, etc.) to match to the part on the machine. The servo-controlled stroke system ensures a consistent crosshatch pattern and can dwell in any part of the bore, end-to-end, selectively removing stock for ultra-precise straightness and roundness.

The vertical design of the SV-1005 conserves shop floor space, requiring just 2,400 x 2,300 x 2,700 mm WxDxH (95 x 91 x 107"). A cast-polymer base and cast-iron column provide enhanced vibration damping for precision honing, while removable stainless steel side doors facilitate integration with automatic part loading systems. The high-torque, belt-driven spindle is rated at 7.5 kW (10 hp) to cover a wide range of sizing and finishing work using Sunnen's MMT TurboHone® multi-stone mandrels, TC precision mandrels, or CGT Krossgrinding tools.

#### For more information:

Sunnen Products Co.
7910 Manchester Ave.
St. Louis, MO 63143
Phone: (314) 781-2110
E-mail: *bdavis@sunnen.com*
Internet: *www.sunnen.com*

## Drake Manufacturing's New Gear Grinders

### DESIGNED TO MOUNT ON A LINEAR MOTOR PLATFORM

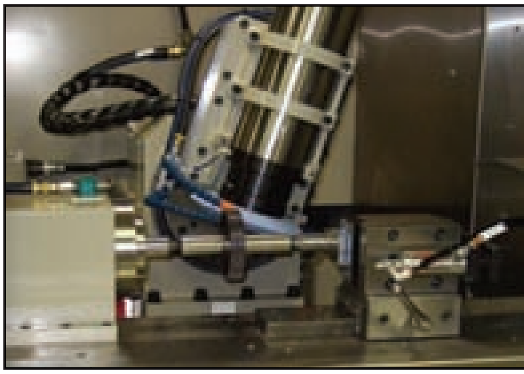
Drake Manufacturing is ready to ship serial number one of its range of GS:G2-LM 200 four-axis linear motor profile gear grinders.

The GS:G2-LM 200 was tooled to produce master gears. Available in two sizes, workpiece diameters from 200–350 can be accommodated. Minimum workpiece diameter is 25 mm. Both models are equipped with a +/–45° helix. An optional worm grind package increases the machine's capability to produce worms and other threads as well. The company says the GS:G2 lets manufacturers source net-shaped or hobbed gears for most suppliers and still retain control over the final product quality.

During the grinding cycle, Drake's SmartSpindle acoustic emission monitor allows fully automated gear tooth location and stock division to equalize grind stock. Fully automated machines with robot load are available. A direct-drive synchronous torque motor with encoder feedback of 0.2 arc seconds controls c-axis positioning. Linear axis positioning resolution is 0.05µm. Drake's GearSmart programming allows 15-minute changeovers. Operators need only to enter specific part and process information into menu-driven screens.

#### For more information:

Drake Manufacturing
4371 N. Leavitt Rd.
Warren, OH 44485
Phone: (330) 847-7291
Internet: *www.drakemfg.com*

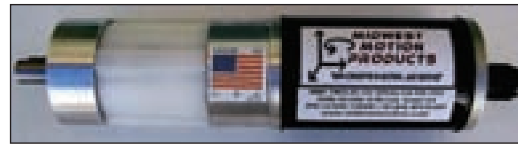


# Midwest Motion

## RELEASES NEW GEARMOTOR

Midwest Motion Products announced the release of a new DC Gear Motor, the Model No. MMP-TM55-90-12V GPk52-124.

Accepting any 12-volt DC source, including battery power, this gear motor measures 2.14" in diameter by 7.7" long and has a keyed output shaft of 12 mm diameter by 25 mm long. Mounting is accomplished with four “face mount” M5-threaded holes, equally spaced on a 40 mm diameter bolt circle.



The output of this reversible gearmotor is rated for 124 in-lbs, continuous torque, at 3.2 rpm, and 178 in-lbs peak.

Despite its size and weight of less than seven pounds, the gearmotor requires just 1.0 Amp at 12 volts DC to generate its full-load torque. Motor windings for 24, 36 and 90 volts are available.

This design is rated at an IP 54 protection level for operation in harsh environments. Typical options available from the company include servo motors with integral optical encoders, failsafe brakes, analog tachometers, and planetary gearheads, with standard ratios ranging from 3:1 to 2653:1, and standard or low backlash precision gearing available.

**For more information:**
Midwest Motion Products Co.
17061 Ahern Ave. S.E.
Watertown, MN 55388
Phone: (952) 955-2626
E-mail: *randy@midwestmotion.com*
Internet: *www.midwestmotion.com*



# MS Fluid Technologies

## INTRODUCES NEW COOLANT

MS Fluid Technologies launched a new product line at MetalForm 2007. The MSF Cool is a full line of coolants designed for use in cutting, grinding, tapping, roll forming, tube rolling, and other metalworking operations. It is currently being used by several manufacturers, including Rassini and Magna Power Train.

According to the company's press release, the improved bio-stability has increased fluid life tenfold at Rassini, and reduced coolant use by 85 percent. In addition, the product eliminated an oil mist cloud that had previously hovered in the machining plant.

**For more information:**

MS Fluid Technologies
2100 Greenbrier Ln.
Indianapolis, IN 46218
Phone (800) 486-1407
Internet: *www.msfluid.com*


## Timken

### EXPANDS ROUND BAR CAPABILITIES

The Timken Co. announced an expansion of its rolled carbon and alloy steel round bar capabilities and its capability to produce a maximum diameter of 15". This is the second time this year that Timken expanded its size ranges.

The round bar is easier for customers to work with as they manufacture their own products. Features include a consistent diameter along the full length of the bar, which can significantly improve the cutting of tight mult weights vs. other types of product. Additionally, the round bars have more hot work than cast ingots, allowing more flexibility in the size of product than is possible with a forger.

Rolled bar is used to produce parts for applications such as gears, rolled

continued


# WHEN LIVES ARE ON THE LINE, YOU CAN'T WORRY ABOUT HOW TIGHT THE BORE TOLERANCES ARE ON A HELICAL GEAR.

## ML-5000 AUTOMATIC HONING MACHINE

Gear bores demand critical tolerances. Sunnen's ML-5000 automatic honing machines hold bore size tolerances to within 5 microns with virtually any surface finish to meet stringent gear specifications.

Plus, it is up to 60% faster than previous honing techniques or I.D. grinding – perfect for mid-to-high volume production requirements. Greater honing speed, consistency and precision all add up to cost savings that can mean payback in just months.

To get your free cost analysis for your gear or other bore sizing application, call 1-800-325-3670 or visit www.sunnen.com/ML-5000.

SUNNEN®

*High Production Honing Solutions*

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I06-1

rings, forgings, bearings and valves for users in the industrial, energy and bearings markets.

According to the company's press release, Timken is the only domestic manufacturer to roll 13", 14" and 15" round bars and produce them in lengths up to 27', 23' and 20', respectively. In addition, the company also announced a $60 million expansion to enable it to competitively produce small bar steel down to 1" in diameter.

**For more information:**
The Timken Co.
P.O. Box 6929
1100 Cherry Ave. SE
Canton, OH 44706
Phone: (330) 471-3514
E-mail: *jeff.dafler@timken.com*
Internet: *www.timken.com*

## ZF's New Gearheads

### DESIGNED FOR BROAD RANGE OF SERVO APPLICATIONS

ZF launched a new range of compact WTE (WT Economy) single-stage, right-angled gearheads for OEM designers and maintenance engineers.

A one-piece aluminum body allows four ratios to be housed in the same size unit. In addition, universal mounting and the ability to fit all servomotors enables motors to be upgraded without requiring gearbox replacement. According to ZF's press release, sealed-for-life internal gearing eliminates the need for maintenance.

By integrating the Gleason hypoid tooth design and quality taper roller bearings, WTE gearheads offer operation in high axial and radial load applications. The body design is machined from a single piece of cast aluminum, offering high levels of torque from a one-piece, lightweight, compact unit that lends itself to use in highly dynamic servo applications. The WTE range covers four ratios from 5:1 to 15:1 in the same sized unit, cutting design

continued

time and facilitating maintenance or upgrades.

Units are compatible with the maximum number of servo applications in industries ranging from packaging to assembly. Two shaft options are available—a solid shaft with input flange/coupling and a choice of output flange mountings. Designed to be mounted in any orientation and to fit almost any motor, the input flange and coupling assembly allows motors to be replaced with higher-power versions or larger frame sizes, without replacing the gearhead.

A coupling-based torque transfer assembly also allows for adjustment for minimizing machine vibration. By shrink fitting the input shaft and gearwheel into the unit, fretting and levels of backlash are reduced to a minimum.

The range is specified for applications requiring input speeds up to 5,000 rpm while creating low noise levels. In addition, the WTE gearheads are approved for use in Atex Zone II applications and are sealed for life.

**For more information:**
ZF North American Operations
15811 Centennial Dr.
Northville, MI 48167
Phone: (734) 416-6200
Internet: *www.zf.com*

# Mahr Federal's New Surface Finish Gage

## INCLUDES USB INTERFACE

Mahr Federal will feature its new Pocket Surf PS1 Portable surface finish gage at the EASTEC 2007 Exposition.

Based on the company's Pocket Surf portable surface finish gages, the new Pocket Surf PS1 weighs 14 oz. and can measure more than 24 surface finish parameters with its high-resolution inductive probe. The PS1 offers a host of new features, including memory, USB connectivity, optional PC software, and a large measuring range.

The unit's large display provides measurement data at a glance and displays all functions in plain text. The most frequently used parameters—Ra and Rz—are directly selectable with more than 22 others easily accessible with scrolling function keys. Cutoff lengths are freely selectable and an integrated calibration master eliminates the need for external calibration.

A large measuring range of up to 350 microns allows versatility of application, including the ability to measure rough surfaces. The drive unit can be rotated and moved longitudinally; and the PS1 can measure upside-down,

continued

mounted on a surface plate or measuring stand, or even perpendicular to the contact surface with an optional end-face vee-block.

A wide range of available pick-ups adds flexibility. A dual-skid pick-up can be used for sheet metal and roller surface measurements; another is designed for concave and convex surfaces; and still others for measurements at such difficult to reach points as deep grooves.

According to Mahr's press release, this is the first instrument of its kind to include a USB interface. Therefore, the Pocket Surf PS1 can be connected to a PC for transfer and storage of data without requiring installation of any additional software or drivers. An optional software package is available for viewing profiles and results on a PC. This functionality makes it possible to collect large amounts of measurement data with the handheld device and transfer this data later to archival systems for quality system documentation requirements.

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Providence, RI 02905
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## Oil-Rite

### REDESIGNS BROAD VIEW LEVEL GAGE

Oil-Rite Corp. redesigned its broad view level gage to reduce the number of unique components and achieve a 15% price reduction.

Liquid level gages provide visible verification of fluid level in a holding tank, hydraulic reservoir, or recirculating tank. The broad view level gage offers a distinct advantage in the amount of area in which the liquid is visible.

The nylon viewing area is 1.75" across in lengths ranging from 3–36". The gage is mounted flush to the tank and allows an unobstructed view from the three visible surfaces. According to the company's press release, it is the preferred gage for monitoring liquid levels from a distance, in dark or confined spaces, or with clear/colorless fluids.

The gage is mounted to a tank with two hollow bolts that allow fluid to enter the nylon viewing area. The upper and lower entry points of the tank equalize atmospheric conditions within the internal chambers of the gage, ensuring that the level of the liquid in the gage is at the exact height of the liquid in the tank.

The broad view gage features red line tape for increased visibility. High viewing area. The gage is designed to utilize equivalent top and bottom components.

Interchangeable bolts allow the gage to be built with shut-off valves (for removal of the gage without emptying the tank) or a dial thermometer to monitor fluid temperature. The gage can be secured from the front (outside) with standard 1/2 x 20" bolts or from the back (inside) using a nut to tighten the gage and create a seal between the gage end blocks and the surface of the tank.

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325 Clipper Drive
P.O. Box 1207
Manitowoc, WI 54221-1207
Phone: (920) 682-6173
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## Inside the Haas Side-Mount Tool Changer

Our unique side-mount tool changer's synchronized cycloidal motion is controlled by a precision globoidal cam manufactured in-house on custom 5-axis Haas machines. This rugged, dependable design features a special Haas worm-gear drive and an electronically controlled start/stop system that is free of mechanical brakes, which often wear out and require replacing. Every Haas SMTC is manufactured completely in-house to ensure consistent high quality and guarantee fast, smooth, reliable operation.

# New Developments in Tooth Contact Analysis (TCA) and Loaded TCA for Spiral Bevel and Hypoid Gear Drives

Dr. Qi Fan and Dr. Lowell Wilcox



**Management Summary**

In the early 1960s, the Tooth Contact Analysis (TCA) technique was introduced for the theoretical analysis of the contact characteristics and running quality of spiral bevel and hypoid gear drives (Ref. 1). Application of the TCA program has substantially reduced the lengthy trial-and-error procedure for the design and development of spiral bevel and hypoid gear drives.

In the late 1970s, the tooth contact analysis under loaded conditions, the Loaded TCA (LTCA), was developed (Ref. 2). The *Loaded Tooth Contact Analysis* (LTCA) program provides a more realistic picture of tooth contact characteristics because tooth deformation and shaft deflection due to loading are taken into account for determination of the actual geometry of contacting tooth surfaces.

Both techniques have been accepted and applied throughout the bevel gear industry and have become powerful tools for the design and manufacturing of high quality spiral bevel and hypoid gears.

In the TCA computation, the gear and pinion tooth surface geometries are mathematically represented by the machine settings and cutter specifications. The existing TCA algorithms and programs were developed specifically corresponding to each method of tooth surface generation process and type of bevel gear drives. The application of modern CNC bevel gear generators has provided more motion freedoms for bevel gear generations. Traditional generating methods such as modified roll and helical motion can be considered as special cases of the possible motions of the CNC 6-axis generators. An advanced tooth surface modification approach has been developed by using the Universal Motion Concept (UMC) (Ref. 3). The UMC technique can be applied for a sophisticated modification of spiral bevel and hypoid gear tooth surfaces.

In order to satisfy the need for accurate modeling and analysis of the advanced design and modification of spiral bevel and hypoid gears, a new generalized tooth surface generation algorithm and a TCA approach are developed. This paper comprehensively describes these developments as applied to spiral bevel and hypoid gears produced by both the face-milling and face-hobbing processes.

LTCA was first developed assuming that the contact tooth surfaces are subject to Hertzian deformation, and approximating tooth stiffness by a cantilever beam model with modifications to improve deflection calculations at the ends of the teeth. With the advances in computational and memory capacities of modern computers, the finite element analysis (FEA) has been applied to gear tooth strength evaluations. A special FEA software package called *T900* was developed for the strength analysis of spiral bevel and hypoid gears (Ref. 4). *T900* provides an integrated environment with automatic pre-processor, post-processor, and graphic visualization of the FEA results, including the behavior of the contact under load, contact stress and bending stress.

Based on the improved FEA models and algorithms, a new LTCA program was developed as a subset of *T900*. LTCA provides the gear designers with detailed information on how the tooth contact pattern and transmission errors behave as a function of torque input, initial contact position and mounting deflections. The LTCA model uses TCA-generated tooth surface and fillet coordinates to define the gear and pinion geometry and to identify the instant contact positions. The nonlinear growth and movement of the area of contact common to the gear and pinion teeth are predicted by the use of specialized gap elements, the applied torque and axle stiffness input data. Multi-tooth finite element models are developed and applied for both the pinion and the gear.

## Introduction

Tooth Contact Analysis (TCA) and Loaded Tooth Contact Analysis (LTCA) are two powerful tools for the design and analysis of spiral bevel and hypoid gear drives. Typical outputs of TCA and LTCA are the graphs of contact patterns and transmission errors. TCA and LTCA respectively simulate gear meshing contact characteristics under light load and under significant load. TCA and LTCA programs have been widely employed by gear engineers and researchers in their design of high strength and low noise spiral bevel and hypoid gear drives.

Application of modern CNC hypoid gear generators has introduced new concepts in design and generation of spiral bevel and hypoid gears with modifications. This article presents new developments in TCA and LTCA of spiral bevel and hypoid gears. The first part of this article describes a new universal tooth surface generation model, which is developed with consideration of the universal motion capabilities of CNC bevel gear generators. The new universal model is based on the kinematical modeling of the basic machine settings and motions of a virtual bevel gear generator, which simulates the cradle-style mechanical hypoid gear generators and integrates both face milling and face hobbing processes. The tool geometry is generally represented by four sections, blade tip, Toprem, profile, and Flankrem. Mathematical descriptions of gear tooth surfaces are represented by a series of coordinate transformations in terms of surface point position vector, unit normal, and unit tangent. Accordingly, a new generalized TCA algorithm and program are developed.

In the second part of this paper, the development of a finite element analysis (FEA) based LTCA is presented. The LTCA contact model is formulated using TCA generated tooth surface and fillet geometries. The FEA models accommodate multiple pairs of meshing teeth to consider a realistic load distribution among the adjacent teeth. An improved flexibility matrix algorithm is formulated, in which the nonlinear formation of the area of contact common to the gear and pinion teeth is predicted by introducing specialized gap elements with considerations of deflection and deformation due to tooth bending, shearing, local Hertzian contact, and axle stiffness.

The advanced TCA and LTCA programs are integrated into *Gleason CAGE™ for Windows* software package. Two numerical examples, a face-hobbing design and a face milling design, are illustrated to verify the developed mathematical models and programs.

