Tribology & Lubrication Technology

SYSTEMS, STRATEGIES & RESEARCH FOR LUBRICATION PROFESSIONALS

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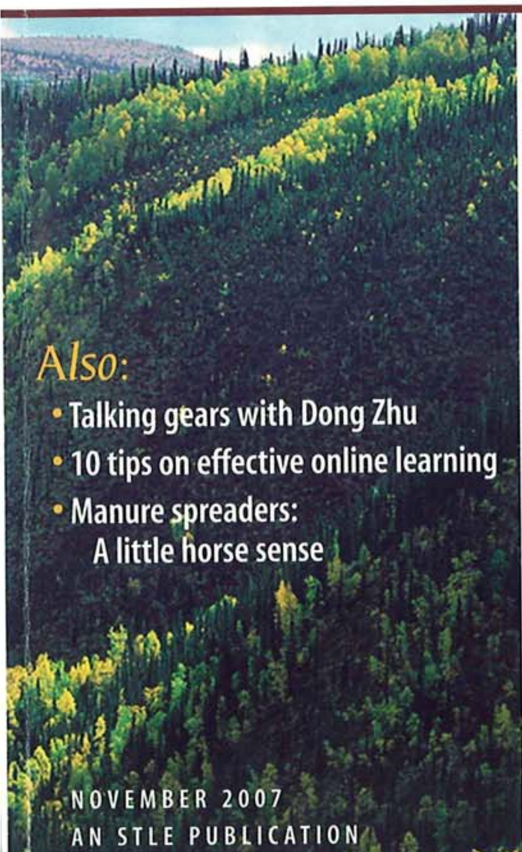

Also:

- Talking gears with Dong Zhu
- 10 tips on effective online learning
- Manure spreaders: A little horse sense

