Nagaraj K. Arakere

This University of Florida professor leads industry and government research on reliable prediction of endurance life of rolling element bearings and tribological systems.

By Rachel Fowler
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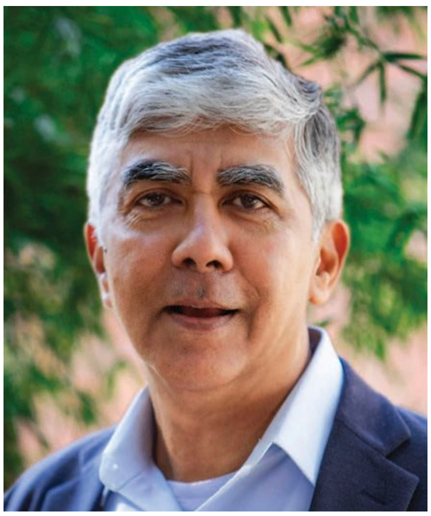

Nagaraj K. Arakere

Nagaraj K. Arakere is a professor in the mechanical and aerospace engineering department at the University of Florida (UF) in Gainesville, Fla. He worked for many years at aircraft engine maker Allied-Signal Aerospace Co. (now Honeywell) in Phoenix, Ariz., in the lubricated components group and on fatigue life evaluation of rolling element bearings, design of air-lubricated foil bearings and carbon face seals.

Arakere received his doctorate in 1988 from Arizona State University. At UF, Arakere is actively involved in research in rolling contact fatigue (RCF), multiaxial fatigue damage of a wide range of structural materials and components and associated finite-element constitutive model development. He teaches a graduate level course in fatigue of materials. At the undergraduate level, he has taught mechanical design and mechanics of materials laboratory. Arakere's research has been supported by industry (Timken, Pratt & Whitney, Cummins) and government research agencies (National Science Foundation, Air Force Research Laboratory [AFRL], NASA, Marshall Space Flight Center). He is widely published in tribology, fatigue, fracture mechanics and mechanics of materials journals. He has received several best paper awards from ASME and STLE. He is an ASME Fellow (2005).

TLT: Which areas of rolling element bearings is your research currently focused on?

Arakere: We have been working on understanding the physics of subsurface initiated rolling contact fatigue (RCF) raceway damage at the microstructural scale. This involves working at the interface of mechanics of materials and materials science.

My interest in this area dates back to the time I worked on life estimation of mainshaft bearings in the aircraft engine industry. I was struck by the wide disparity between predicted and observed bearing life. Bearing fatigue life has an exponential dependence on raceway contact stress. The elastic Hertzian stress is a sensitive function of bearing support loads, conformity between ball and raceway and operating internal clearance. Bearing L_{10} life, defined as the number of cycles at which 90% of bearings survive under a rated load and speed, is estimated using subsurface crack-initiation-based probabilistic life model by Lundberg and Palmgren (LP), proposed in 1947. This approach worked reasonably for older technology bearing steels ("dirty steels"). However, for aerospace bearings made of ultra clean VIM-VAR steels such as M50 and case-hardened M50-NiL, predicted L_{10} life can vary orders of magnitude from observed bearing life in the field. The stress-life correction factors to LP model adopted by ASME, STLE and ISO continues to deviate from observed bearing life. This discrepancy stems from the many empirical material constants that are introduced in the LP model. Aircraft engine and bearing companies come up with their own fitting constants specific to their applications to reconcile large discrepancies between predicted and observed bearing L_{10} life. This life model is empirical in nature, not specific to the bearing steel being used, and does not account for localized behavior under contact loading, elastic-plastic material properties, accumulated damage and evolution of material properties/microstructure with fatigue cycling. Fatigue life of a bearing is not a constant value that can be determined for a virgin bearing based on operating conditions but evolves with time history of load and cycling. We are working on developing material-specific RCF life prediction models.

We also are working on developing life models for hybrid bearings with case-hardened raceways and silicon nitride ceramic balls. Another area we have investigated is spall propagation in bearings.