### Face Milling and Face Hobbing

There are two methods for manufacturing spiral bevel and hypoid gears—face milling and face hobbing—both of which are widely employed by the gear manufacturing industry and can be implemented on modern CNC bevel gear generators (Refs. 5, 6). However, the kinematical differences between the two methods are still not clear to some gear engineers and researchers.

The major differences between the face milling process and the face hobbing process are:

(1) In the face hobbing process, a timed continuous indexing is provided, while in face milling, the indexing is intermittently provided after cutting each tooth side or slot, which is also called single indexing (Fig. 1). Similar to face milling, in face hobbing, the pinion is cut with generating method, while the gear can be cut with either generating method or non-generating (FORMATE) method. The FORMATE method offers higher productivity than the

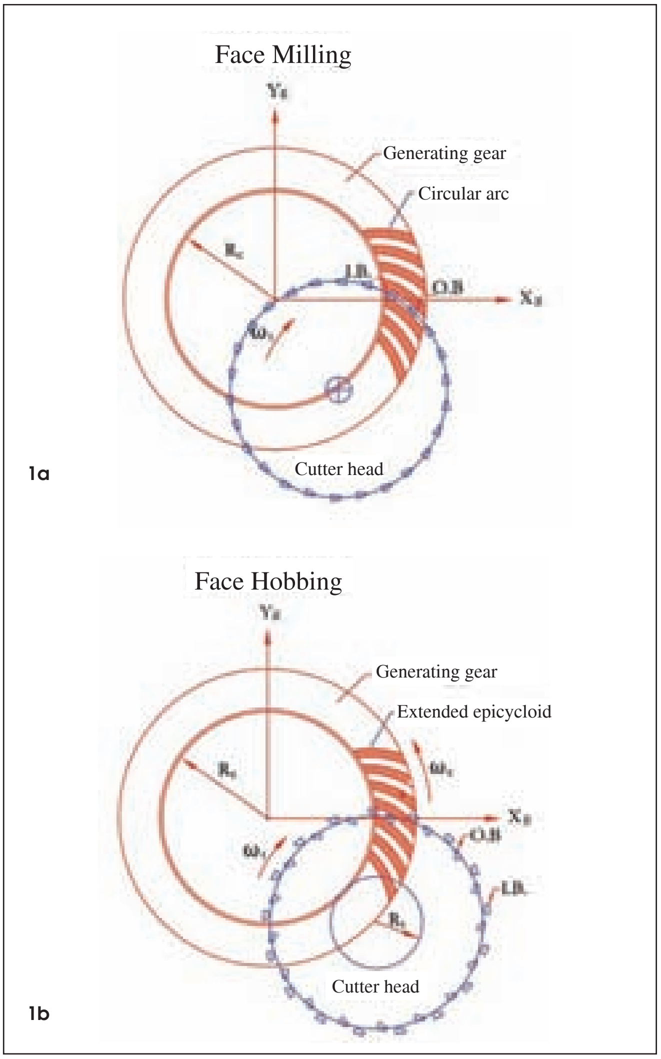


**Figure 1—Face milling vs. face hobbing.**

***Dr. Qi Fan*** *is a bevel gear theoretician at The Gleason Works of Rochester, NY. Prior to that, he worked in the Gear Research Center at the Mechanical and Industrial Engineering Department at the University of Illinois at Chicago. He was associate professor from 1987–1998 at Wuhan University of Technology, China. Fan has authored more than 20 papers on bevel gear research.*

*The late* ***Dr. Lowell E. Wilcox*** *worked at the Boeing Vertol Division in Philadelphia, PA in the Rotor Loads and Methodology Group where he was a senior engineer responsible for numerical modeling of helicopter rotor loads and dynamics. Since leaving The Boeing Company, he worked at The Gleason Works in Rochester, NY for 32 years where he was senior research staff engineer responsible for analyzing the performance of new gear cutting and grinding machines. Wilcox developed comprehensive commercial software system named T900 for the strength analysis of bevel gears, which has been broadly used by many bevel gear engineers and researchers. In addition he was an adjunct professor from 1983 until 1988 at Rochester Institute of Technology teaching strength of materials and introduction to the finite element method. He died January 11, 2005.*

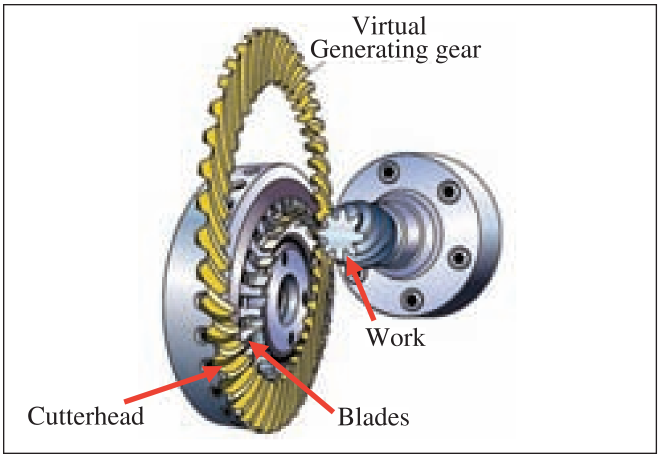


**Figure 2—Generalized bevel gear generation configuration.**


**Figure 3— Phoenix® II 275HC hypoid gear generator.**

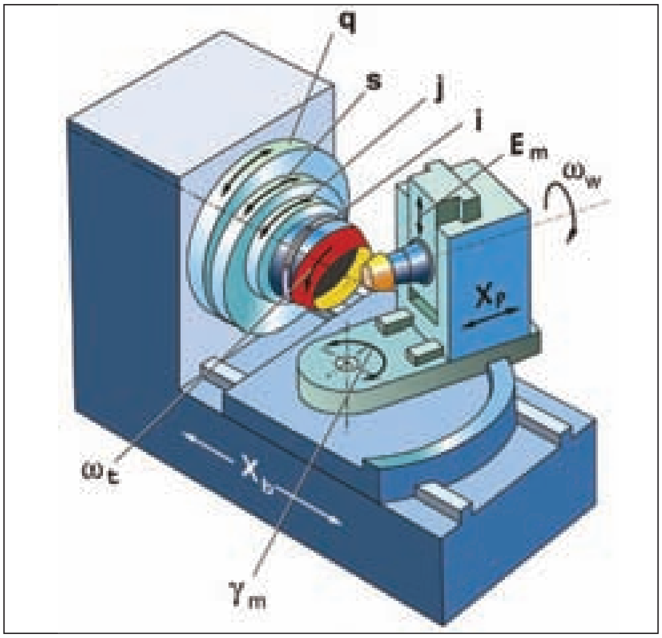


**Figure 4—Kinematical model of a hypoid gear generator.**

generating method because the generating roll is not applied. However, the generating method offers more freedom in controlling the tooth surface geometries.

(2) The lengthwise tooth curve of face-milled bevel gears is a circular arc with a curvature radius equal to the radius of the cutter, while the lengthwise tooth curve of face-hobbed gears is an extended epicycloid that is kinematically generated during the relative indexing motion.

(3) Face hobbing gear designs use uniform tooth depth systems while face milling gear designs may use either uniform depth or various tapered tooth depth systems.

Theoretically, the bevel gear cutting process is based on the generalized concept of bevel gear generation in which the mating gear and the pinion can be considered respectively generated by the complementary virtual generating gears. Figure 2 shows a configuration of a bevel pinion generation, which consists of a virtual generating gear, a cutter head with blades, and the workpiece (the pinion). The rotational motion of the virtual generating gear is implemented by the cradle mechanism of a bevel gear generator. Generally, the tooth surfaces of the generating gears are kinematically formed by the traces of the cutting edges of the blades. In practice, in order to introduce mismatch of the generated tooth surfaces, modification is applied on the generating gear tooth surface and on the generating motion.

In the spiral bevel and hypoid gear generation process, two sets of related motions are generally defined. The first set of related motion is the rotation of the tool (cutter head) and rotation of the workpiece, namely,

$$\frac{\omega_t}{\omega_w} = \frac{N_w}{N_t} \tag{1}$$

Here, $\omega_t$ and $\omega_w$ denote the angular velocities of the tool and the workpiece; $N_t$ and $N_w$ denote the number of the blade groups and the number of teeth of the workpiece, respectively. This related motion provides the continuous indexing between the tool and the work for the face hobbing process. The indexing relationship also exists between the rotation of the tool and the generating gear as,

$$\frac{\omega_t}{\omega_c} = \frac{N_c}{N_t} \tag{2}$$

where $\omega_c$ and $N_c$ denote the angular velocity and the number of teeth of the generating gear, respectively. In the face hobbing process, the indexing motion between the tool and the generating gear kinematically forms the tooth surface of the generating gear with an extended-epicycloid lengthwise tooth curve.

However, Equations 1 and 2 are not applicable for the face milling process where the cutter rotates independently at its selected cutting speed and forms a surface of revolution for the generating gear teeth with a circular lengthwise curve as shown in Fig. 1a.

The second set of related motions is the rotation of the generating gear and rotation of the workpiece. Such a related motion is called rolling or generating motion and is represented as

$$\frac{\omega_w}{\omega_c} = \frac{N_c}{N_w} = R_a \qquad (3)$$

where $R_a$ is called the ratio of roll. The generating motion is provided for both face milling and face hobbing processes when the gear or pinion is cut in the generating method. In the non-generating (FORMATE) process, which is usually applied to the gear, both the generating gear and the workpiece are held at rest, and only the cutter rotation is provided. Therefore, the gear tooth surfaces are actually the complementary copy of the generating tooth surfaces, which are formed by the cutter motion described above.

## Generalized Spiral Bevel and Hypoid Gear Tooth Surface Generation Model

Both face milling and face hobbing processes can be implemented on the CNC hypoid gear generating machines. Figure 3 shows a Phoenix® II 275HC Hypoid Gear Generator. A new kinematical model of tooth surface generation is developed, based on the traditional cradle-style mechanical machine. The purpose of developing this model is to virtually represent each machine tool setting element as an individual motion unit and to implement a given function of motion. These virtual motions can be realized by the CNC hypoid gear generator through the computer translation codes on the machine. The six axes of the CNC hypoid gear generator move together in a numerically controlled relationship with changes in displacements, velocities, and accelerations to implement the prescribed motions and produce the target tooth surface geometry.

The generalized tooth surface generation model consists of the eleven motion elements shown in Figure 4. The cradle

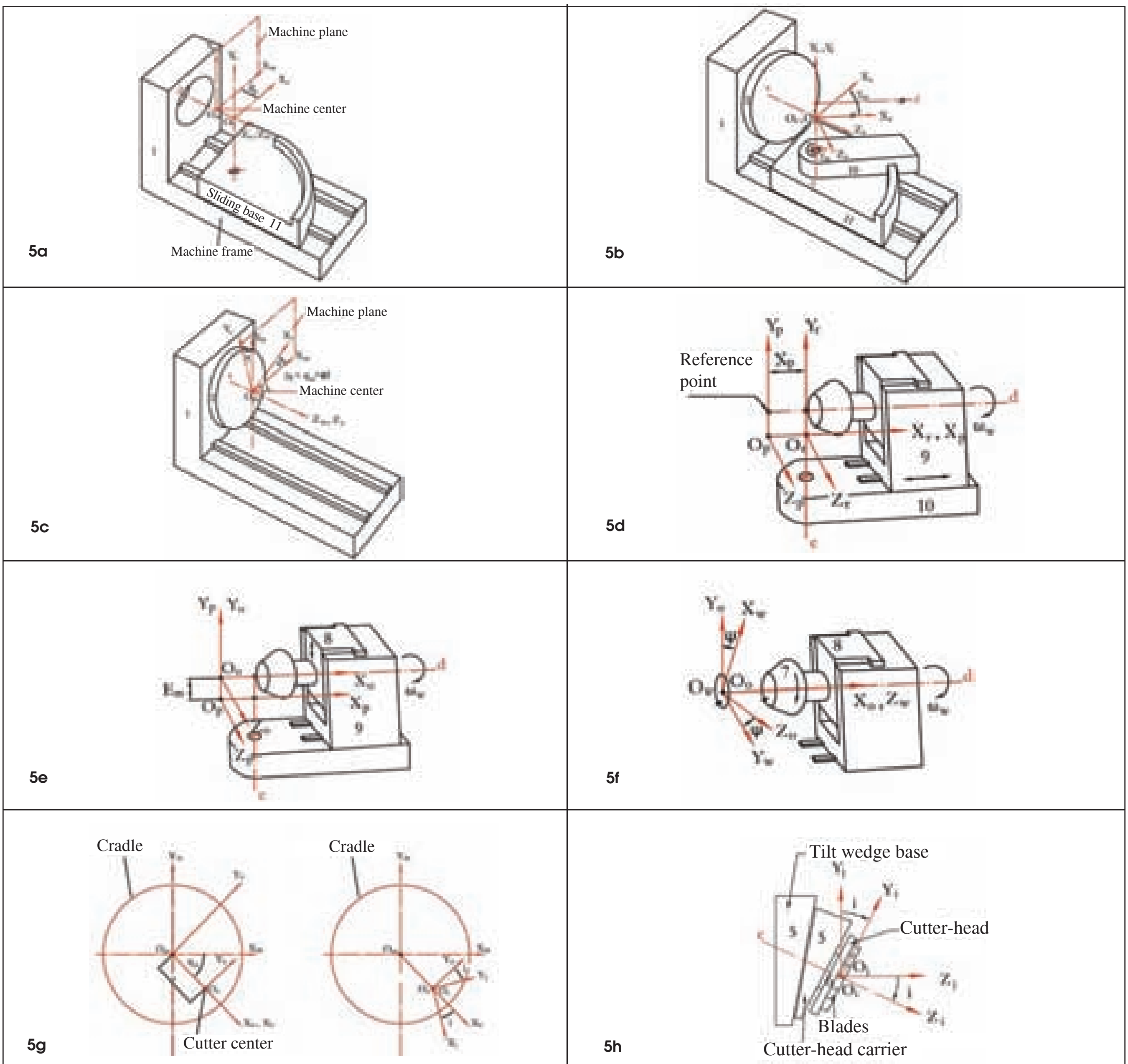


Figure 5—Machine motion elements with applied coordinate systems.

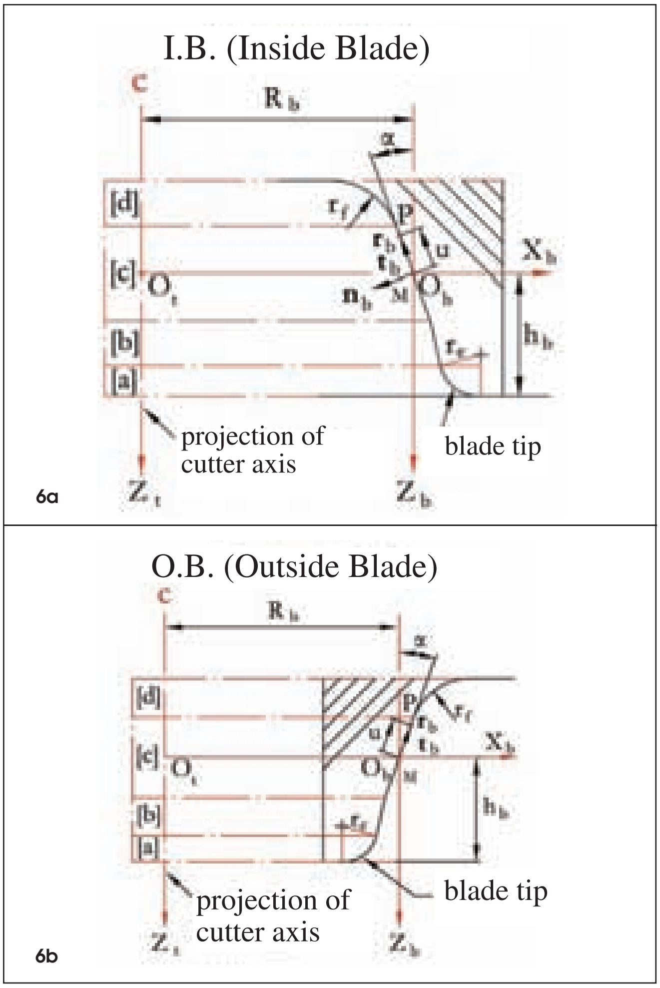


**Figure 6—Basic geometry of blades. (a) Pinion tooth surfaces. (b) Gear tooth surfaces.**

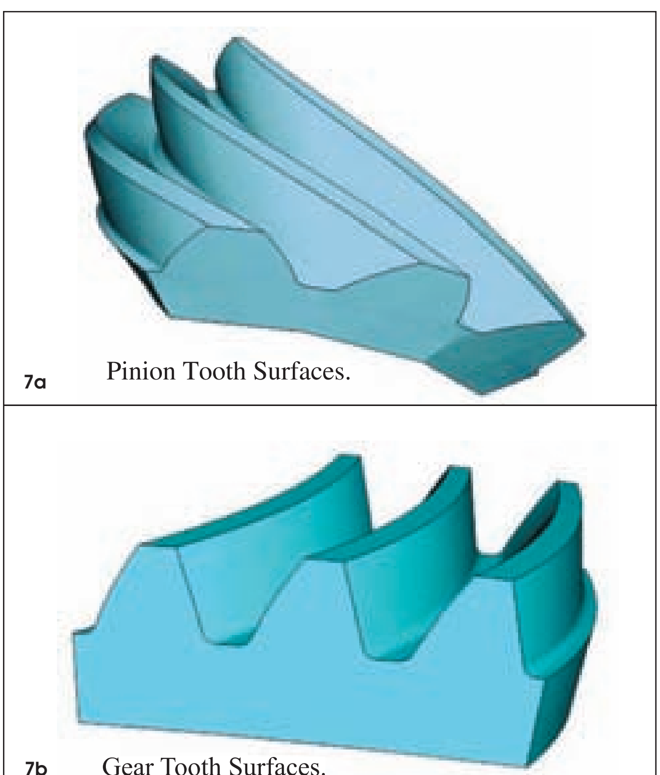


**Figure 7—Pinion and gear tooth surfaces of a hypoid gear drive.**

represents the generating gear, which provides generating roll motion between the generating gear and the generated workpiece. In the non-generating process, the cradle is held stationary. Basically, these motion elements represent the machine tool settings in a dynamic manner in terms of the cradle rotation parameter.