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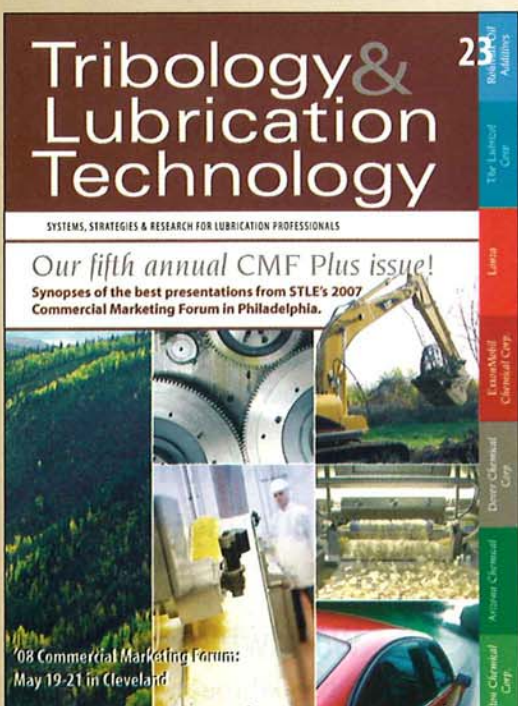
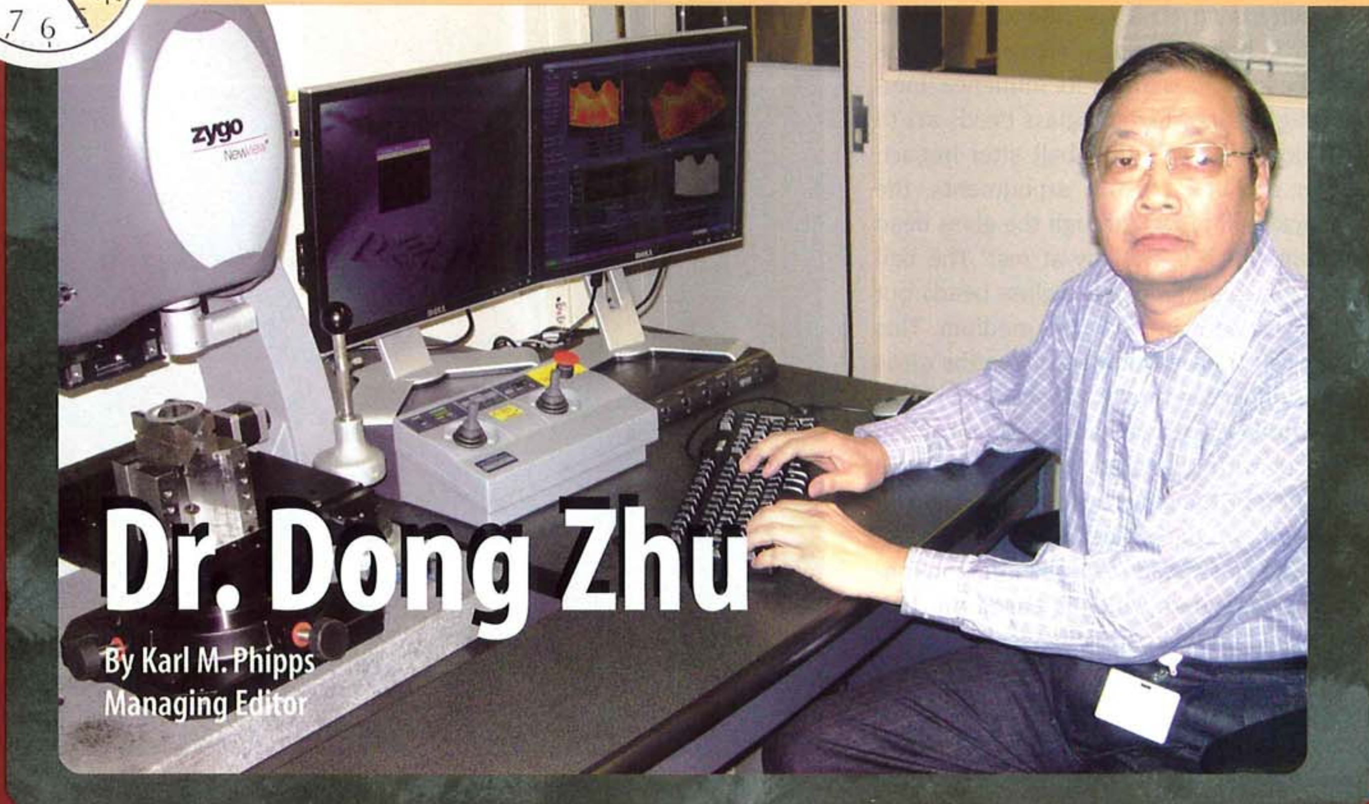




Dr. Dong Zhu

By Karl M. Phipps
Managing Editor

Working with scientists from around the world, this dedicated researcher is advancing our understanding of gear failures and the surface contact and lubrication analysis methods that may lead to the increase of gear efficiency and durability.

Editor's Note: *Dr. Zhu's name was submitted for a 20 Minutes profile by STLE's Gears Technical Committee.*

Professional experience

- Eaton Corp., Southfield, Mich., Principal Engineer, 1994-Present.
- Tsinghua University, Beijing, China, Adjunct Professor, 2000-Present.
- Northwestern University, Evanston, Ill., Adjunct Professor, 2002-2004.
- Alcoa, Inc., Pittsburgh, Pa., Staff Engineer, 1991-1994.
- Northwestern University, Evanston, Ill., Center for Engineering Tribology, Research Fellow, 1986-1991.
- Tsinghua University, Beijing, China, State Key Laboratory of Tribology, Assistant Professor, 1984-1986.

Education

- Tsinghua University, Beijing, China. Doctorate in Mechanical Engineering, 1984.
- Tsinghua University, Beijing, China. Master of Science in Mechanical Engineering,1981.

Professional Affiliations

- STLE
- Member, STLE Annual Meeting Program Committee, 2006-Present.
- Associate Editor, STLE *Tribology Transactions*, 2003-Present.
- Vice-Chairman and Chairman, STLE Gears and Gear Lubrication Technical Committee, 2004-2006.
- Membership Chairman, STLE Detroit Section, 2001-2004.
- Chairman, STLE Wear Technical Committee, 2001-2003.
- ASME
- Member, ASME Research Committee on Tribology, 2003-Present.
- Member, ASME Tribology Division, Honors and Awards Committee, 2003-Present.

