Publications / *Technical Articles*

Those That Preceded Us

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INTRODUCTION

In our daily activities within Bently Pressurized Bearing Company, we are constantly reminded that others preceded us and developed many of the engineering principles that we employ every day. Routinely we reference individuals whose previous work and contributions have advanced the understanding of mechanical engineering, thermodynamics, fluid dynamics, and rotordynamics.

In this issue of *The Bearing News*, I wanted to take a few minutes and formally introduce you to a few of those significant contributors.

BIOGRAPHICAL HISTORIES

Dr. Fredric F. Ehrich (1928 – ____) was born in New York City on December 17, 1928. That date, the 25th anniversary of powered flight by the Wright brothers, had particular resonance in his career – he spent his entire career in research, analysis, design, and development of aircraft engines. He received his professional training at the Massachusetts Institute of Technology and was awarded his S.B. (1947), M.E. (1950), and Sc.D. (1951) degrees in Mechanical Engineering there.

He was elected to the academic honorary societies Tau Beta Pi, Pi Tau Sigma, and Sigma Xi, and to membership in the National Academy of Engineering in 1992. He is a Fellow of the American Society of Mechanical Engineers (ASME). In 1995, he was inducted into the General Electric (GE) Propulsion Hall of Fame.

From 1951 to 1957 he worked for the Westinghouse Aircraft Gas Turbine Division and from 1957 to 1994 for GE’s Aircraft Engine Division in senior engineering and engineering managerial positions in research, analysis, design, and development, including activities in aerodynamics, stress, and vibrations. He has also held positions in preliminary design, product planning, and as a technical consultant and staff engineer. Dr. Ehrich is still active in consulting in rotordynamics and in teaching and research on the gas bearings and rotordynamics of the MIT / Gas Turbine Laboratory Microengine Program as a Senior Lecturer at MIT.

Dr. Ehrich’s major technical interest has been in the field of rotordynamics of high-speed rotating machinery. His contributions to the field, as documented in his original writings, were all grounded in his intense involvement in the development of high performance gas turbine engines. His writings deal with such diverse topics as rotordynamic instabilities (such as hysteretic whirl, fluid trapped in rotors, dry friction whip, and turbomachinery tip clearance effect), and nonlinear rotordynamics (such as bistable vibration of rotors in rolling-element bearings; sum and difference frequency responses; stator whirl in rotors with bearing clearances; and subharmonic, superharmonic, and chaotic vibration phenomena in rotors in mounts with anisotropic stiffness); and pseudo-high-speed balancing.

More recently, he made major contributions to the design and development of high-speed gas bearings for high-power microengines.

Dr. Ehrich is:

1. the author of the chapters on "Self-Excited Vibration" and "Nonlinear Vibration"

of the McGraw-Hill *Handbook of Shock and Vibration*

2. the editor-in-chief of and a principal contributor to the *Handbook of Rotordynamics* published in 1991 by McGraw-Hill

3. active in American Society of Mechanical Engineers (ASME) activities as Editor of the Journal of Vibration and Acoustics, and as Chairman of the Design Engineering Division.

Dr. Ehrich organized and was Program Chairman of the very first ASME Vibrations Conference in 1967 and has written extensively on the phenomena of rubs in rotating machinery.[1]

Walter R. Evans (1920 – 1999) was born in St. Louis, Missouri on January 15, 1920. Walter Evans, brilliant electrical engineer, developer of the Root-Locus Method, author, founder and president of The Spirule Company, inspiring mentor, husband, father, and volunteer, was influential in many people's lives. He had a way of taking complex problems, finding answers to them, and communicating the process to people of more ordinary intellectual ability. The practicality and simplicity of his ideas made Root-Locus Analysis a major advancement in the development of feedback control systems and dynamics systems. Mr. Evans was awarded the prestigious Rufus Oldenburger Medal by the American Society of Mechanical Engineers in 1987, and the Richard E. Bellman Control Heritage Award by the American Automatic Control Council in 1988. Although a genius, he never looked down on others. He sought to teach, instruct, be a model, and serve.