The generalized machine settings are: (1) ratio of roll $R_a$; (2) sliding base $X_b$; (3) radial setting $s$; (4) offset $E_m$; (5) work head setting $X_p$; (6) root angle $\gamma_m$; (7) swivel $j$; and (8) tool tilt $i$. The Universal Motion Concept (UMC) represents these machine settings in higher-order polynomials and provides strong flexibility of generating comprehensively crowned tooth surfaces (Ref. 3). The UMC is the extension of traditional modified roll, helical motion, and vertical motion to all machine settings.

The motion elements of the kinematical model in Figure 4 are analytically isolated relative to each other (Fig. 5). A sequence of coordinate systems is associated with the model to transform the relative motions of the elements. Coordinate system $S_m$, called machine coordinate system, is fixed to the machine frame and considered as the reference of the related motions. System $S_m$ defines the machine plane and the machine center. The sequence of the applied coordinate systems is $S_w$, $S_o$, $S_p$, $S_r$, $S_s$, $S_m$, $S_c$, $S_e$, $S_j$, and $S_i$, which defines the position vector, unit tangent, and unit normal at a point on the work tooth surface in two-parameter forms as

$$\mathbf{r}_w = \mathbf{r}_w(u,\theta) \tag{4}$$

$$\mathbf{t}_w = \mathbf{t}_w(u,\theta) \tag{5}$$

$$\mathbf{n}_w = \mathbf{n}_w(u,\theta) \tag{6}$$

“here subscript *w*” denotes that the vectors are represented in the work coordinate system $S_w$. This generalized formulation of the generating process accommodates both face milling and face hobbing processes with both generating and long-generating cutting methods.

In addition, a generalized representation of the blade geometry is also developed (Fig. 6). The tool geometry is defined by the parameters of the blade sharpening and installation in the cutter head, which are nominal blade pressure angle, blade offset angle, rake angle, and effective hook angle. The blades are generally considered consisting of four segments—(a), (b), (c), (d)—corresponding to the blade tip, Toprem, profile, and Flankrem.

An example of the pinion and gear tooth surfaces of a hypoid gear drive is generated by using the developed mathematical models and is illustrated in Figure 7. The tooth surface generation algorithm is fundamental to the tooth contact analysis and automatic generation of finite element discrete models.

### Advanced Tooth Contact Analysis (TCA)

Tooth Contact Analysis (TCA) is a computational approach for analyzing the nature and quality of the meshing contact in a pair of gears. The concept of TCA was originally introduced in early 1960s as a research tool, and applied to spiral bevel and hypoid gears (Refs. 1, 7). Application of TCA technology has resulted in significant improvement in the development of bevel gear pairs, under given contact conditions.

Based on the new tooth surface generation model discussed above, an advanced TCA program is developed. The new TCA algorithm is based on the following mathematical formulations, namely,

$$\begin{cases} \mathbf{r}_f^{[1]} - \mathbf{r}_f^{[2]} = 0 \\ (\mathbf{n}_f^{[2]} \times \mathbf{t}_f^{[2]}) \cdot \mathbf{n}_f^{[1]} = 0 \\ \mathbf{t}_f^{[2]} \cdot \mathbf{n}_f^{[1]} = 0 \end{cases} \quad (7)$$

$$\begin{cases} \mathbf{r}_f^{[1]} - \mathbf{r}_f^{[2]} = 0 \\ (\mathbf{n}_f^{[1]} \times \mathbf{t}_f^{[1]}) \cdot \mathbf{n}_f^{[2]} = 0 \\ \mathbf{t}_f^{[1]} \cdot \mathbf{n}_f^{[2]} = 0 \end{cases} \quad (8)$$

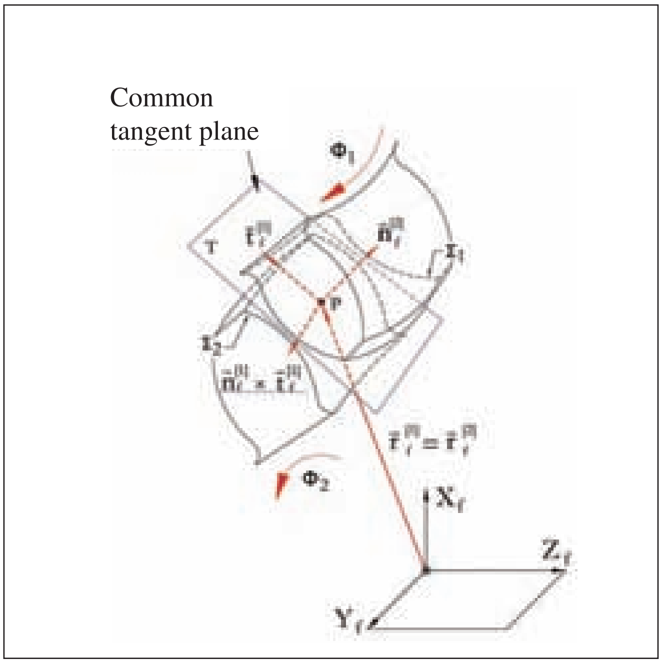


Figure 8—Tooth surface contact.

Geometrically, vector $\mathbf{n}_f^{[i]} \times \mathbf{t}_f^{[i]}$ and $\mathbf{t}_f^{[i]}$ ($i$=1, 2) are two orthogonal vectors that lie in the tangent planes of the pinion tooth surface $\Sigma_1$ ($i$=1) and gear tooth surface $\Sigma_2$ ($i$=2). When the two surfaces contact at point P, the tangent planes coincide and become a common tangent plane (Fig. 8). Considering the equations of meshing, Equations 7 or 8 generally yield five independent equations, and can be solved if the related Jacobian differs from zero (Ref. 8). Consequently, a series of contact points and the corresponding transmission errors can be obtained, which formulate the TCA output as the bearing contact patterns and the graph of transmission errors. The transmission error ($TE$) is defined as

$$TE = (\phi_2 - \phi_{20}) - (\phi_1 - \phi_{10}) \frac{N_1}{N_2} \quad (9)$$

Where $\phi_{10}$ and $\phi_{20}$ are the initial angular displacement of the pinion and the gear when the tooth surfaces are in contact at the initial conjugate contact position where the $TE$ = 0; $N_1$ and $N_2$ are the tooth numbers of the pinion and the gear, respectively.

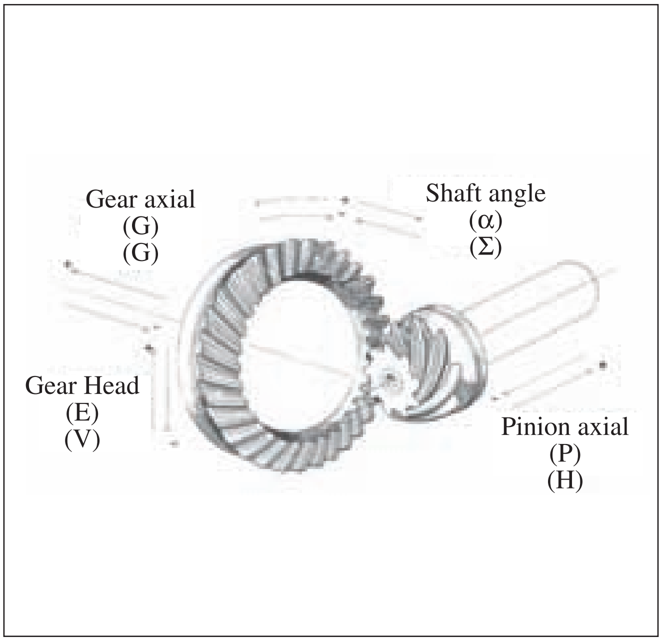


Figure 9—Definition of mounting deflections and adjustments.

Simulation of changes of the assembly errors and misalignments caused by the deflection of the gear shafts are taken into account. For this purpose, the adjusting parameters, gear head offset change $\Delta E$, gear axial change, $\Delta G$ pinion axial change $\Delta P$, and shaft angle change are $\Delta\Sigma$ incorporated into the TCA model (Fig. 9). The output of a TCA program is the scaled graphs of transmission errors and tooth-bearing contact patterns that predict the results from a bevel gear testing machine. The program incorporates tooth Toprem, Flankrem, and edge contact on the whole tooth surface, including those surface parts that are generated by the blade Toprem and Flankrem.

Conventionally, there are two cases of bearing contact patterns that are identified as "single meshing pattern" and "multiple meshing pattern." In the multiple meshing patterns, the adjacent pairs of meshing teeth are considered simultaneously. And, the path of contact reflects one pitch meshing because the following pairs of teeth take over the meshing process. In single meshing pattern, only one pair of teeth meshing is investigated and the adjacent meshing is ignored. In this case, the contact pattern covers the larger area of the tooth surface. Meanwhile, tooth tip edge contact or Toprem contact might be observed in the single meshing case because no neighboring teeth interrupt the meshing process.

In practice, when the surface separation of the mating gears is small, or the two mating surfaces are close to conjugate, a large contact pattern might be observed from the testing machine, which may correspond to the single meshing

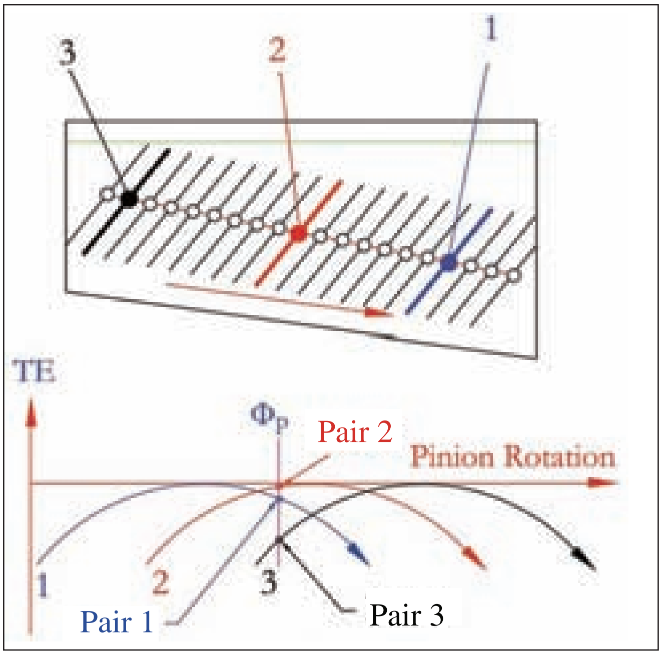


**Figure 10—Identification of instant contact positions of multiple pairs of contact teeth.**

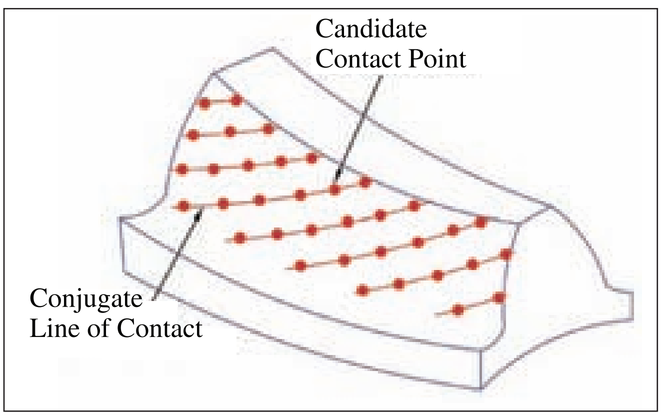


**Figure 11—Conjugate lines and contact points on the gear tooth surface.**

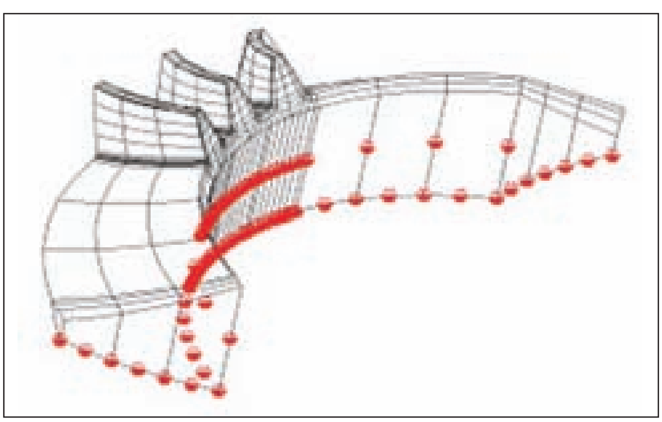

**Figure 12— FEA model of the gear.**

contact pattern of TCA. When the tooth surface separation is considerable, or the magnitude of tooth surface crowning is significant, the multiple meshing contact patterns might be obtained from the testing machine.

The developed program is able to simulate both the single meshing and the multiple meshing of a gear set pair. TCA results for the mean, toe, and heel positions are provided, which is the Gleason convention of *TCA* outputs. The adjusting parameters $\Delta E$ and $\Delta P$ are computed in order to achieve the given bearing contact pattern positions.

The *TCA* program is able to simulate the 'zero' assembling conditions under which all the adjusting parameters are equal to zero. The developed *TCA* program accommodates all kinds of modified and corrected tooth surfaces, generated by both face milling and face hobbing processes. The tip edge contact and the Toprem contact can be simulated.

Edge contact results in unexpected early failure of a gear drive because of highly concentrated contact stress generated between the tip of one member and the root flank of the other. Edge contact should be avoided by increasing the magnitude of the tooth surface crowning. The program offers the ability for the users to simulate meshing contact under user-defined misalignments, or user-defined, initial conjugate contact positions.

## Development of FEA-Based Loaded Tooth Contact Analysis (LTCA)

Loaded TCA provides a realistic picture of tooth contact behavior under given loads (applied torques) and axle deflections. The advanced development of LTCA is based upon following ideas and considerations:

(1) Tooth surface geometry is exactly defined and the TCA is executed. The TCA results provide bench contact pattern and the motion graph from which instant contact positions, and the number of adjacent meshing tooth pairs, can be identified. For example, Figure 10 shows the positions of contact lines respectively on three pairs of contact teeth at a given pinion rotation angle $\Phi_p$.

(2) Loaded contact is assumed along the conjugate line of tooth contact, which is close to the major axis of the contact ellipse (Fig.11). Therefore, the conjugate contact lines on the gear and pinion tooth surfaces are generated and represented by discrete points, which are the potential candidate contact points under load.

(3) The governing equations are derived by using the general concept of flexibility matrix approach, namely,

$$\mathbf{Cf} = \mathbf{d} \tag{10}$$

$$\mathbf{f} \times \mathbf{r} = \mathbf{T} \tag{11}$$

where *C* is the combined compliance matrix which reflects the compliances of the gear, pinion and housing; *f* is the vector of normal load distribution along the line of contact; *d* is the displacement vector representing the gaps between the corresponding contact nodes of the gear and the pinion under a given torque; $r$ is the position vector of contacting points; and $T$ is the applied torque vector.

(4) The compliance matrix $C$ consists of two major parts, (i) simulated stiffness of axle housing by parameters $\Delta E$, $\Delta P$, $\Delta G$, and $\Delta a$ in proportion to the applied torque and (ii) the gear and pinion compliances determined by FEA process, in which a special gap element is formulated by adding the Weber's components of deflection (Ref. 4). Application of the special gap elements allows including the deflection and deformation due to not only bending and shearing, but also the local Hertzian contact. Parameters $\Delta E$, $\Delta P$, $\Delta G$, and $\Delta \alpha$ are defined as the relative axle deflections of the pinion, with respect to the gear. They are normally derived from experimental measurements of axle deflections under controlled conditions, and they can also be estimated through FEA calculation.

(5) The FEA meshing models with multiple teeth are automatically generated, using the exact tooth surface generating model for the spiral bevel and hypoid gears generated on both mechanical and CNC machines. The multiple-tooth models allow simulating load sharing among several adjacent pairs of teeth. Figures 12 and 13 show the gear and pinion FEA models with the emphasized nodes representing the boundary constraints.

(6) The total number of elements in the models can be chosen by the designer through the input interface by selecting the element numbers in tooth thickness, profile, and lengthwise directions. This feature provides flexibility for the program running on computers with different CPU levels to balance the running time and accuracy. The input torque can be applied through either pinion or gear.