Major Awards and Honors

- ASME Fellow, 2007.
- STLE Fellow, 2006.
- STLE Edmond E. Bisson Award, 2003.
- First-Class Award of National Science and Technology Advancement, National Education Commission of China, 1989.

Publications

- Author/co-author of about 75 papers published in technical journals and peer-reviewed conference proceedings.

How did you begin your career working in the field of gear tribology?

In the late 1970s I participated in gear strength research projects and started to use the finite element method (FEM) to evaluate gear tooth bending strength. At that time, I first began writing some early research papers. In 1984 I received my doctorate from Tsinghua University in Beijing, China, where my thesis work was on thermal elastohydrodynamic lubrication (EHL), which is fundamental to gear lubrication. My thesis advisors were professors L. Zheng and S. Wen. In 1986 I joined Northwestern University's Center for Engineering Tribology as a research fellow, working with professor Herbert S. Cheng to develop a Helical Gear Code for prediction of gear tribological performance.

What kinds of products does Eaton Corp. manufacture and market?

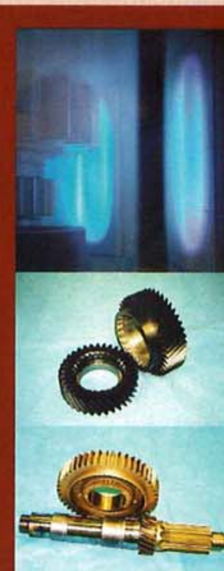
I joined the Eaton Corporate R&D Center in 1994. Eaton is a global supplier of automobile, truck, hydraulic and aeronautical components and has dominant market shares in North America for many geared products such as heavy-duty truck transmissions.

Eaton offers warranties of 750,000 up to a million miles for heavy-duty transmissions, and each transmission may operate on the road well beyond its warranty. Therefore, gear durability, reliability and efficiency are extremely important, and the market constantly imposes great challenges to R&D engineers. This has been the driving force for my gear research activities to pursue technological advancements for continuously improving gear performance, efficiency, life and reliability.

What do you enjoy the most about your job?

I enjoy working with both product engineers and university professors as a bridge in between. By doing this I know what the problems are in engineering practice and what advanced technologies are available or ought to be developed. I appreciate that Eaton has provided me with good opportunities to do fundamental research and develop cutting-edge technologies, while tackling practical problems for a wide range of Eaton products.

Pictured are coated gear samples (*shown below*) which Dr. Dong Zhu of Eaton Corp. has processed and tested in his PVD coating lab (*shown above*).



What are your research focus points in order to solve engineering problems such as pitting and wear failures that often occur in gears?

It is well known that mechanical component failures can be categorized into two groups: structure (or bulk) failures and surface failures. For structure failures, predicting and preventing technologies have been much better developed. For example, not long ago people still relied on photoelasticity experiments, strain gauges and destructive tests to evaluate structure strength. As FEM/CAD technologies have been well developed with commercial software packages readily available, today fewer and fewer people still rely on photoelasticity/strain gauges and destructive tests. Component structure strength can now be quickly and accurately predicted using computers. Product design cycles have been shortened greatly, and destructive tests can be avoided in most cases.

On the other hand, it has been found that in reality about 80%-90% of component failures fall in the surface failure category. These include major gear failures such as sliding wear and pitting due to contact

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fatigue. Unfortunately, so far no commercial software is available that can help engineers to accurately analyze surface strength of various components. In fact, modeling tribological problems and predicting interface performance, strength and life often appear to be a bottleneck in advanced product design and development. My research activities, therefore, have been focused on the following three areas:

1. Surface failure simulation/prediction models such as those for pitting and sliding wear.
2. Surface contact and mixed lubrication models in order to provide a good fundamental base for surface failure and friction/efficiency analyses.
3. Gear surface modification methods such as coating, polishing and other improved machining and surface treatment processes in order to enhance surface strength and increase gear efficiency.