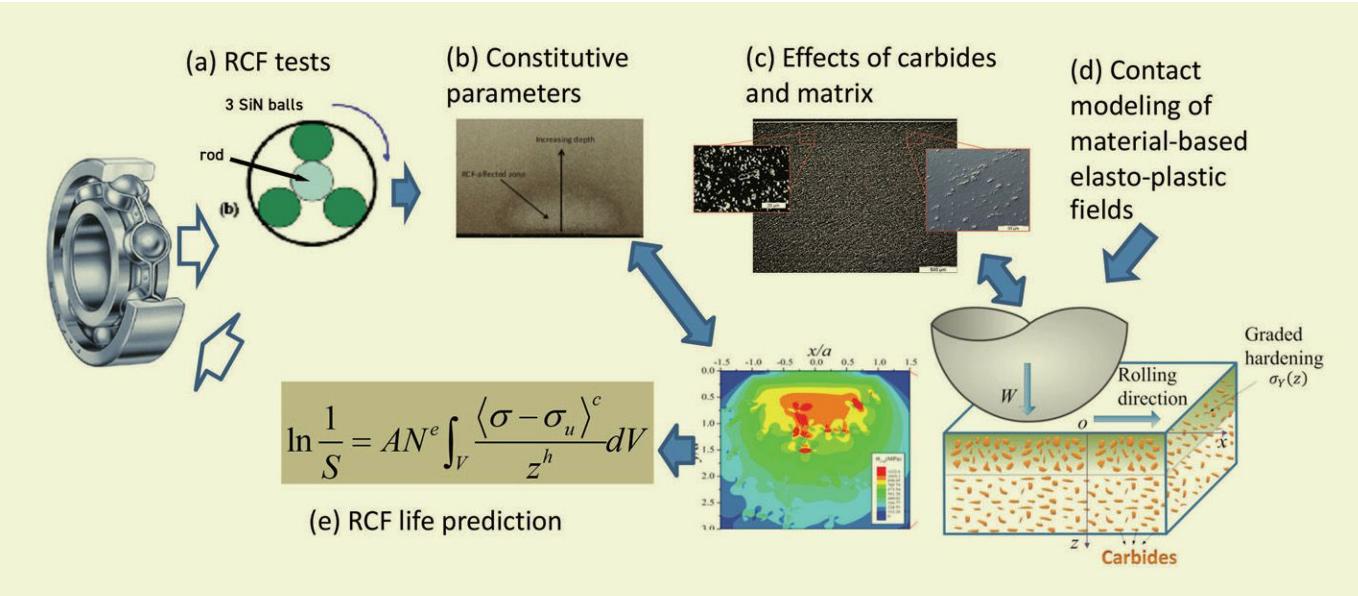

Figure 1. **Reliable life prediction of bearing steels.**

In military aircraft engines, it is of interest to understand how rapidly a raceway spall will propagate and how long the bearing will survive under continued operation.

TLT: You have done significant research on aerospace bearings and materials. Can you highlight some of the achievements of your research toward reliable prediction of endurance life of rolling element bearings and tribological systems?

Arakere: For quantifying RCF-induced damage, we must be able to measure meaningful localized material property changes. When bearing endurance testing is performed, the number of rotations of the inner ring is recorded after a fatigue spall is induced and testing stopped. However, fatigue damage induced near and subsurface to the spall region is not probed or quantified in any way. X-ray diffraction has been used to measure residual stress development in the spalled region. But reliable measurements are difficult, and using this information for modeling also is not practical. We have developed methods where we section, polish and measure microhardness in RCF rod specimens, bearing raceways and balls. The Vickers hardness diagonal in M50 bearing steel is about 10 μ m, and this measurement is very localized. We have carefully mapped subsurface microhardness evolution in M50 and case-hardened M50-NiL (with my colleague professor G. Subhash) steel as a function of contact stress and cycles. This data represents the first meaningful hardness measurements within the RCF micro-plastic zone. Bearing steel carbide distribution and volume fraction play a key role in strain accumulation and hardness evolution during cycling. Hardness evolution is a key marker of damage accumulation at the microstructural level. We have used this measured hardness (and, hence, yield stress) distribution to extract localized monotonic and cyclic constitutive properties via elastic-plastic finite element modeling. Our goal is to use measured damage evolution parameters to develop material-specific life prediction models and also enhance LP models *(see Figure 1)*. Quantifying damage also can help in designing better bearing steels.

To better understand structure-property relationships in case-hardened M50-NiL and other steels, we have used microindentation, nanoindentation, ultrasonic measurements and compression testing of miniature specimens extracted from the RCF-affected zone. The results presented are of engineering relevance to the bearing industry, steel design and modeling of microstructure and its effects on RCF life.

Toward enhancing existing LP life models, we have recently used statistical calibration techniques along with the Bayesian probability approach and reevaluated the load life exponent for ball bearings from 3 to 4.1, and for cylindrical roller bearings from 3.33 to 5.5. Life predictions using calibrated load life exponents show better agreement with observed fatigue life data.

Hardness evolution is a key marker of damage accumulation at the microstructural level.