(7) The displacement field of the FEA meshing nodes on the tooth surface is determined by applying a unit load on each surface node. By using this displacement field, a higher-order polynomial interpolation scheme is used to determine the primary and secondary deflections of loaded contact points, which are normally not coincident with the FEA meshing nodes on the tooth surface (Fig. 14).

(8) Solving the governing equations needs an iteration process in which the kinematical approach k can be assumed, and eventually determined together with the load distribution and gap vectors. As an LTCA result, the loaded transmission error and contact pattern identified by the gaps at each contact position can be determined. The kinematical approach k represents the loaded transmission errors.

(9) Two values of torque need to be specified in LTCA. The first value of torque is the full-load torque applied to the gear or pinion, corresponding to the torque used in evaluating the strength performance of the gear design. The second value of torque corresponds to the torque used in the deflection tests that were conducted to determine $\Delta E$, $\Delta P$, $\Delta G$, and $\Delta \alpha$. In general, the two values of torque may not be the same. The torque can be gradually applied as the percentage of the full torque. As torque is applied to a gear set, the area of contact between the gear and pinion teeth changes as the

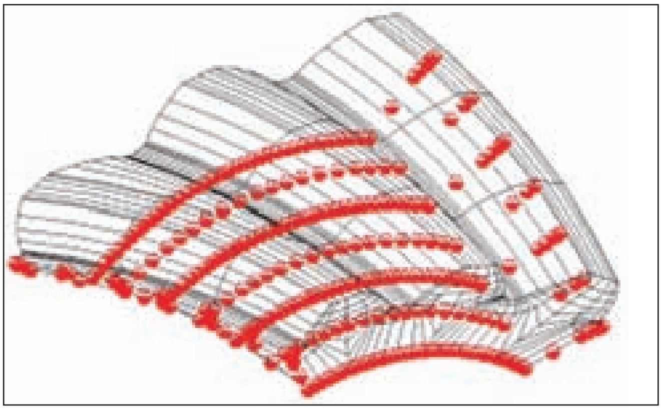

Figure 13— FEA model of the pinion.

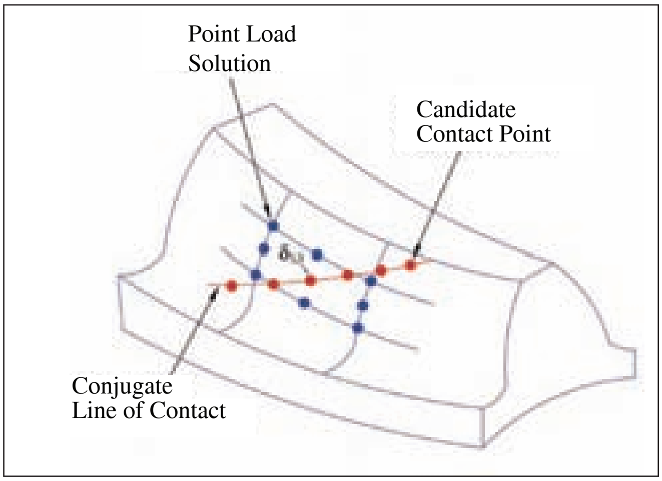


Figure 14—Interpolation scheme.

**Table 1—Data of Design A and B.**

| | Design A: Face Hobbing (Hypoid) (FORMATE Gear) | | Design B: Face Milling (Hypoid) (Generated Gear) | |
|---|---|---|---|---|
| | Pinion (Left Hand) | Gear (Right Hand) | Pinion (Right Hand) | Gear (Left Hand) |
| Number of teeth | 11 | 39 | 17 | 27 |
| Diametral Pitch | 5.015 | 4.480 | | |
| Face Width | 1.611" | 1.325" | 1.575" | 1.575" |
| Pinion Offset | 1.5" | 0.394" | | |
| Shaft Angle | 90° | 90° | | |
| Outer Cone Distance | 3.821" | 4.390" | 3.648" 3.744" | |
| Mean Cone Distance | 2.965" | 3.681" | 2.851" | 2.964" |
| Outside Diameter | 3.737" | 7.825" | 4.674" | 6.214" |
| Cutter Radius | 3.465" | 2.500" | | |

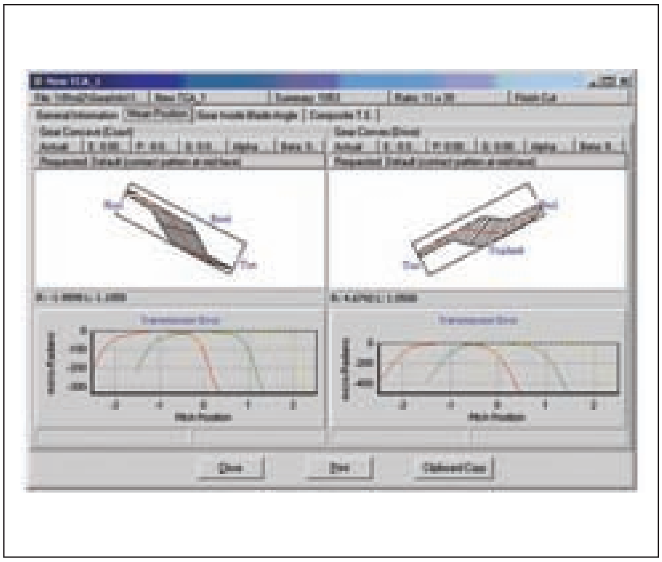

Figure 15— Single meshing (Design A)—mean contact.

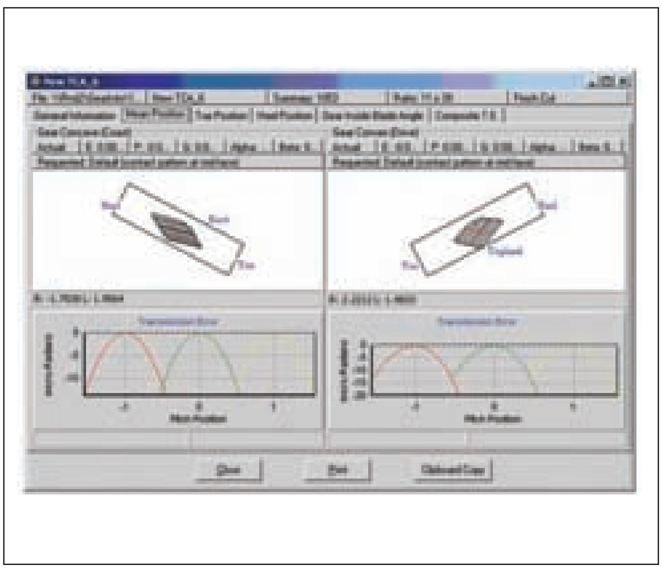

Figure 16—Multiple meshing (Design A)—mean contact.

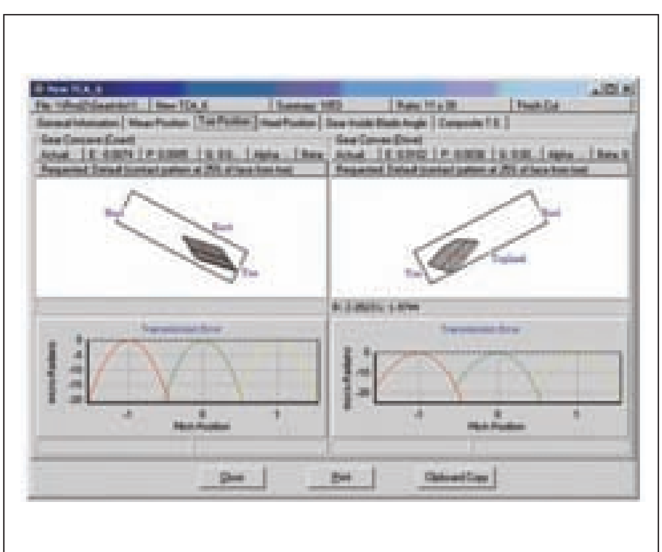

Figure 17—Multiple meshing (Design A)—toe contact.

tooth surfaces deform and the gear housing deflects. These changes are usually observed as a growth in the contact pattern area, along with a movement of the contact area. The number of the steps for applying the torque can be selected. In order to visualize the change in contact, all the LTCA results are illustrated as a function of each applied torque.

(10) Parameters $V$, $H$, $G$ and $\Sigma$ illustrated in Figure 9 have the same geometric definition corresponding to $E$, $P$, $G$ and $\alpha$, except that they represent the adjustment of the position of the initial bench-contact pattern.

## Numerical Examples

The advanced TCA and LTCA programs have been integrated into the *CAGE™ for Windows* system, which is a released software tool for design and analysis of spiral bevel and hypoid gears. The TCA and LTCA results of two numerical examples, a face hobbing and a face milling, are illustrated below. Table 1 shows the dimension data of the two designs (Design A and B) which are a non-generated (FORMATE) hypoid gear drive (Design A) produced by the face hobbing process and a generated spiral bevel gear drive (Design B) produced by the face milling process. In Design A, the pinion has left-hand spiral angle. In Design B, the pinion has right-hand spiral angle. Figure 15 shows the single meshing TCA results of Design A at the mean contact position. Figures 16, 17 and 18 show the multiple meshing TCA results of Design A, respectively, at mean, toe and heel contact positions. Figure 19 illustrates the LTCA result of Design A for the drive side. In the LTCA program, the drive side and the coast side are calculated by separate executions of the program. Figures 20 and 21 demonstrate the TCA and LTCA result of Design B for the mean contact position. The mean contact position for this design is positioned close to the toe. The TCA and LTCA program can simulate the misalignments and assembly adjustment.

## Conclusion

This paper presents the new developments in TCA and LTCA. A generalized kinematical model for generation of spiral bevel and hypoid gear tooth surfaces is developed. The mathematical model is directly associated with the physical machine setting and motion elements of a bevel gear generator, which is the basis of computerized modeling and simulation of spiral bevel and hypoid gear drives, and can be applied to both face milling and face hobbing processes with both non-generated and generated methods. An improved TCA algorithm is proposed. The geometric models are exactly generated with consideration of various tooth surface modifications. A special gap element is formulated to include the deflections due to tooth bending, shearing and local Hertzian contact. The axle deflection is also simulated. Advanced TCA and LTCA programs are developed based on the improved TCA algorithm and formulation of the gear tooth contact solutions. The outputs of the TCA and LTCA programs are transmission errors and contact patterns. These two program modules are integrated into Gleason *CAGE™ for Windows* software package applied to design and analysis of spiral bevel and hypoid gears. Two numerical examples are illustrated with TCA and LTCA results.


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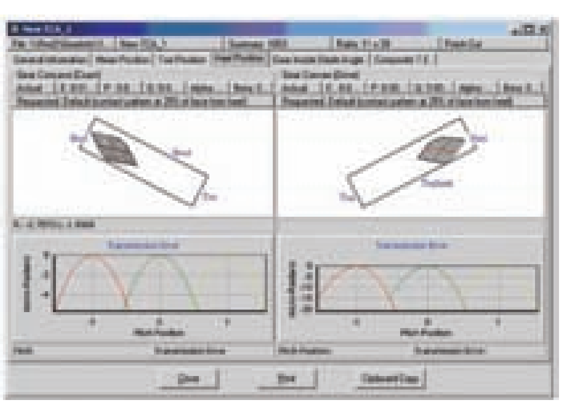

Figure 18— Multiple meshing (Design A)—heel contact.

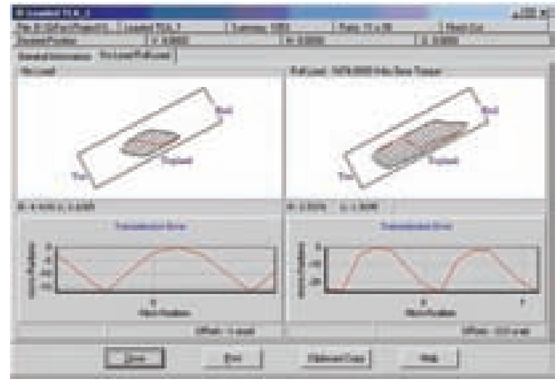

Figure 19—LTCA output of Design A—drive side.

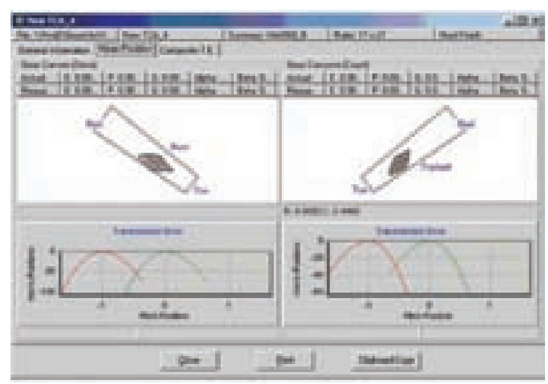

Figure 20— TCA output of Design B—mean contact.

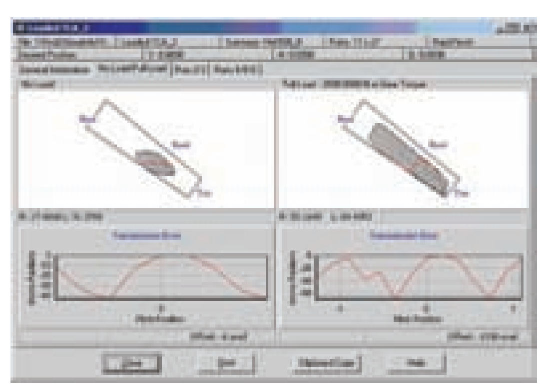

Figure 21—LTCA output of Design B—drive side.

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# Operational Influence on Thermal Behavior of High-Speed Helical Gear Trains

Robert F. Handschuh and Charles J. Kilmain

**Management Summary**

An experimental effort has been conducted on an aerospace-quality helical gear train to investigate the thermal behavior of the gear system as many important operational conditions were varied. Drive system performance measurements were made at varying speeds and loads (to 5,000 hp and 15,000 rpm). Also, an analytical effort was undertaken for comparison to the measured results. The influence of the various loss mechanisms from the analysis for this high-speed helical gearbox will be presented and compared to the experimental results.

Figure 1—Tiltrotor aircraft.

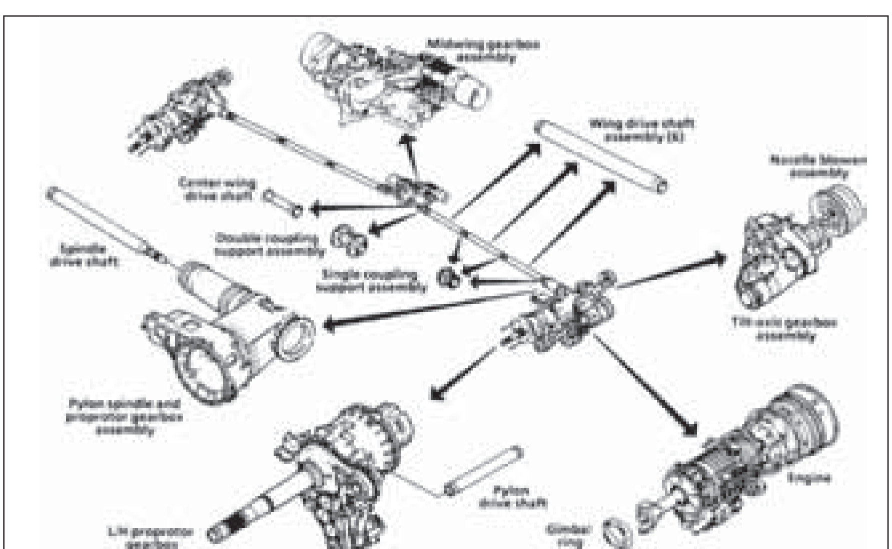


Figure 2—Typical tiltrotor aircraft propulsion system arrangement.

## Introduction and Background

Current and future high-speed, heavily loaded, and lightweight gearing components will be a part of all propulsion systems for rotorcraft. These systems are expected to deliver high power from the gas turbine engines to the high-torque/low-speed rotor with reduction ratios in the range of 25:1 to 100:1 (Refs. 1–14). Gearing systems in these extreme-duty applications can also have thermal behavior issues due to the high pitch-line velocities. While design considerations for gear tooth bending and contact capacities are usually considered initially, high-speed gearing design needs to carefully consider the consequences of pitch-line velocities approaching 25,000 ft/min. In prior studies, the thermal behavior characteristics of mechanical components have been the least understood and have received a minimum amount of attention in the open literature (Refs. 15–19).

In rotorcraft drive systems, such as those of tiltrotors (Fig. 1), a helical gear train is used to connect the parallel engine and mast shafting on the aircraft. Therefore, the drive system is not only needed to provide the necessary reduction between the engine and rotor, but also has to make the system operate in emergency conditions (Refs. 20 and 21) such as one engine inoperative and oil out conditions. The propulsion configuration for a tiltrotor aircraft is shown in Figure 2 (Ref. 22).

For the drive system components of interest in this study, the gearing between the parallel axes of rotation of the engine and mast is composed of a series of helical gears (or gear train). In this arrangement, the idler gears receive two thermal cycles per revolution. Since these gears are extremely light-weight (low heat-carrying capacity), the successful operation of the system in all possible normal and emergency conditions can be difficult. Other recent publications have looked at several topics of interest with respect to this high-speed gear train (Refs. 23 and 24). Effects of speed, load, shrouds and lubrication flow rate have been studied. The most drastic performance effect caused by any of the conditions that can be imposed is that caused by increased pitch-line velocity of the system. The resultant gear windage from the high-speed components can produce a dramatic increase in power loss.