What is the current status of gear pitting and wear prediction methods, and what are you currently doing in order to improve gear design and reliability analysis techniques?

Commonly used gear pitting life prediction methods found in AGMA, ISO and other industrial standards are still based on simplified normal contact stress calculation with the Hertzian contact theory that was developed in 1882 under smooth surface and dry contact assumptions. It is well known, however, that (1.) most gears operate in mixed EHL regime, and lubrication may significantly affect gear performance and life, (2.) machined gear surfaces are not smooth, and surface roughness may greatly influence contact severity and lubrication condition and (3.) subsurface von Mises stress is much better correlated to material failures in the contact than normal pressure applied on the surface.

Although a large amount of test data have been accumulated over the last several decades and modification factors have been introduced into the AGMA and ISO standards in order to include the lubrication and roughness effects, intrinsic problems still exist because the fundamental base and framework of those standards were done more than 50 years ago when engineers were using manual slide rules for calculations. In fact, with current methods discrepancies are often found between predicted pitting life and testing results. Today advanced computer technologies are available to every engineer, so the conventional design and life prediction methods ought to be revolutionized.

A model-based pitting life prediction method is being developed in collaboration with professors Leon Keer and Qian (Jane) Wang of Northwestern University. It includes the following steps:

1. Input data directly from gear design software package and product database.
2. Full-scale mixed EHL analysis for critical conditions during engagement.
3. Subsurface von Mises stress calculation based on mixed EHL results.
4. Pitting life prediction with Dr. Erv Zaretsky's life model based on von Mises stress field obtained.
5. Comparison of prediction with available testing data and adjustment of material parameters in the life model, if necessary.

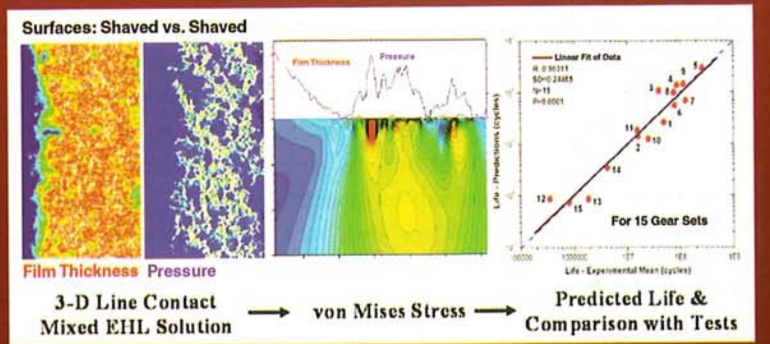
This method is based on sophisticated mixed EHL analysis taking into account the effects of surface roughness/topography, lubricant and additives, as well as operating conditions, so that no simplified model and empirical modification factors are needed. The failure analysis is based on the subsurface von Mises stress field with the advanced Zaretsky model. Also, the entire procedure can be computerized. Preliminary results from this method agree with available transmission gear pitting test data very well, as shown in Figure 1. It shows a good potential to be used in product design and development.

For sliding wear in gears, it is similar that currently used wear models are typically in the form of a simple empirical formula with a few parameters. Most models of this kind were developed long ago for the purpose of rough estimate of wear with manual calculation tools. They do not seem able to describe very complicated wear phenomena and mutual dependence between the wear and mixed lubrication characteristics.

Today new wear simulation and prediction models need to be developed using advanced computer technologies. A collaborative effort has been made with professor Y.Z. Hu's group at Tsinghua University and professor Jane Wang's group at Northwestern University to develop a deterministic sliding wear simulation approach based on an available mixed lubrication model. It can predict contact severity at each asperity contact and simulate material removal at local spots where material failure criteria are met. The modified surface profile, after material removal at current time step, will be used for the next time step and surface evolution due to wear that can then be simulated step-by-step.[1] Concurrent efforts with similar approaches have also been made for wear simulation by different researchers such as Dr. Daniel Nelias at INSA Lyons in France and Dr. Diann Hua et al. at Caterpillar, Inc., in Peoria, Ill. Further efforts, of course, are still needed to integrate this kind of wear simulation and prediction with gear design.