Evans love of math began at an early age. His father was an engineer, and Walt knew when he was young that he wanted to be one, too. He learned to play chess from his grandmother, Eveline Burgess, U.S. Women's Champion for thirty years, 1906-1936, thus enhancing his ability to think a problem through many steps to a solution. Walt's widow, Arline, recalls sitting in front of him in geometry class when they were sophomores in high school, where he would bring in models to prove his answers.

Walt earned his B.S. in Electrical Engineering from Washington University in St. Louis in 1941, completed the three-year Advanced Engineering Training Program at the General Electric Company in 1944, worked as an instructor at Washington University from 1946 to 1948, and obtained his M.S. in Electrical Engineering from the University of California, Los Angeles, in 1951.

Walter Evans' principal contribution to the field of automatic control was his invention of the Evans Root Locus Method in 1948 and his subsequent invention of the Spirule, a tool used in conjunction with the root-locus method. Because it codifies very useful frequency information about a feedback system in such intuitive and appealing graphical form, Evan's root-locus method has enjoyed widespread use in the design of control systems and is now a standard chapter in texts on feedback control systems. During his lifetime, he worked as an engineer at several companies, including General Electric, Autonetics (then a division of North American Aviation, now known as Rockwell International), and Ford Aeronautic Company. He also served as an instructor at Washington University for a few years.

On September 30, 1954, the McGraw-Hill Company published *Control-System Dynamics* by Walter R. Evans as the fortieth entry in its popular Electronic and Electrical Engineer Series. Six years earlier Evans had helped usher in a revolution in the practice of servomechanism design with his root-locus method. Engineers trained in its use were suddenly empowered to control both the transient and frequency response of their designs by locating the pole and zero positions of the system’s characteristic equation. However, its dissemination into university classrooms would require new textbooks.

Walter R. Evans passed away at the age of 79 on July 10, 1999 in Whittier, CA. He is survived by his wife Arline and their four children.

George Washington Gale Ferris Jr. (1859-1896) was born in Pittsburgh, Pennsylvania. Spending the majority of his childhood in Carson City, Nevada he returned to Pittsburgh to attend Rensselear Polytechnic Institute, graduating in 1881 with a civil engineering degree. His career began in the railroad industry but he left to follow a desire to build bridges. Anticipating a demand increase for structural steel, he founded the G.W.G. Ferris & Co. to test and inspect metals for bridge and railroad builders.

The 1893 World's Fair in Chicago's 1893 was to commemorate the 400th anniversary of Columbus landing in America. Organizers wanted an attraction to surpass in design and scale the landmark Eiffel tower built for the 1889 Paris Universal Exposition celebrating the Centennial of the French Revolution.

Daniel H. Burnham, the exposition architect charged with selecting the project, lamented to his colleagues at an engineer's banquet in 1891 that nothing yet had been found that "met the expectations of the people." Ferris, in attendance, had an epiphany during dinner. He scrawled on a napkin his design for a giant circular bridge that would lead to nowhere but would bring joy to thousands. Thus was born the Ferris Wheel.

Built by the Detroit Bridge and Iron Works, the 250-foot diameter wheel rotated on an axle 32 inches in diameter and 45-feet long. Weighing 140,000 pounds the axle was at that time the single largest piece of forged steel ever made. Driven by two 1000-horsepower steam engines the wheel had a total capacity of 2,160 passengers. A ride cost fifty cents.

The Ferris Wheel was used again for the 1904 St. Louis Exposition but two years later was disassembled for the last time and sold for scrap. Nevertheless, in more than a century since it was first constructed, it remains a spectacle of 19th Century engineering.

Jacob Pieter Den Hartog (1901 to 1989) has been described by his colleagues as the most distinguished teacher of mechanical vibrations in the world. While at the Research Department of Westinghouse, he was introduced to vibration mechanics by Dr. Stephen Timoshenko and quickly gained a reputation for solving complex problems.