The objective of this paper is to present the effects of speed and load on the operating performance (power loss) of the helical gear train. A high-speed helical drive train facility that utilizes full-scale, aerospace-quality components was used to generate the data presented in this study. The system can operate to 15,000 rpm (to simulate the engine input rotational speed) and at power levels to 5,000 hp. Also, an analysis of the gearing, bearing, and windage losses was conducted. The experimentally measured efficiency is compared to that attained via analysis methods.

## Experimental Setup

***Test Facility***. A schematic of rhe test facility used for this study is shown in Figure 3 (Ref. 23). The facility is a closed-loop, torque-regenerative testing system. A test gearbox and slave gearbox are basically mirror images of each other. Each gearbox has an input gear, three idlers, and one bull gear. The gearboxes are joined together through the input gears and bull gears via shafting.

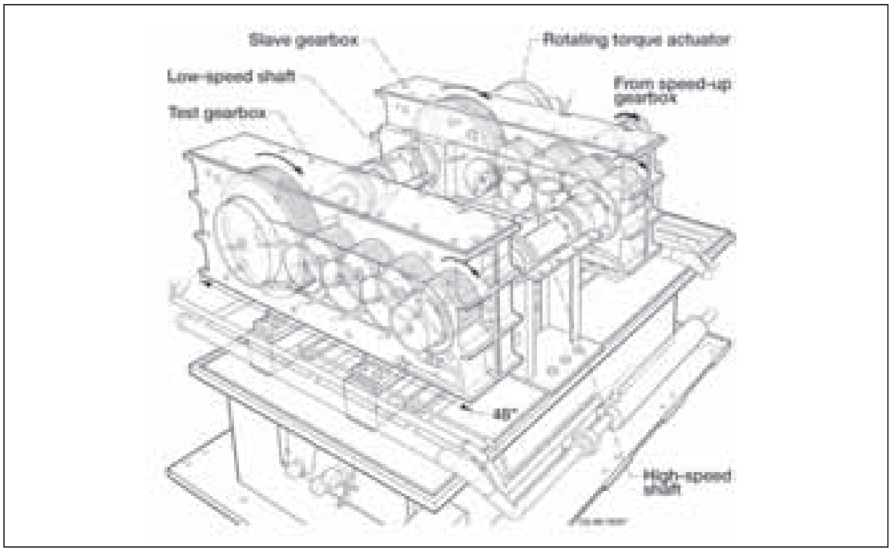


Figure 3—NASA High-Speed Helical Gear Train Test Facility.

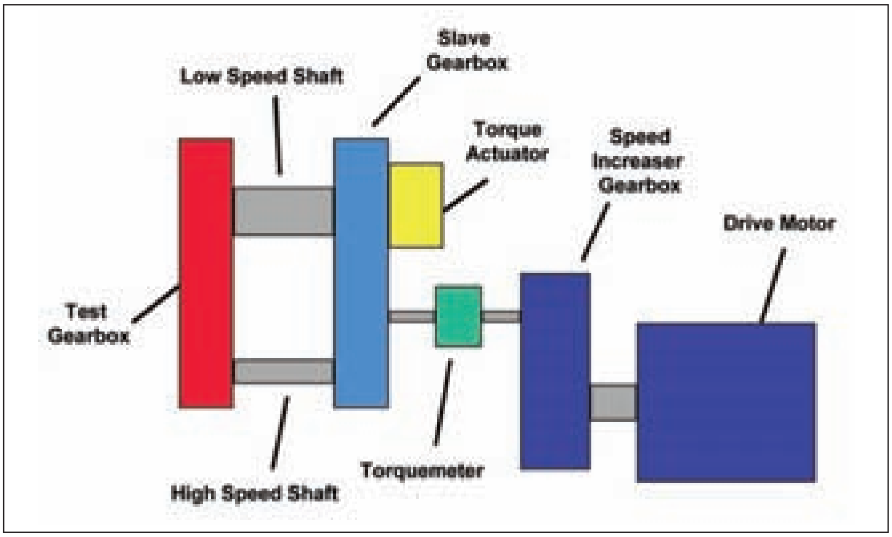


Figure 4—Layout of NASA High-Speed Helical Gear Train Test Facility.

The facility is powered by a 500 hp DC drive motor, and its output speed is increased using a speed-increasing gearbox. The output of the speed-increasing gearbox then passes through a torque and speed sensor before connecting to the slave gearbox. A diagram of the entire test stand configuration is shown in Figure 4.

Each gearbox has separate supply pumps, scavenge pumps, and reservoirs. Lubrication system flow rate is controlled using the supply pressure. Temperature is controlled via immersion heaters in the reservoir and heat exchangers that cool the lubricant returned from the gearboxes. Each lubrication system has a very fine 3-micron filtration. Nominal jet pressure into the test or slave gearboxes is at 80 psi. The lubricant used in the tests to be described was a synthetic turbine engine lubricant (DoD–PRF–85734).

***Test Instrumentation/Data Acquisition***. The test instrumentation used in this study only required measurement of the oil inlet and exit temperatures from the test gearbox, the loop torque (measured via a strain gaged shaft and telemetry), the lubricant supply pressure, and the test gearbox's outside case temperature. This data was collected at two-second intervals throughout the test and averaged over a 30-second period at steady-state conditions.

***Test Hardware***. The test hardware used in the tests to be described is aerospace quality hardware. The basic gear design information is contained in Table

1. The input and bull gear shafts have ball bearings to contain the resultant thrust loads, whereas the idler gears only have roller bearings. The partially disassembled test gearbox is shown in Figure 5. The bearing inner race is integral to the shafts on the idler gears and at other radially loaded bearings on the input and bull gear shafts. Shrouds for the gears used to minimize the windage losses are shown in Figure 6.

***Test Operation***. For a given set of conditions—speed, load, lubricant pressure, and lubricant oil inlet temperature—the facility was operated for at least five minutes, or until the temperatures of interest had stabilized.

**Analytical Method**

An analysis of the losses of the test gearbox will now be described. In the test gearbox, there are a total of five gears and four gear meshes. All the gear meshing and bearing power losses were found for a total of six conditions. The conditions were at two input shaft speeds—12,500 and 15,000 rpm—and at three levels of applied loop torque—33, 67, and 100 percent of full load.

Each mesh was analyzed using the method of Anderson and Lowenthal (Ref. 25) for the gear sliding and rolling losses. This gear meshing analysis can only analyze spur gears. Therefore, the gear train components were assumed to be spur gears with the same diametral pitch and face width as the test hardware. Since the gears have only a 12° helix angle, this effect was assumed to be negligible.

The gear meshing losses are found along the line of action and numerically integrated. The gear sliding losses use a position-varying friction coefficient based on the gear tooth sliding/rolling velocity, lubricant inlet temperature, and the load being applied. The sliding losses are calculated by the following equation:

$$P_{Sliding}(x) = C_1 V_{Sliding}(x) f(x) W(x) \qquad (1)$$

where:

$C_1$ Constant
$V_{Sliding}$ Sliding velocity
$f$ Friction coefficient
$W$ Applied load
$x$ Position along the line of action

The rolling power losses are given by:

$$P_{Rolling} = C_2 V_{Rolling}(x) h(x) \varphi_t(x) \qquad (2)$$

where:

$C_2$ Constant
$V_{Rolling}$ Rolling velocity
$h$ Lubricant film thickness
$\phi_t$ Lubricant film thickness thermal reduction factor

The gear windage is based on the method contained in the work of Dawson (Ref. 26). In this model, the effects of gear size, shrouding, rotational speed and environment can be treat-

| TABLE 1—BASIC DESIGN DATA FOR GEARS IN HIGH-SPEED HELICAL GEAR TRAIN TEST FACILITY | |
|---|---|
| Number of teeth, Input and 2nd Idler/1st and 3rd Idler/Bull Gear | 50/51/139 |
| Module (mm), (Diametral Pitch (1/in)) | 3.033 (8.375) |
| Face Width, mm (in) | 67.2 (2.625) |
| Helix Angle, deg. | 12 |
| Gear Material | Pyrowear EX-53 |

Figure 5—NASA high-speed helical gear train test facility components.

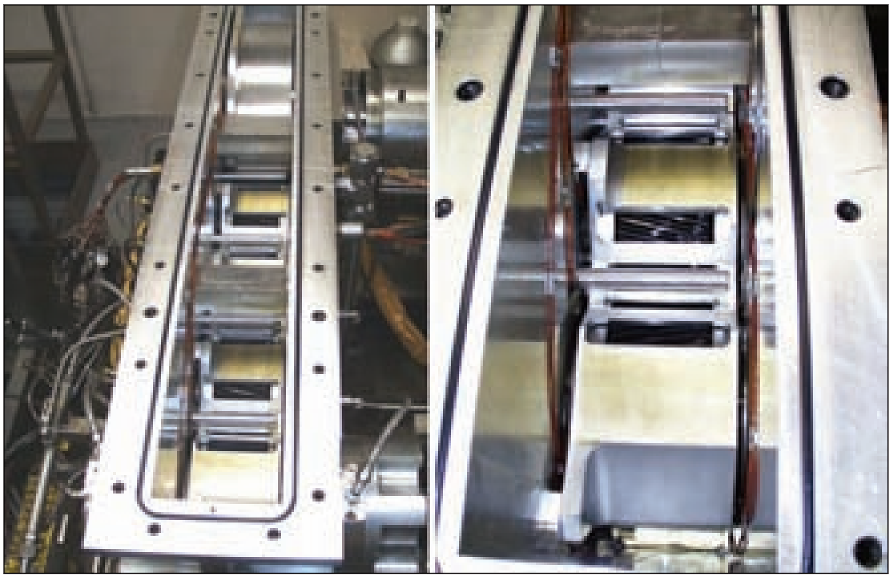

Figure 6—Photographs of shrouding on the test gearbox. Left: entire gearbox. Right: close-up of the input-1st idler gear shrouds.

ed. This portion of the gearing losses is given by the following equation:

$$P_{Windage}=C_3C'\rho N^{2.85}D^{4.7}{}_{\nu}0.15_{\lambda} \quad (3)$$

where:

| | |
|---|---|
| $C_3$ | Constant |
| $C'$ | Shape factor, related to the number of teeth, face width to diameter ratio of the gear |
| $\rho$ | Density of environment (air and lubricant) |
| $N$ | Gear rotational speed |
| $D$ | Gear diameter |
| $\nu$ | Kinematic viscosity (air and lubricant) |
| $\lambda$ | Enclosure factor, 0.5 for tight fitting housing |

As an example of the lubricant/air effect on the windage of the helical gear train discussed in this paper, the method of Anderson and Lowenthal (Ref. 25) is used, and the results are shown in Figure 7. In the calculation, lubricant/air percentages are varied. Assuming just air in the gearbox produces very low windage losses. By increasing the lubricant/air percentage to just 1 percent lubricant and 99 percent air results in a 20x increase in windage losses.

The bearing losses were found using the method in Reference 27. The friction torque necessary to rotate the bearings under the assumed power and speed conditions was calculated. The calculation is based on the type of bearing, bearing size, applied load and rotational speed. The power loss from the bearings is given by the following:

$$P_{Bearing}=\sum_{i=1}^{j} C_4\left(M_{li}+M_{vi}\right) \quad (4)$$

where the friction torque due to the applied load is given by:

$$M_l=f_l F_\beta\, d_m \quad (5)$$

| | |
|---|---|
| $f_l$ | Factor dependent on bearing design and relative bearing load |
| $F_\beta$ | Dependent on magnitude and direction of the applied load |
| $d_m$ | pitch diameter of the bearing |

and where the viscous friction torque is

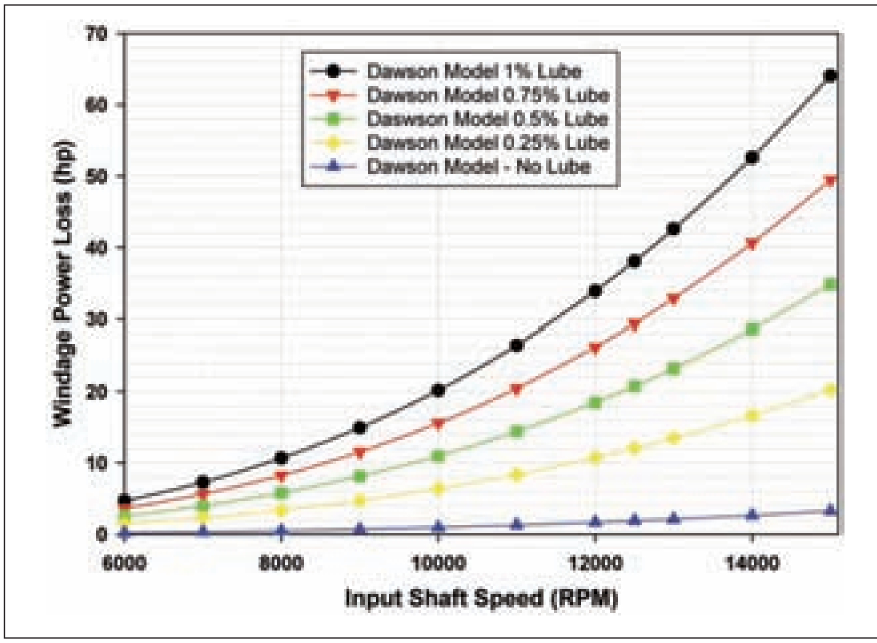


**Figure 7—Effect of lubricant-air mixture on windage of high-speed helical gear train.**

given by:

$$M_v=C_5 f_o (v_o n)^{2/3} d_m^3 \quad (6)$$

or

$$M_v=C_6 f_o d_m^3 \text{ for } v_o n\le 2000 \quad (7)$$

| | |
|---|---|
| $C_4, C_5, C_6$ | Constants |
| $f_o$ | Parameter dependent on bearing type and lubrication method |
| $v_o$ | Kinematic viscosity of the lubricant |
| $n$ | Bearing rpm |

The seals on the test rig are only at the input and bull gear shaft locations. The input shaft has a labyrinth seal, and the bull gear uses a carbon face seal. The losses from the sealing system were found to be negligible for this system for the conditions under study in this paper.

### Summary of Losses via Analysis

A summary of the analytical results for the gear system under study are presented in Table 2. As mentioned earlier, six conditions were analyzed. A breakdown of the loss mechanisms is also shown in Figure 8 for the 15,000 rpm input shaft speed with the load varying between 33 and 100 percent. The windage losses were assumed to have a lubricant/air mixture of 0.75 and 99.25 percent, respectively. The predicted efficiency ranged from 95.81 to 98.29 percent, depending on the conditions applied.

### Measured Losses

The losses from the test facility are a combination of the heat transferred to the lubricant and surroundings via convection. These loss mechanisms are overcome by the power supplied to the test facility. For the conditions of interest (approximately the same conditions analyzed), the amount of drive motor power supplied as a function of load and speed is shown in Figure 9. The drive motor rotates the test and slave gearboxes and supplies the necessary power to maintain the operating conditions. For a given operation input speed, increasing load results in a linear increase in drive motor power. Increasing speed from 12,500 to 15,000 rpm input speed (16 percent increase) results in a much larger increase of operating power (30 percent increase) required.

The heat transferred to the lubricant is simply the product of the lubricant mass flow rate, specific heat of the lubricant, and the temperature difference across the gearbox and given by the following equation:

$$P_{Lube}=C_7 m C_P \Delta T \quad (8)$$

| TABLE 2.—POWER LOSS AND EFFICIENCY PREDICTIONS AT GIVEN CONDITIONS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| High speed input shaft torque | High speed input shaft speed | Gear Sliding and rolling losses | Gear Windage losses (0.75 % lube) | Roller bearing losses | Ball bearing losses | Total Power Loss | Loop power | Efficiency |
| (in*lb) | (rpm) | (hp) | (hp) | (hp) | (hp) | (hp) | (hp) | (%) |
| 6834 | 12500 | 10.891 | 29.406 | 3.34 | 0.34 | 43.977 | 1355.4 | 96.756 |
| 14028 | 12500 | 20.982 | 29.406 | 7.03 | 0.90 | 58.318 | 2782.3 | 97.904 |
| 20863 | 12500 | 29.942 | 29.406 | 10.10 | 1.45 | 70.898 | 4137.9 | 98.287 |
| 6834 | 15000 | 13.331 | 49.443 | 4.81 | 0.52 | 68.104 | 1626.5 | 95.813 |
| 14028 | 1500 | 25.300 | 49.443 | 9.80 | 1.3 | 85.863 | 3338.7 | 97.428 |
| 20863 | 1500 | 36.078 | 49.443 | 14.54 | 2.22 | 102.281 | 4965.5 | 97.940 |

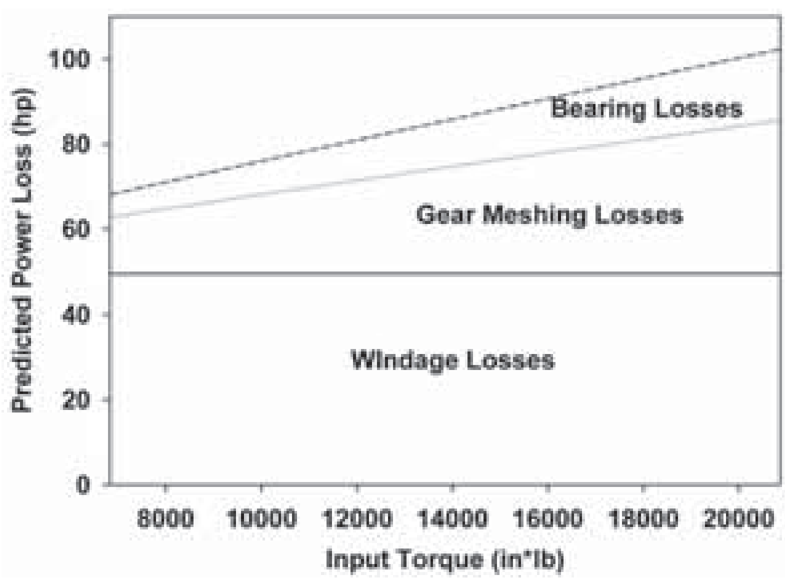


Figure 8—Predicted power loss at 15,000 rpm input shaft speed for each of the components in test gearbox.