Hybrid bearings use steel raceways and silicon nitride balls. Silicon nitride balls have many desirable physical properties that allow for advancing bearing technology, including low density and high compressive strength but also have low fracture toughness of 4-6 MPa√m. This low fracture toughness, in combination with unavoidable ball-to-ball collisions in the manufacturing (lapping) process, often results in ring or *c*-cracks (partial cone cracks) in balls. These flaws can grow under RCF when placed in service and result in a spall on the ball surface. This failure mechanism is very different from RCF damage in metal balls. We have developed a fracture mechanics lifting approach where we determine the critical flaw size (CFS) below, which the surface flaws will not propagate due to RCF in silicon nitride balls. The CFS value is used to screen balls during the Non-Destructive Inspection (NDI) process.

We have modeled spall propagation using advanced elastic-plastic FE procedures to understand the conditions under which the spall edge will advance. Spall propagation tests of hybrid bearings were conducted at AFRL, Wright-Patterson Air Force Base, Ohio. The goal was to understand why spalls in M50 bearings propagated more rapidly compared to M50-NiL and other bearings.

Rolling element bearings are key precision components used in nearly all machinery.

I previously worked on the analysis and design of air-lubricated foil journal bearings for high-temperature rotor support. They are a key technology for realizing oil-free industrial small-scale gas-turbine engines. The foil-journal bearing consists of a series of thin overlapping circular metal foils, one end of which is attached to the bearing housing and the other end resting on an adjacent foil. The compliant bearing surface allows for a greater degree of tolerance toward shaft misalignment and variations in bearing clearance due to shaft centrifugal growth and differential thermal expansion. Advantages of foil bearings are their ability to operate at high temperatures (1,000-1,200 F), low-viscous friction losses, simple construction, elimination of an oil supply and no inherent speed limitations as with rolling element bearings.

TLT: What differentiates aerospace bearings and materials from other applications such as automotive, heavy industries, etc.?

Arakere: Aerospace bearing steels are subjected to the most severe loading conditions in engineering systems to billions of RCF cycles, at a Hertzian contact stress of about 2.1 GPa. They are ultra-high-strength materials with tensile strengths exceeding 2.7 GPa and hardness values beyond 900 HV (~9 GPa).

RCF damage also is highly localized in the contact region and is very different from bulk-loaded structures subjected to conventional high cycle fatigue (HCF) for 10-100 million cycles. Aircraft engine industries have been aggressively pursuing development of new bearing steels to meet the challenging requirements for high-power density applications, operation under transient adverse conditions and reliability of bearings for applications accumulating over 100 billion contact cycles or L_{10} life requirement of about 30,000 hours.

Currently used through-hardened 52100 and M50 bearing steels cannot meet these requirements. Technological advancements have resulted in a new generation of hybrid bearings with plastically graded case-hardened raceway materials (M50-NiL) and silicon nitride ceramic balls to withstand these operational demands.

Rolling bearing applications in automotive and heavy industries are subjected to lower contact stresses and also far fewer cycles.

Design and development of new high-performance bearing steels is a lengthy process taking up to 20 years from inception to application, involving composition and processing, metallurgical evaluation, sub-scale bearing and, eventually, application testing.

TLT: Rolling contact fatigue modeling of bearings started in the 1950s. Why is it still relevant today, and why does it interest researchers after 70 years? What are some of the remaining challenges that need to be solved?

Arakere: Rolling element bearings are key precision components used in nearly all machinery. The annual revenue associated with bearings is a substantial $50 billion worldwide. This deceptively simple mechanism remains relevant because of its widespread use in diverse applications, such as skateboards, automobiles, aircraft and rocket engines, trains and wind turbines. Bearing technology encompasses a wide range of disciplines and continues to challenge researchers: fatigue, lubrication, metallurgy of high-strength bearing steels, ceramics, precision manufacturing, surface characteristics, contact mechanics and dynamics.

Challenges in advancing RCF life models will require measuring and modeling relevant monotonic and cyclic material properties at the scale of the microstructure, and tracking damage evolution with contact cycles *(see Figure 1)*. This will be a highly interdisciplinary endeavor. This research will have influence beyond the rolling bearing industry since cyclic contact stresses impact gears, functional cams, railway wheels and tracks, manufacturing tooling, as well as parts subjected to fatigue wear in a general sense.

There has been a longer tradition of tribological education and research in Europe.

TLT: How do you promote interests of undergraduate and graduate students in the field of tribology through classroom teaching and research activities? What can be done to develop the next generation of talent?

Arakere: This is a challenging task. The knowledge base associated with rolling bearing design and manufacture is disappearing from domestic teaching and academic research. Undergraduate students are exposed to lubrication and bearings in their design class, to a limited extent. Graduate training is dependent on funded research in the area. There has been a longer tradition of tribological education and research in Europe. Several of my graduate students trained in this field have joined related industry and government research labs.

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