Furthermore, for gear tooth bending fatigue prediction, currently used methods found in the ISO and AGMA standards are still based on a simplified beam-bending theory developed in the 1950s. We have seen that efforts are currently being made by different researchers to integrate full-scale FEM with gear mesh model generation in design packages in order to develop better bending failure models. I am confident that in the near future model-based tribological failure analysis and prediction software packages will be available commercially that will greatly help design engineers to computerize design and analysis, improve product reliability and shorten

Figure 1.



product development cycle time, just like what we have already achieved for structure strength analysis and prediction.

Can you explain the status of the mixed lubrication study that's applicable to gear tribology?

It is well known that most machine elements operate in the mixed lubrication regime, where both surface contact and hydrodynamic lubrication coexist. For gears, operating conditions are typically severe, as power is transmitted directly through gear tooth contacts where surfaces are usually rough (as making surfaces super-smooth for gears is more difficult than that for many other components). The importance of the mixed EHL study can never be overestimated, as it is fundamental to gear lubrication effectiveness, efficiency, durability and reliability. The key issues in developing mixed EHL models include:

1. How to handle surface roughness. There are basically two approaches: stochastic and deterministic. Stochastic approaches use a small number of statistic parameters to describe the rough surface characteristics and their influences on contact and lubrication. They predict global performance and average values, but localized details and peak values (which may be directly correlated to failures) are missed. In the last 10 years, more attention has been given to deterministic approaches due to advancements in computer technologies. Rough surfaces can now be digitized and

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Modeling tribological problems and predicting interface performance, strength and life often appear to be a bottleneck in advanced product design and development.

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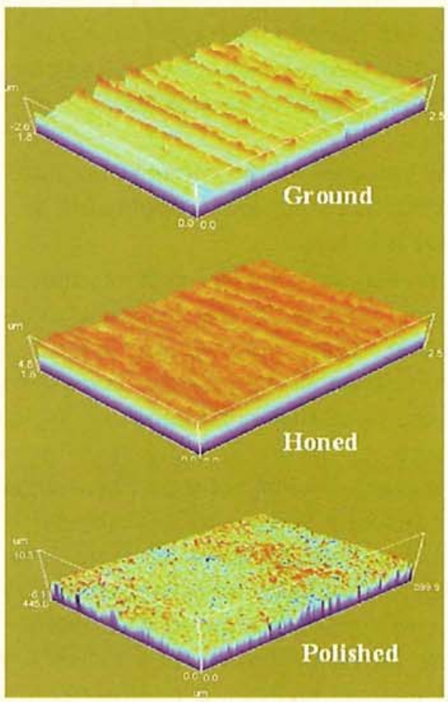
data matrices used directly in mixed EHL models as input data, so no statistic parameters are necessary (*see Figure* 2). This type of model can provide complete details for lubricant film thickness and pressure distributions, as well as subsurface stresses. It enables in-depth study on lubrication transition and breakdown, as well as surface failure mechanisms.

Figure 2. Digitization of gear tooth surfaces



2. How to model surface contact and hydrodynamic lubrication simultaneously. There are also two types of models. The first simulates contact and lubrication separately with different approaches. For contact, a dry contact model is used, while for lubrication the Reynolds equation is employed. This approach may work well in many cases. However, it may be difficult to determine borders and handle boundary conditions between contact and lubrication areas, especially when random or irregular surface roughness is involved. Concurrently, unified approaches are developed for solving both contact and lubrication with the same Reynolds equation system. Since dry contact is an extreme case of lubricated contact at ultralow viscosity and/or ultralow speed, theoretically dry contact can be simulated with lubrication models as long as the numerical solver is sufficiently robust to handle ultralow viscosity and ultralow speed.[2]