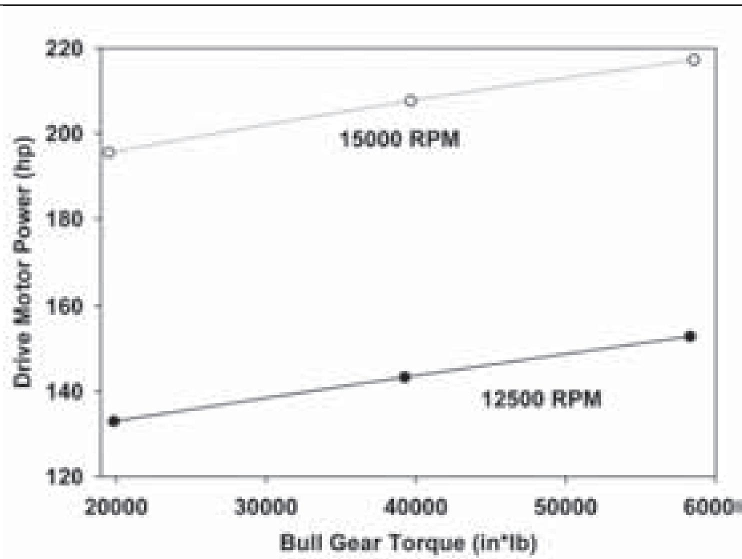


Figure 9—Drive motor power required to rotate the entire test facility system.

where:

| | |
|---|---|
| $C_7$ | Constant |
| $m$ | Mass flow rate |
| $Cp$ | Specific heat of the lubricant |
| $\Delta T$ | Lubricant temperature change across the gearbox |

The convection losses are those due to free convection. Flat plate heat transfer coefficients were assumed for the six faces of the gearbox (Ref. 28). The surface temperature of the gearbox was measured at the mid-height and width. This temperature was assumed to exist on each face of the gearbox. The ambient temperature was assumed to be 75°F, since the system is operated in a temperature-controlled (air conditioned) test facility. These losses are given by the following equation:

$$P_{Conv} = \sum_{i=1}^{6} h_i A_i \Delta T \tag{9}$$

where:

| | |
|---|---|
| $h_i$ | Free convection heat transfer coefficient |
| $A_i$ | Area of convection surface i |
| $\Delta T$ | Temperature difference between outside of case and ambient conditions |

The losses measured are shown in Table 3. Table 3 shows the average of 15 readings over a 30-second period of time after the test facility had reached steady state. As shown in the table, the vast majority of the heat is absorbed in the lubricant, and the convection only makes up a very small percentage of the overall losses. The efficiency for each of the conditions is also shown in this table.

**Comparison of Analytical and Experimental Results**

For the six conditions of interest, the results from analysis and experiment are shown in Figure 10. As can be seen from the figure, results generated by analysis and experiments indicated that the efficiency increases with increasing load and decreases with increasing input rotational speed. For the analytical results shown, the windage losses are a substantial percentage of the losses. As was mentioned earlier, the power losses are affected by the assumed lubricant/air mixture content that is used for the windage analysis. For this study, the lubricant portion (0.75 percent) was chosen to match the maximum power loss at the highest speed condition and then fixed. The results followed the experimental trends for the conditions under study, but the results diverged at lower power levels.

The windage assessment is believed to be the weakest portion of the analytical tools available for predicting the resultant losses. A rigorous windage assessment program needs to be developed to further understand the basic physics of this phenomenon. As prior studies on high-speed gear systems have shown, configuration and environmental conditions can definitely affect the results. Therefore, a model capable of handling these system and environment issues is needed for use in a relevant aerospace environment where gear windage is often the dominant power loss mechanism.

## Conclusions

Based on the analytical and experimental work completed in this study, the following conclusions can be drawn:

1. From the experimental data and analysis results, power loss increases linearly if the load is increased at constant shaft speed. A large increase in power is required to change rotational speed from 12,500 to 15,000 rpm. Changing speed has the most dramatic effect on the windage loss for a constant air/oil environment.

2. Each of the gears and bearings was analyzed for its power loss contribution, for various input speeds and transmitted powers. Gear windage is a large contributor to the total power to drive the system loss at all of the conditions of interest in this study, since the pitch-line velocities at the two conditions of interest were approximately 20,000 ft/min. and 24,000 ft/min.

3. A comparison of the results indicated that the analysis followed the measured efficiency trends and the lubricant/air mixture assumption can alter the predicted loss and efficiency predicted.

**TABLE 3.—EXPERIMENTAL RESULTS AT SIX CONDITIONS, 200° F LUBRICANT INLET TEMPERATURE, 80 PSI LUBRICANT JET PRESSURE**

| Low speed input shaft torque | Low speed input shaft speed | Input power to test gearbox | Heat rejected to the lube | Heat coverted to enviornment | Total heat rejection | Efficiency |
|---|---|---|---|---|---|---|
| (in*lb) | (rpm) | (hp) | (hp) | (hp) | (hp) | (%) |
| 19895 | 12540.0 | 1423.94 | 56.34 | 1.32 | 57.66 | 95.95 |
| 39266 | 12529.6 | 2808.04 | 58.52 | 1.35 | 59.87 | 97.87 |
| 58306 | 12527.9 | 4169.09 | 63.45 | 1.40 | 64.85 | 98.44 |
| 19511.8 | 15023.9 | 1673.13 | 83.82 | 1.54 | 85.36 | 94.90 |
| 39663.5 | 15070.8 | 3411.75 | 91.25 | 1.59 | 92.84 | 97.28 |
| 58555.9 | 15024.7 | 5021.41 | 98.70 | 1.64 | 100.33 | 98.00 |

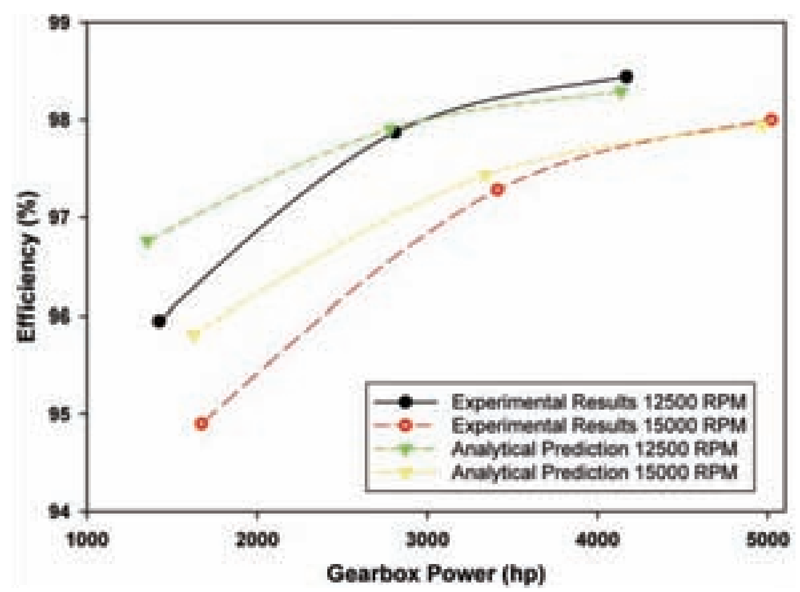


Figure 10—Comparison of experimentally attained and analytically predicted efficiency.


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***Dr. Robert F. Handschuh*** *(fellow, ASME and a member of ASME's power transmission and gearing committee) has been an aerospace engineer in the U.S. Army research laboratory, vehicle technology directorate, at the NASA Glenn Research Center in Cleveland, OH, since 1982. Since 1984, he has devoted his expertise to power transmission, focusing on experimental and analytical studies of planetary, spiral bevel, face and high-speed gearing. The author of 110 papers, he holds a patent on a gas turbine engine shroud seal, and two patents on gas turbine bearing coking and minimization removal.*

***Charles Kilmain*** *is chief of tiltrotor drive system design and research for Bell Helicopter-Textron where he has been since 1985. He has worked there as lead engineer for the V-22 proprotor gearbox (EMD), the BA609 commercial tiltrotor midwing gearbox and interconnect shafting system, and for Bell's heavy-lift rotorcraft drive system configuration. He has conducted research on advanced rotorcraft transmission and gear technology, and on high-speed helical gear loss-of-lube evaluation at the NASA Glenn Research Center. Published papers include V-22 Drive System Description and Design, and Composite Applications for Rotorcraft Drive System Housings.*

**GRC chief of space operations Angel Otero is shown demonstrating to a reporter how the center's work has helped make the shuttle flights safer. Otero oversaw all of GRC's Return to Flight efforts, to which more than 200 Glenn employees contributed.**

# NASA's "Return to Flight" TAKES WING AT GLENN RESEARCH CENTER

Jack McGuinn, Senior Editor

On February 1, 2003, the Space Shuttle Columbia and its seven-member crew were precious minutes away from completing the spacecraft's 28th mission when it literally fell to pieces upon re-entry over Texas. There were no survivors.

A NASA investigation attributed the root cause of the tradegy to a puncture on the leading edge of one of the spacecraft's wings, which in turn allowed extremely hot air to enter and degrade the wing's internal support structure. This degradation, exacerbated by the intense heat typically encountered upon re-entering the atmosphere, precipitated Columbia's disintegration.

But the investigation did not end there. What followed was an intensive, two-year testing-and-analysis period—dubbed Return to Flight—that led ultimately to the successful launch and return in 2005 of the Discovery space shuttle.

Involved in a number of ways during that two-year re-evaluation was the Cleveland-based NASA Glenn Research Center (GRC). Named for Ohio native John Glenn, who in 1962 became the first American astronaut to orbit the earth, the center states its mission as follows: "To work as a diverse team in partnership with government, industry, and academia to increase national wealth, safety, and security; protect the environment; and explore the universe. To develop and transfer critical technologies that address national priorities through research, technology development, and systems development for safe and reliable aeronautics, aerospace, and space applications."


In clearing the runway for Discovery, that mission was put to the test. And Glenn passed with flying colors. For Angel Otero, chief of GRC's space operations division, the validation was not unexpected.

"NASA as a whole has come to appreciate Glenn's expertise in mechanisms, gears, lubrication, high-temperature materials and impact testing and modeling," he says. "We have been working in these areas for the last 45 years to the benefit of the agency. As a result of the Columbia accident, our capabilities were called upon again."

And while indeed the center was involved in a variety of test areas—ballistic impact; environment seals compression optimization; on-board repair protocols; and carbon-carbon degradation among them—we will concentrate here on the GRC Shuttle Actuators Investigation Team. Their primary charge was the identification and resolution of mechanical component and lubrication issues in the space shuttle actuators. As is often the case when attempting to identify and explain cause-and-effect issues, the team soon found that one clue leads to another. In this case, an examination of a potential lubrication problem eventually led to gear-specific issues, including fretting and pitting, cycling and dithering.

***E-mail launches grease, gears investigation***. "How we got involved with the actuators was a very interesting story," Otero reveals. "When (NASA) was getting Discovery ready for launch they took all the rudder speed brakes out of Discovery, and GRC's involvement started due to the grease issue. (*Editor's note: Beta testing at the Johnson Space Center in Houston for Discovery had revealed a discoloration and contamination of the grease lubricant in the spacecraft's rudder/speed brake actuators.*) There was a question about the degradation of the grease, and someone in Houston was looking through the literature (technical papers) about questions on grease and he ran into the name of Erwin Zaretsky, who is a Glenn employee.

"And his sending (Zaretsky) an e-mail developed into a two-year involvement for us. First, with grease because we have tribology experts here. But as we started talking it over, it also became a gear issue, with questions about cycling and things like that."

Robert F. Handschuh, an aero-

**Space shuttle Discovery makes a perfect early morning landing at Edwards Air Force Base. It marked the successful end of the Return to Flight program, in which the Glenn Research Center played a vital role.**

space engineer in the Army Research Laboratory at GRC (and a *Gear Technology* contributor), was a member of the Actuators Investigation Team. His area of expertise is gears for rotorcraft—not spacecraft—and so the shuttle actuators presented a new, but not insurmountable challenge.

"In general, fretting and wear can result in the loss of gear surface material, and fretting pits can lead to signs of failure; you lose part of the drive capability of the gear tooth at that point," he says. "Some of these wear mechanisms can snowball and you end up with a system that can't carry the load. And the shuttle is designed a little differently from, say, your car or a helicopter. We had to think a little differently when we started tackling the problem for the shuttle, but fortunately we have enough expertise here to know that the technology from the aerospace world applies to the space world. It's just that we were operating in a different zone of the fatigue curve."

The shuttle has two sets of actuators—the body flap (a thermal shield for the spacecraft's main engines during re-entry that provides pitch control for the orbiter during its atmospheric flight after entry), which travels up and down, and the tail's rudder/speed brake. As the latter component's name implies, it performs two functions. On ascent and descent, it acts like a rudder for vehicle guidance. But upon touchdown, the actuators transform the tail into a speed brake. Otero points out that the danger a failure of that function presents is directly influenced by where the shuttle is to land.

"(If the shuttle) is landing in the desert and the speed brake fails, they just have to chase it down until it stops rolling, because it has its own runway," he says. "But if the rudder part of it fails, that's a larger (issue) if they can't control the flight landing surface (the ocean, e.g.). It's what is considered a "Crit-1" (Criticality-1) item. It's very important to make sure that the (actuator) works.

"The engineering thought process was that these (actuators) are not cycled very often—like a helicopter or airplane—because the shuttle doesn't fly that often; it's only used on the way up, and again on the way down.

"But one thing that we had not realized was going on was what we

> *"Every time the shuttle was powered up, the actuators were moving basically like a washing machine, just kind of back and forth in place. So that adds a lot more cycles than the original designers had envisioned. Our guys here had to do a test program to simulate the dithering and we made an assessment that, yes, there are more cycles, but maybe not enough to cause a problem."*
> —Angel Otero

call dithering—the way the hydraulic system in the shuttle works. Every time the shuttle was powered up, the actuators were moving basically like a washing machine, just kind of back and forth in place. So that adds a lot more cycles than the original designers had envisioned. Our guys here had to do a test program to simulate the dithering and we made an assessment that, yes, there are more cycles, but maybe not enough to cause a problem."

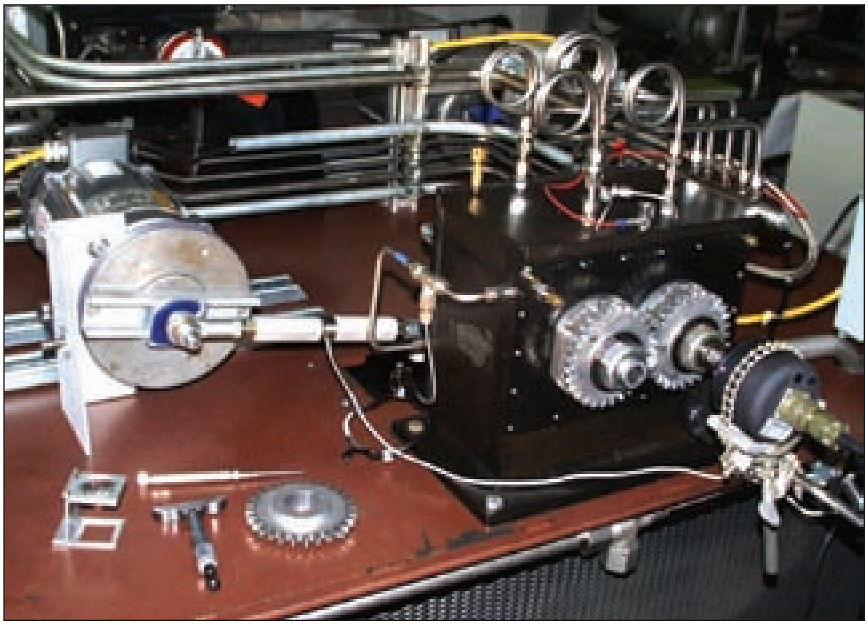
***Testing needed. But how?***

Handschuh points out that the testing and modeling were intrinsically necessary due to the fact that apples-to-apples testing was not an option for the investigative team. That's because there were no actual, in-use parts to test."These actuator systems aren't pulled out routinely, and even the ones that we've had access to were pulled out of a shuttle that had flown (only) 30 missions. (The actuators) were designed to last for the life of the shuttle, which is 100 flights or 10 years. And now things have dragged on a lot longer for a lot of these systems. The cycle count of 100 flights hasn't been as long as they thought, but more years have elapsed."