As a Harvard University professor, he published the first two editions of *Mechanical Vibrations*, which over the years has been published in several languages and is probably the best known text on the subject. During his tenure at Harvard, Den Hartog came into his own as a lecturer, researcher, and consultant. Den Hartog was gifted with an uncommon, intuitive understanding of mechanical concepts and the ability to elucidate these using simple terms and models.

Den Hartog joined the Massachusetts Institute of Technology's department of Mechanical Engineering in 1945. There he completed the third and fourth editions of *Mechanical Vibrations* and two additional textbooks, *Strength of Materials* and *Mechanics*.

During his career, Den Hartog received numerous honorary degrees and memberships in major engineering societies. He was elected to both the National Academies of Sciences and Engineering, and won eight major awards, including the Timoshenko and James Watt Medals.

A pioneering researcher who made singular contributions to mechanical engineering, he was also honored for teaching excellence. The J.P. Den Hartog Distinguished Educator award was established by MIT in 1981.

The training auditorium in Building 1 at Bently Pressurized Bearing's Corporate Headquarters in Minden, NV is named in Dr. Den Hartog's honor.

Henry Homan Jeffcott (1877-1937) is credited with the development of the modern rotor dynamic equations. He is best known for "Jeffcott's Model", an idealized model used to analyze lateral vibrations of a rotating shaft.

Jeffcott was appointed Professor of Engineering at the Royal College of Science for Ireland in 1910 and remained there until 1922. The publication of his landmark article *"The Lateral Vibration of Loaded Shafts in the Neighborhood of a Whirling Speed - The Effect of Want of Balance"* introduced the Jeffcott model.

The model consists of a uniform and symmetric shaft supported by rigid bearings at each end. Shaft mass is concentrated at the midspan and the remainder, now massless, acts as the supporting springs. Jeffcott also introduced a damping force proportional to the velocity of the lateral motion to make it more representative of actual rotor dynamic behavior.

Jeffcott's model explains the effect of unbalance when rotational speed is near the natural frequency of the rotor, the region where vibration amplitude increases rapidly. It was believed at the time that rotor velocity could not exceed this "critical speed" (a concept introduced by Rankine 50 years earlier), known today as the first balance resonance. Another key element of Jeffcott's rotor is the inclusion of both the vertical and horizontal components of movement and thus defines orbital motion.

Jørgen W. Lund (1930-2000) was born in Horsens, Denmark. A world-renowned scientist, he specialized in the study of Rotating Machinery Vibration. With his Masters Degree in Mechanical Engineering from the Technical University of Denmark he immigrated to the United States in 1956. Early in his career he worked at General Electric and Boeing Aircraft Company. In 1961, Lund left GE to co-found Mechanical Technology Inc.

Lund received a Ph. D in 1966 in Mechanics from Rensselaer Polytechnic Institute, his thesis employing short bearing theory. That work completed the bearing force linearization proposed earlier by Aurel Stodola, considered by many to be the first Control Engineer. Lund was the first to explain the influence of fluid-film bearings on the stability of rigid and flexible rotors.

Returning to Denmark in 1967, Lund joined the Technical University, was named a full professor in 1990 and remained there until his retirement. His numerous research efforts during that time included influential work on hydrodynamic and hydrostatic gas bearings. Lund preceded others in grasping the nature of whirl frequency ratio for fluid-film bearings and began evaluating the stability of fixed-arc bearings using this parameter. His 1974 paper broke new ground by applying Walter R. Evan's Root Locus theory for stability analysis of rotating machinery.

Lund was the recipient of the 2001 Den Hartog Award presented by the American Society of Mechanical Engineer's Technical Committee on vibration and sound. The honor is bestowed upon those with a lifetime of contributions to the teaching and practice of vibration engineering. I stated, in my endorsement letter, that Dr. Lund's work was "richly deserving of the Den Hartog Award" and he provided "an excellent foundation upon which my own rotor dynamic research could proceed."

Burt L. Newkirk (1876 to 1964) is considered the first individual to properly describe the phenomenon of oil whirl.

Newkirk spent the better part of the 1920's and 30's at General Electric's Research Laboratory in Schenectady, New York. There he focused on eliminating roughness from turbine generator operation. His theoretical work on the mechanics of rotating equipment led to his developing an optical method for observing the orbit at the end of a vibrating shaft.