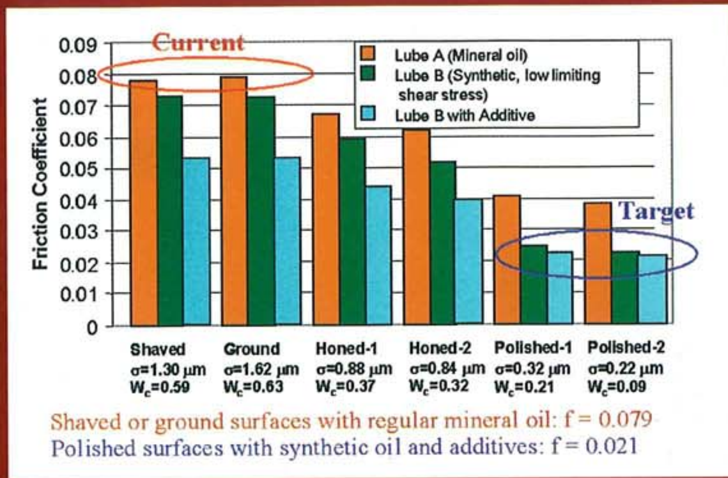
In the last 10 years, great efforts have been made by different researchers for developing 3-D deterministic mixed EHL models, which includes professors H.P. Evans and Ray Snidle's group at Cardiff University in the United Kingdom, Farshid Sadeghi's group at Purdue University in West Lafayette, Ind., Y.Z. Hu's group at Tsinghua University and Jane Wang's group at Northwestern, among others. I have been closely collaborating with Northwestern and Tsinghua. Now our model is capable of simulating the entire transition from full film and mixed down to boundary lubrication with a unified approach under severe operating conditions. This appears to be a useful tool for in-depth study on gear tribology. Recently, the model has been validated with experimental data and results from other models and other researchers. Also, effects of differential scheme and mesh density have been investigated and the approach for handling contact studied.[3,4]

Most recently, two accomplishments have been made in collaboration with Northwestern: (1.) a full numerical solution for mixed EHL with coated surfaces, which may be useful for components with coatings or hardened layers and (2.) a three-dimensional line contact mixed EHL model that can handle two-dimensional, macro-contact geometry together with three-dimensional surface roughness. This is extremely important for gears, as most gears are typical line contact components but the surface topography is usually three-dimensional.

What are some of the major factors that affect the gear train efficiency? How can we improve gear efficiency based on the current understanding of gear tribology? Many factors may affect gear efficiency, including surface roughness, lubricant rheology, boundary film additives, operating temperature and churning. Other than churning, which is a practical issue more difficult to simulate, most factors can be modeled and predicted based on current understanding of mixed EHL. Basically, friction in gear tooth contact consists of hydrodynamic friction due to lubricant shearing and contact friction at local contact spots where boundary films may form.

Boundary friction can be readily estimated experimentally, while hydrodynamic friction can be predicted if the lubricant frictional behavior is known. Figure 3 shows that there may be three practical means to reduce gear friction: (1.) reduce surface roughness that may significantly reduce surface contact, (2.) use synthetic lubricants that may have low shear stress and more favorable thermal behavior and (3.) use advanced additive packages with friction modifiers that may considerably reduce boundary friction. With these three methods combined, the total gear tooth contact friction can possibly be reduced by more than 50%.

Figure 3. Friction reduction in gears



What are the basic trends of technology development in the area of gear tribology? What do you expect will happen in the near future?

Gears are critical components to many vehicles, machines and equipments, so great efforts are being made to improve gear efficiency, durability and reliability. The technology development currently covers many areas and I expect that many things may happen in the near future. However, as a tribologist, I want to emphasize that the following situations will take place:

1. Simulation-based models for tribological analysis, failure prediction and design integration and optimization will be developed and commercialized. They will become user-friendly tools for engineers. Conventional analysis and design methods based on simplified models and empirical data will be revolutionized.

2. More precise machining and advanced surface treatments/coatings will be widely used for gears. They will become efficient and cost-effective means for high power-density critical gears. Lubrication condition can be greatly improved by reducing roughness, and surface strength can be significantly enhanced by better engineering the surfaces. <<

I am confident that in the near future model-based tribological failure analysis and prediction software packages will be available commercially that will greatly help design engineers to computerize design and analysis, improve product reliability and shorten product development cycle time.

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