To put it another way, think of the way that medical science conducts experimental testing. Testing with humans is often out of the question, so substitutes are used. GRC was the best go-to resource to unravel unknowns because of their state-of-the-art testing and modeling capabilities, some of which are unmatched anywhere in the world.

"Actually, that's (our capabilities) what drove our involvement," says Otero. "If (the actuator system) was designed to be taken out (for inspection) after every mission, then they didn't need to come to us. All they had to do after every flight was open a box, add new grease and, OK—the grease issue is resolved. But that's a major disassembly that has to occur to get to those actuators. So they needed us to look at it in a lab environment and simulate the conditions so they could get answers without actually having to go in and tear those actuators apart."

The grease and cycling issues presented a number of challenges for the investigative team, among them creating the proper model for simulation purposes, and then extrapolating the results of those simulations to determine with relative certainty whether life- or flight-threatening conditions exist. Keep in mind, these were parts, systems and other components that were designed and built over 20 years ago.



This GRC test rig played a key role in evaluating grease and damage tolerance issues with Discovery's actuator gears.

"When they came to us with the grease questions—'We have this grease and it's discoloring; what can you tell us about the behavior of Braycote grease and 9310 steel?'—what you normally do is you go to the literature," says Otero. "And normally, you (cite the technical reports) of a Bob Handschuh, an Erwin Zaretsky, or a Wilfredo Morales (another GRC staffer), and you give them the answer.

"The problem was, there was no literature on a 17-, 20-year lifecycle of a 9310 steel gear system lubricated with Braycote. So we had to start doing aging tests. And by calling (Braycote) we realized they had changed the process of how they made the grease—there was now an older grease and a newer product—so our tribology guys had to test all those things here in order to determine that, yes, the grease is discoloring and decomposing a little. But it really didn't impact the relationship between it and the gears."

Determining that the grease was not severely impacting functionality was a relief to all concerned. That's because—given that the current shuttle program was nearing the end of its intended lifespan (2010)—finding and qualifying a new grease was not a realistic option.

"When things like a grease get space-qualified, it's like they're cast in concrete," Handschuh explains. " 'Thou shalt use it until this vehicle is done being used.'"

"Making a grease change on the shuttle would be a big job and cost a bunch of money to get everything re-qualified," Otero adds. "First you'd have to find the grease that does the job and then be able to figure out what is the proper qualification program. Remember that with the constraint that the shuttle is to retire in 2010, the realization is that if it is going to take four or five years to get a new subsystem qualified, it doesn't make sense to try and change it.

"This grease had a history of not having failed, so they wanted us to make sure that there wasn't anything that they were missing by having those gears lubricated with Braycote. And the answer was 'no,' as far as we could tell. But if that grease were to stay in there for another 20 years, then you start asking questions again. But the reality was that it wasn't going to happen."

From there, it was on to the actuators' dithering/cycling issues. Were the actuators a "GO," or not? Again, model simulation testing and analysis was required.

"We did dithering testing; we converted one of our contact fatigue rigs to do the dithering motion to check for gear surface wear," says Handschuh. "And we did some work on single tooth bending, and at some pretty high loads. We were looking at low-cycle fatigue behavior of 9310 steel and we will probably be presenting a report this year at the ASME (International Design Engineering Technical Conferences) in September."

***Testing and verifying probability.***

But to really get their minds around the gear questions, the team employed probabilistic analysis to best determine the lifespan and reliability of the actuators. In other words, with what certainty could the investigators determine the probability of either the efficacy or malfunction of the actuators? The answer, says Otero, is test and verify. Often.

"The simplest explanation is that one test is not enough. That's something we had to explain to the program because they were always saying, 'OK, we'll do one test and you tell us if the gears are OK.'

"I have a sign on my desk that says 'One test isn't worth 1,000 experts' opinions.'

"If you do just one test and pick the one bad one (outlier, or misleading, data point) in the set, you'll be giving them a bad answer. Or if you pick the one good one in the set, you might also be giving them a bad answer. You have to do enough tests to show that your scatter (variance) is within the band that they're worried about. If you do only one test you might be getting the one outlier data point. We were asked that if we were shown old actuators that were made at the same time as the ones that are in orbit, could we tell them if the ones in flight were okay."

Otero points out that looking at one set of gears might result in overly optimistic conclusions, or, conversely, in a great deal of unnecessary work and cost. Either way, an incorrect finding can lead to significant—if not fatal—consequences.

"If you just look at that one (bad) one and it happens to be the one outlier point on the backside, you go through this whole test program unnecessarily. Or worse, if you look at it and it happens to be a good one—but it might not be where the majority of data is going to be—you might give them a false sense of security. In a probabilistic situation you have to do enough tests to build enough data to be able to answer the question properly."

Upon completion of all the necessary modeling, simulating, analysis and other testing, the conclusion of the investigative team was that the lubrication and actuators issues were resolved to everyone's satisfaction, and no further work was required specific to operations in the final years of the 26-year shuttle program.

As one of NASA's 10 field centers, the invaluable work the GRC performed for the Return to Flight program helped the agency get back on track with the successful Discovery flight in 2005. But aside from that specific task, the center conducts ongoing research and testing that will enable NASA to go forward with space exploration.

And while it is commonly known that the technology developed by NASA often finds its way into any number of general-use applications, that synergy is sometimes reversed. The automotive industry's influence on rotorcraft is a surprising example.

"Actually, the people on the automotive end have been getting closer to being at an aerospace level of technology in their manufacture of what comes out on your car," says Handschuh. "We go to the same (conferences) that people from the automotive industry attend, and our technology transfer to report writing is how we distribute results.

"Some of the people from the automotive arena can teach us, too. They do some interesting things in the automotive world now that we hopefully can apply to things for our helicopters in the future. They (automotive transmission designers) are real sensitive to noise—you don't want a noisy transmission in your car—and there's some technologies they've really pushed hard. In fact, some of the leading researchers in our country doing gear technology have backgrounds in automotive."

But let's face it: It is rocket science, after all, that most excites the imagination and sense of wonder in many of us. And perhaps that is best summed up by NASA's stated vision:

"To improve life here. To extend life to there. To find life beyond."

### For more information:

NASA Glenn Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
Phone: (216) 433-4000
Website: *www.grc.nasa.gov*



**Dr. Robert Handschuh, an aerospace engineer in the Army Research Laboratory at GRC and member of the Actuators Investigation Team. An expert in rotorcraft, Handschuh was able to adapt and apply his skill in that sector in order to help conduct critical evaluation of the actuators' grease, fretting, wear and dithering issues.**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# MARCO POLO HAD IT RIGHT— East Meets West At CIMT And Everybody Wins

The just-opened, 22,600-sq. ft. Gleason Gear Technology (Suzhou) Co. Ltd., which will produce machine tools and possibly other products exclusively for the Chinese market.

**Jack McGuinn, Senior Editor**

When, in 1266, Marco Polo journeyed to China in search of lucrative trade routes and untold riches, he was firm in his belief that the Asian continent was an untapped source awaiting economic development. The intrepid Venetian may have been eight centuries ahead of his time, but his vision's validation was amply demonstrated at the 10th China International Machine Tool Show (CIMT), held April 9–15 in Beijing.

Staged bi-annually at the China International Exhibition Center, CIMT is China's largest and most sophisticated machine tool exhibition, and it now ranks among the top four machine tool shows in the world. With more than 1,200 exhibitors and 26 countries represented, CIMT has become a destination show for exhibitors and attendees alike since its inception in 1987.

***Marketing 101***. For Alan R. Finegan, director of marketing for Gleason Corp., exhibiting at CIMT was just good business.

"It's no secret that China is the largest growth market in the world, and has become by far the largest consumer of machine tools and related equipment in the world," he says. "I cannot think of a machine tool technology show that makes more sense to include in our promotional plans than CIMT."

To that end, Gleason showcased several products, including the Genesis 130H hobbing machine, a recent addition to its line of cylindrical gear manufacturing equipment; the 275HC CNC bevel gear cutting machine; and a gear metrology technology demonstration with its Sigma 7 Gear Inspection and Analysis System.

For Gleason, both the China market and CIMT have become a far-flung but welcoming home away from home, the company having made its Marco Polo-like trek to China back in 1987. Gleason Corp. now enjoys—and aggressively cultivates—high-profile status among Chinese tool buyers.

"Gleason had a presence in China long before the trends of the last few years," says Finegan. "Gleason Sales-China, our sales-and-service organization in Beijing, is celebrating its 20th anniversary this year, and over the years it has grown dramatically in both size and capabilities." Finegan also points to a 2005 joint venture with Chinese Harbin No. 1 Tool Corp.—Gleason Yi Gong (Harbin) Cutting Tools Co. Ltd.—to produce precision gear cutting tools in Harbin in Heilongjiang Province. The facility serves as another example of the company's proactive Chinese market development. And just before the start of CIMT last month, the company announced its grand opening of the Gleason Gear Technology (Suzhou) Co. Ltd., which will produce machine tools and, perhaps later, other products made exclusively for the Chinese market.

Ohio-based Process Equipment Co. (PECo) is another American company that gets it. CIMT is not only a showcase for its new products, but can also be a springboard to other opportunities for global presence.

"We feel that the market awareness generated at this show will help us further penetrate the global market," says Brian Slone, PECo business unit manager/metrology systems division. "We have several meetings scheduled with European companies to discuss opportunities as well."

At the show, PECo unveiled its ND430 CNC gear measurement system with automatic probe changer. The unit, which helps meet the increasing demand by Chinese manufacturers for better-precision components, also featured a Mandarin Chinese language module that allows for data entry and inspection analysis displays in the native language. And as that demand continues to grow, Slone sees PECo as a ready-willing-and-


Making its Asian debut at CIMT is Gleason's 130H hobber. Manufacture of the 130H will be the primary focus at its new Gleason (Suzhou) Co. Ltd.

able resource.

"From conversations with the Chinese Gear Manufacturers Association (CGMA), it appears that the Chinese market will have a need for 'hundreds' of gear measurement machines over the next five years. We anticipate having a large percentage of those machines," he says. Slone adds that, in an accelerated variation of China's traditional Five Year Plan benchmark, PECo will be developing strategies at the show with its international sales partners (U.S., German and Turkish companies) for the next two years.

In support of those plans, PECo is also "walking the walk" relative to establishing itself as a player in the China gear industry market.

"We have hired a full-time sales and service team for the Chinese market, and have translated all of our documentation necessary to support the sales and service function into the Chinese language," he says. "We are finding that working with U.S. transplants in China is going to be a strong point for us with the language capabilities that we have developed." He adds that the company is considering opening a facility there to manufacture and assemble components for the Chinese market. As with Gleason Corp., that investment will probably be in the form of a joint venture with companies that will work with PECo to everyone's mutual benefit.

***In the beginning***. Gleason and PECo were just two American companies exhibiting at CIMT under the aegis of the Association for Manufacturing and Technology (AMT). If Marco Polo receives credit as China's first Western agent of economic development, the AMT is certainly its Lewis & Clark. With its first trade mission to China in 1975, the AMT has over the years succeeded in helping to expand American companies' presence. That success continues today as the AMT/USA Pavilion at CIMT 2007 was completely sold out, represented by more than 60 U.S. companies.

"The China market is growing rapidly and is very attractive to U.S. builders," says AMT president John B. Byrd III. "The USA Pavilion is just one of several AMT initiatives to help our members serve the China market." The AMT also has a USA Technology and Service Center in the Waigaoqiao Free Trade Zone in Shanghai, along with three representative offices in Beijing, Shanghai and Guangzhou.

And the American companies that today are assiduously putting down roots

PECo's ND430 Next-Dimension® Gear Measurement System.

in China's and other Asian markets' rich economic soil are poised to be the sure winners as the manufacturing miracle continues to take shape and pay dividends. And companies like Gleason and PECo are more than willing partners in helping to make that happen.

"As the quality of gears made by Chinese manufacturers improves through better metrology, I believe you will see more 'high-volume loose gearing' product shipping to all parts of the world," says PECo's Slone. "Communication between technical personnel in the various trading countries will be the key in maintaining a quality product that meets each individual market's demand."

For Gleason's Finegan, China is doing all the right things in developing the groundwork for a vibrant industrial base.

"China is developing and acquiring the necessary technologies to achieve its goals, and this extends from motor vehicles to appliances, industrial machinery, and to many other products, including gears.

"It is only natural that in developing capabilities to satisfy their domestic demands for gears, China has the potential to become a significant player in the global market as well."

(*Editor's note: For a complete listing of CIMT exhibitors, please go to* http://www.cimtshow.com*. For a complete listing of AMT/USA Pavilion exhibitors, please go to* www.mfgtech.org)

**For more information:**
The Association for American Technology (AMT)
7901 Westpark Drive
McLean, VA 22102-4206
Phone: (703) 893-2900;
(800) 524-0475
Fax: (703) 893-1151
E-mail: *AMT@AMTonline.org*
Website: *www.mfgtech.org*

Gleason Corp.
1000 University Avenue
P.O. Box 22970
Rochester, NY 14692-2970
Phone: (585) 473-1000
Fax: (585) 461-4348
E-mail: *sales@gleason.com*
Website: *www.gleason.com*

Process Equipment Co.
6555 South State Route 202
Tipp City, OH 45371
Phone: (800) 998-4191;
(937) 667-7105
Fax: (937) 667-9322
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**May 9–11—Modern Furnace Brazing.** Holiday Inn, Madison Heights, MI. Design, metallurgical and production engineers will learn about such topics as joint selection, interaction of base and filler metals, protective atmospheres, joint preparation, fixturing, and quality control. $1,550. A discounted rate of $1,450 is available for additional members of the same company. For more information, contact Wall Colmonoy Corp. by telephone at (248) 585-6400 or on the Internet at *www.wallcolmonoy.com.*

**May 13–16—PowderMet 2007: International Conference on Powder Metallurgy and Particulate Materials.** Colorado Convention Center, Denver, CO. Worldwide event featuring the latest in PM Equipment, powders, products and services. International technical program includes 180 papers presented in technical sessions, special interest programs, and a poster program. Special events include a keynote address by Clyde Fessler of Harley-Davidson and a reception at Coors Field. Registration ranges from $50-$1,750. For more information, visit the association's website at *www.mpif.org*.

**May 16–18—Gear Design Seminar: Beyond Simple Service Factors.** Lago Mar Resort, Fort Lauderdale, FL. Taught by Ray Drago, Drive System Technology, this course is designed for gear engineers, designers, and application engineers. Attendees will be introduced to gear rating theory and standardization, differences in stress states among surface durability failure modes, extended load capacity analysis techniques, optimization of gear tooth design parameters and more. For AGMA members, the cost is $1,395 for the first registrant from a company and $1,195 for the second registrant from the same company. For non-members, the cost is $1,895 for the first registrant and $1,695 for the second. For more information contact the AGMA online at *www.agma.org*.

**May 22–24—EASTEC 2007** Eastern States Exposition Center, West Springfield, MA. Attendees include manufacturers and buyers from the aerospace, defense, medical, consumer products and other industries. In 2006, EASTEC exhibits were reorganized in technology clusters by building. In 2007, EASTEC's exhibit layout is further refined to make it easier for attendees to find the exhibitors, products and services they want to see. The event also offers a technology-focused Automation, Lean & Quality Resource Center and an Energy & Environmental Assessment Day. Registration is free. For more information, visit the show's website at *www.sme.org/eastec*.

**June 12–14—Automation Technology Expo East.** Jacob K. Javits Convention Center, New York, NY. Four shows are co-located within this event:

- **MD&M East**—For the medical device and manufacturing market.
- **EastPack**—The East Coast's largest packaging event.
- **Atlantic Design and Manufacturing Show.**
- **PlastTec East 2007** For registration information, call the registration hotline at (301) 445-4200 or visit the show's website at *www.devicelink.com/expo/ate2007*.

**June 14–17—GIMT + AMB China 2007.** Guangzhou International Convention and Exhibition Center, The GIMT, South China's leading machine tool exhibition, will be combined for the second year in a row with the AMB. The show is jointly organized by Business Media China AG, Messe Stuttgart International and BMC Zhenwei International Exhibitions Co. Ltd. For registration and related additional information, visit the show's website. For more information, contact GIMB + AMB by e-mail at *rhung520@aol.com* or on the Internet at *www.china-machinetool.com*.

**June 25–28—KISSsoft Calculation Program Seminar.** KISSsoft facility, Rapperswil, Switzerland. Dr. Kissling, a member of the Swiss Standard Association, will teach a range of subjects including special know-how about properties of gears and how to take them into account in the sizing and optimization process. The third day will introduce participants into the shaft and bearings calculation, other machine elements, as well as into some basic functions of KISSsoft like material database and reports. The fourth day is dedicated to programming KISSsys and will teach participants to model entire systems of machine elements such as a gearbox or a power train. Seminars are conducted in English. For more information, visit the company's website at *www.kisssoft.ch* or contact *info@kisssoft.ch*.

# Gleason

## ACQUIRES LECOUNT

Gleason Corp. announced it has acquired the assets and business of LeCount Inc., a producer of expanding mandrels and other workholding equipment for inspection and machining applications including grinding, sharpening and polishing.

John J. Perrotti, president and CEO of Gleason Corp., says, "We are pleased and excited to add the well-known LeCount name to our portfolio of products and services for the gear industry worldwide. LeCount products perfectly complement our Gleason-M&M gear inspection and analysis systems, and strengthen our ability to serve our global markets. By leveraging Gleason's leadership in gear technology and our global reach, we believe opportunities exist to greatly expand sales of LeCount products."

Gleason will move LeCount's operations from White River Junction, VT, to its facility located in Rochester, NY. Certain key LeCount personnel will be retained and relocated to Rochester to assure a smooth transition. Sales and distribution channels will be integrated with Gleason's existing sales offices and representatives in most markets.


John J. Perrotti

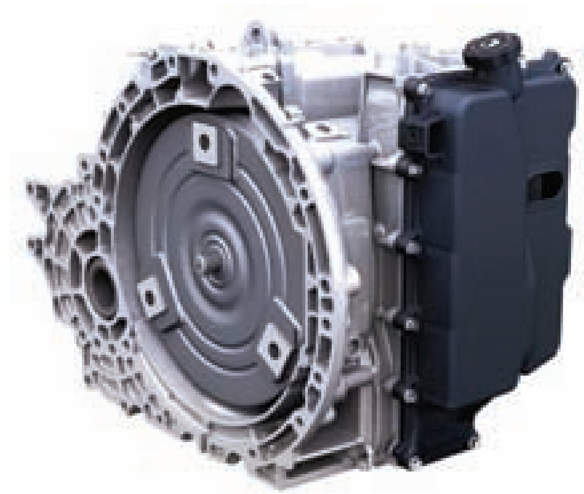
LeCount's products are sold worldwide and consist of a line of expanding mandrels that are used primarily to hold gears and other parts in precise position for inspection and, more recently, machining applications such as grinding.

Gleason Corp. develops, manufactures and sells gear production machinery and related equipment used by customers in the automotive, truck, aircraft, agriculture, construction, power tool, energy, and marine industries and by a diverse set of customers serving various industrial equipment markets.

# Ford

## INVESTS $200 MILLION IN TRANSMISSION PLANT

Ford Motor Co. announced a $200 million investment



in the Sharonville, OH, transmission plant for a future high-performance, fuel-efficient transmission.

The investment will be used to retool the plant for flexible manufacturing and advanced powertrain production. The company says details of the transmission will be disclosed at a future date.

According to the company's press release, the investment is supported by a significant incentive package from the State of Ohio, Hamilton County and the City of Sharonville.

"Sharonville is working hard to achieve world-class productivity levels," says Joe Hinrichs, vice president, North America manufacturing. "We appreciate the show of support from the state and local governments, and the UAW, which is working with us to make our plants competitive."

# Gear Motions

## HIRES EXECUTIVE VICE PRESIDENT

Sam Haines, president of the Gear Motions companies (Oliver Gear in Buffalo, NY, and Nixon Gear in Syracuse, NY) announced the appointment of Barbara Stone to executive vice president of Gear Motions Inc.

According to a company press release, Stone began work at Gear Motions in early April.

Stone's experience includes serving as director of operations and finance at Higbee Inc. and manager of production control at New Venture Gear (NVG) in Syracuse. She was promoted to the corporate offices of NVG in Troy, MI, where she became manager of production control and planning. While at corporate, she was a member of the executive team and was selected to join the Volkswagen

Focused Factory Launch Team in Roitzch, Germany. She eventually returned to NVG where she spent four years as manufacturing area manager.

Sam Haines says, "Gear Motions is excited to have Ms. Stone become a member of our team. Her remarkable manufacturing and planning experience combined with an extensive financial background will add an entirely new global perspective to our growing company."


Barbara Stone

## Robert Doshi

### BACK TO SCHAFER GEAR

Robert Doshi returned to Schafer Gear Works as production manager.

According to a company press release, Doshi held this position before departing for military service with the U.S. Army in Afghanistan. Upon his return from the army, Doshi worked as distribution manager for Memorial Hospital and Health System.

His responsibilities include managing operations, training and quality control.


Robert Doshi

## Samputensili

### INVESTS 4.7 MILLION EUROS IN ENVIRONMENTALLY FRIENDLY FACILITY

Samputensili S.p.A. announced an investment of 4.7 million euros for the building of a new manufacturing facility in Ortona (Chieti, Italy). The new plant will be located alongside the existing gear cutting tool and rotor plant.

According to the company's press release, the new plant will be constructed with a focus on ecology. Designed to comply with ISO 14001 environmental certification, the facility was designed with thermal cut, double glazed windows and insulated boundary walls and foundation.

Samputensili is also installing an integrated photovoltaic system that will be able to generate 380 MWh/year, covering 8% of the factory's annual energy requirements. Panels are made from micro-crystalline modules with two inverter devices in a master/slave configuration. At dawn, the master inverter is turned on and, when the workload reaches a sufficiently high level, the parallel slave inverter is activated. This configuration makes it possible to save a further 2% and to save on long-term maintenance costs, as the system does not contain any moving mechanical parts.

The 1.7 million euro photovoltaic system was designed by Enerray, a Maccaferri Industrial Group company that operates in the field of environmentally friendly energy performance systems. Samputensili is also part of the Maccaferri Industrial Group.

# Linamar

## EXPANDS GEAR PRODUCTION FACILITY

**Michael Annable, executive vice president of administration, Gary Goodyear, Member of Parliament for Cambridge, Ontario, Canada and Jim Jarrell, Linamar president and COO.**

Linamar Corp. announced plans to add 100,000 square feet to its existing facility to accommodate new and future gear manufacturing programs resulting from the company's investment in gear product and process innovations.

Linamar will perform advanced gear processing development work in the expanded space in conjunction with its new R&D and training center.

The advancement is supported by loans from the company, the government of Canada and the provincial government through the Ontario Automotive Investment Strategy. According to a company press release, Canada's new government announced a repayable loan specifically for gear technology.

Construction will begin this spring and is expected to commence by the end of 2007.

Jim Jarrell, Linamar Gear president and COO, Gary Goodyear, Member of Parliament for Cambridge, Ontario, Canada and Paul Bunnaman, plant manager at Linamar Gear.

## Lenze

### OPENS NEW SALES OFFICE

Lenze opened a new regional sales office in Leeds, U.K., which will be used for technical sales and local application support, meetings, training and product demonstrations.

The new facility is timed to coincide with the new 9400 servo system that is being launched to customers in the offices at the end of March. Customers can see demonstrations and presentations on the product features and machine safety, says Roger Purkiss, national sales manager for the U.K.

# Honda

## BEGINS PRODUCTION AT CHINESE PLANT

Production began on March 8 at the new Honda Auto Parts Manufacturing Co. Ltd. (CHAM) plant in Nanhai Industrial Park District, Foshan City. The company is wholly owned by Honda.

CHAM will manufacture powertrain components including automobile transmissions, which will be supplied to Honda's automobile production joint venture operations in China.

With the annual production capacity of 240,000 units (transmissions), the new plant will initially accommodate machining and assembly of transmissions and drive shafts as well as machining of crankshafts and connecting rods for engines.

According to a press release, the company is planning to add the machining of gears as well as production of control parts. Both key, high-value transmission components are currently supplied from Japan.

In China, Honda manufactures automobiles with three joint venture companies: Guangzhou Honda Automobile Co. Ltd., Dongfeng Honda Automobile Co. Ltd., and Honda Automobile (China) Co. Ltd., which manufactures automobiles for export.

The combined annual production capacity has now reached 530,000 units—360,000 units at Guangzhou Honda; 120,000 units at Dongfeng Honda; and 50,000 units at Honda Automobile (China). CHAM is Honda's fourth integrated automatic transmission production plant in the world following operations in Ohio, Georgia and Indonesia.

# P&F Industries

## BUYS HY-TECH MACHINE FOR APPROXIMATELY $16.9 MILLION

P&F Industries, Inc. announced that, through a newly formed subsidiary, it has acquired substantially all of the assets comprising the business of Hy-Tech Machine, Inc., a Pennsylvania manufacturer and distributor of pneumatic tools and parts for industrial applications.

In addition, the company acquired substantially all of the assets of Quality Gear & Machine, Inc., an entity related to

Hy-Tech and a supplier of component parts to Hy-Tech and others. The aggregate purchase price for these two businesses consisted of $16.9 million in cash, the assumption of certain payables and liabilities and the obligation to make certain contingent payments. The company also acquired certain real estate from HTM Associates, an entity related to Hy-Tech, for $2.2 million in cash. This acquisition will be immediately accretive to earnings.

The newly acquired business is headquartered in Cranberry Township, PA and maintains a component manufacturing operation in Punxsutawney, PA. Hy-Tech reported $14 million in revenues in 2005. Certain members of management and other employees of Hy-Tech will remain active in the operations of the business.

P&F Industries, Inc., through its three wholly owned operating subsidiaries, Florida Pneumatic Manufacturing Corp., Continental Tool Group, Inc., and Countrywide Hardware, Inc., manufactures and/or imports air-powered tools sold principally to the industrial, retail and automotive markets, as well as various residential hardware.

## Ikona Gear

### SHIPS MUD PUMP DRIVE TO NORTH AMERICAN CUSTOMERS

Ikona Gear made its first commercial shipments of its new Mud Pump Drives (MPD) to major oil and gas companies in Canada and the U.S. According to the company's press release, it is in the final stages of equipping its new oil and gas product assembling facilities in Coquitlan, British Columbia and intends to expand the MPD production over the coming months. The company says the MPD 1100 Series 1- and 2-speed mud pumps sell for approximately $45,000.

In March, Ikona plans to begin shipments of its $500,000 Draw Works (DW) products.

A drilling rig requires at least one MPD and one DW. Mud pump drives facilitate the desired speed and power of the drilling rig mud pump and produce the required flow and pressure for powering the drilling head.

"With our new oil and gas product assembly facility capable of producing more than $30 million in sales, we are highly focused on rapidly building our oil and gas customer base," says Laith Nosh, Ikona's CEO and president. "The incorporation of our proprietary gear technology allows our mud pump drives to be designed lighter and more compact than competitive equipment with a comparable rating. A key benefit of Ikona's lighter, more compact MPD design is the reduction of downtime when moving a rig between drilling locations."

## Wall Colmonoy

### EXPANDS AEROSPACE FACILITY

The Aerospace Technologies Group of Wall Colmonoy Corp. in Oklahoma City, OK, completed a plant expansion with the addition of a new 7,800 square foot building. The building will be used to inventory and prepare raw materials as well as house their shipping department.

As part of the plant expansion, Wall Colmonoy installed a new water jet machine to cut stainless steel components used in the aerospace and heat exchanger products manufactured at their facility. According to the company's press release, this dual-cutting-head machine has a bed size of 13' X 6'.

## Gleason

### OPENS THIRD OPERATION IN CHINA

Gleason Corp. announced in April the grand opening and dedication of Gleason Gear Technology (Suzhou), Co., Ltd. in Suzhou, Jiangsu Province, China.

The dedication of the new facility took place in April and was attended by approximately 100 customers, suppliers, trade associations, and local government and other organizations.

According to Gleason's press release, the new 2,100 square meter (22,600 sq. ft.) facility will initially focus on meeting Chinese domestic demand and producing the Genesis 130H gear hobbing machine. The first 130H built in Suzhou was exhibited last month at the China International Machine Tool Show (CIMT) in Beijing. GGTS employees have been hired and trained at Gleason's headquarters in Rochester, NY.

In April, Gleason Sales (China) in Beijing, the sales and service arm of Gleason, celebrated its 20th anniversary. In 2005, Gleason formed a joint venture company, Gleason Yi Gong (Harbin) Cutting Tools Co., Ltd., to produce precision cutting tools in Harbin, China. "Gleason Gear Technology (Suzhou) is a logical extension of our strategic plan to bring Gleason technology to this important market, but with the level of service and support that only a local presence can provide," says John J.Perrotti, president and CEO of Gleason Corp.

# Monnier + Zahner

BUYS LAMBERT-WAHLI

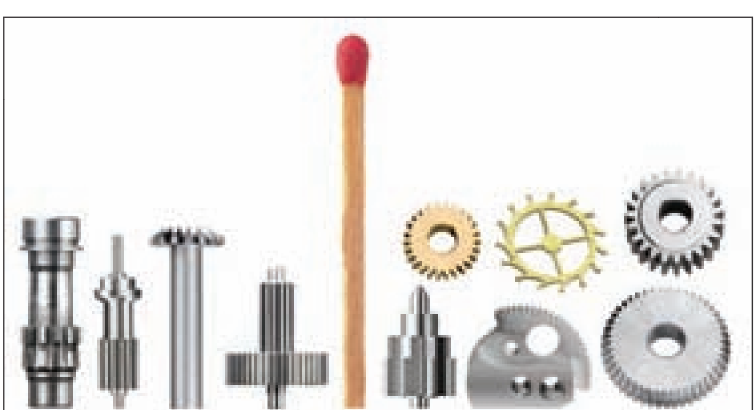
In December 2006 Meyco Holding, the parent company of Monnier + Zahner AG, completed the purchase of Lambert-Wahli AG, a manufacturer of fine pitch gear hobbing and worm milling machines located in Safnern, Switzerland.

According to the company's press release, operations at Lambert-Wahli shall be continued as before, with the same staff.

Roland Waelti, managing director of Monnier + Zahner AG, was appointed the new managing director of Lambert-Wahli AG as well.

Koepfer America, located in South Elgin, IL is the North American representative for both Lambert-Wahli AG and Monnier + Zahner AG.

Monnier + Zahner AG is also a manufacturer of quality gear hobbing and worm milling equipment in Safnern, Switzerland.



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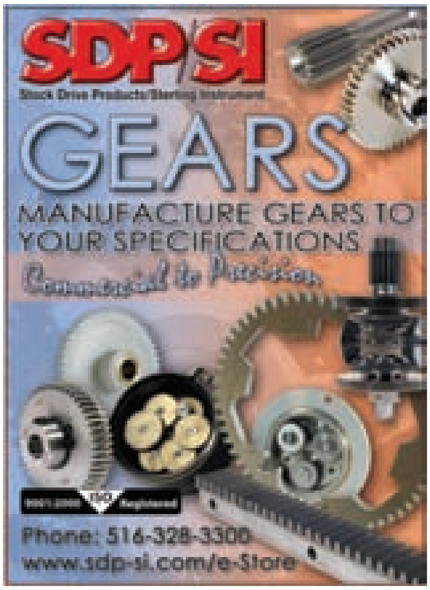


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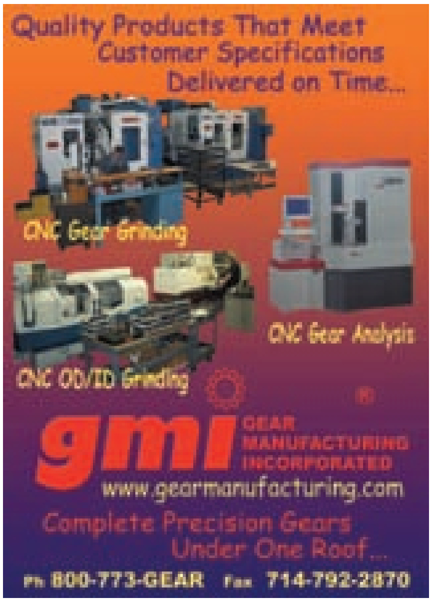
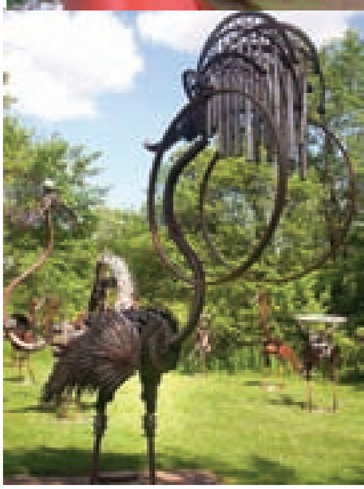


# One Man's Junk = Fellow Gear Lover's Treasures





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As a retired industrial wrecker, Tom Every, a.k.a. Dr. Evermore, has a collection of gears that would rival many small warehouses. Instead of building a page on E-bay, Every decided it was time to find a home for some of his gears.

He did exactly that, but rather than fill up his own garage with the gears, he started building sculptures that contained gears by the ton in 1983. Housed in North Freedom-Baraboo, WI, behind a surplus store, Every's industrial sculpture site is a must-see for every avid road tripper and gear lover.

Most well-known is "The Forevertron," which he calls a mechanical fantasy and a testement to the Industrial Revolution. Weighing in at 400 tons, the sculpture is dotted with gears that are both functional and decorative. Every hopes that, in hundreds of years when archeological specialists uncover his creation, they'll come away with a new appreciation for gears.

"I love gears and would never distort one," he says. "They represent an energy point. If I want to accent a point of motion, I use a gear as an additive. For instance, I made one small sculpture of a bird and used a gear on the breast plate to demonstrate its movement."

Most of Every's gears came from the world's largest paper mill manufacturer and old Milwaukee breweries that he demolished.

"Some of these gears cost thousands of dollars to make. I loved those little machine shops that made the gears and wanted to honor them," he explains as motivation behind his unconventional retirement occupation.

His creations are unmarked, so you'll need to talk to Dr. Evermore himself to learn the significance, but it's definitely worth driving a few miles off the beaten path to meet a fellow lover of gears.

Every's sculptures are located at:
US Highway 12
North Freedom-Baraboo, WI
(Across the highway from the Badger Army Ammunition Plant and behind Delaney's Surplus.)
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