Newkirk was still at GE when he first described oil whirl of a shaft as due to a restoring force component that is not directed towards the equilibrium position. In 1934 he co-developed a special, partially grooved bearing ending in a dam that increased the loading and raised the whirling threshold.

Newkirk joined the Department of Aeronautical Engineering at Rensselaer Polytechnic Institute in the late 1930's. His efforts at RPI developed into the field of Aeroelastic Dynamics. He was a pioneer in the application of high-speed schlieren photography for studying flow in aircraft centrifugal superchargers.

In 1975, to honor this great scientist, the ASME created the Burt L. Newkirk award. It recognizes individuals who have made notable research and development contributions to the field of tribology.

William J. Macquorn Rankine (1820-1872) was one of the founders of the science of thermodynamics, particularly as it applied to steam-engine theory and introduced much of its terminology and notation, most of which is still in use today. He coined the terms "potential energy" and "critical speed" among others.

In 1855 Rankine was appointed to the Queen Victoria chair of civil engineering and mechanics at the University of Glasgow. His classic *Manual of the Steam Engine and Other Prime Movers,* published in 1859, was the first attempt at a practical approach to steam-engine theory. The Rankine cycle, described in the text, is a thermodynamic sequence of events and is still used as a standard for rating steam power plant performance.

Rankine published his *Centrifugal Whirling of Shafts* in 1869, the first work on the dynamics of rotating shafts. This became the classical starting point of the new discipline known today as Rotordynamics, and ultimately, Rotating Machinery Dynamics.

Osborne Reynolds (1842-1912) was born in Belfast, Northern Ireland. At the age of 19, he took an apprenticeship with the engineering firm of Edward Hayes in 1861. Reynolds, after gaining experience in the engineering firm, studied mathematics at Cambridge, graduating in 1867.

As his father had before him, Reynolds was elected to a scholarship at Queens' College. He again took up a post with an engineering firm, this time the c ivil engineers John Lawson of London, spending a year as a practicing civil engineer. In 1868 Reynolds became the first professor of engineering in Manchester (and the second in England). Reynolds held this post until he retired in 1905.

His early work was on magnetism and electricity but he soon concentrated on hydraulics and hydrodynamics. He also worked on electromagnetic properties of the sun and of comets, and considered tidal motions in rivers.

After 1873 Reynolds concentrated mainly on fluid dynamics and it was in this area that his contributions were of world leading importance. He studied the change in a flow along a pipe when it goes from laminar flow to turbulent flow.

In 1886 he formulated a theory of lubrication. Reynolds' conclusions formed the basis for early understanding of the "wedge" shaped pressure profile in a hydrodynamic bearing. On 11 February 1886, in a paper entitled: *On the Theory of Lubrication and its Application to Mr. Beauchamp Tower's Experiments, Including an Experimental Determination of the Viscosity of Olive Oil*, in the first three sections, Reynolds discusses previous hydrodynamic bearing experiments and in the fourth section, (*The Equations of Hydrodynamics as Applied to Lubrication*), Reynolds defines, for the first time, the ***Reynolds' Equation***. Three years later he produced an important theoretical model for turbulent flow that has become the standard mathematical framework used in the study of turbulent fluid flow to this day. Reynolds is also credited with defining the ***attitude angle*** for fluid bearings.

Reynolds became a Fellow of the Royal Society in 1877 and, 11 years later, won their Royal Medal. In 1884 he was awarded an honorary degree by the University of Glasgow. By the beginning of the 1900s Reynolds health began to fail and he retired in 1905. Not only did he deteriorate physically but also mentally, which was sad to see in so brilliant a man who was hardly 60 years old.

Despite his intense interest in education, Reynolds was not a great lecturer. His lectures were difficult to follow, and he frequently wandered among topics with little or no connection. One of Reynolds' colleagues, who knew him well as both a man and as a fellow worker in fluid dynamics, wrote: *"The character of Reynolds was like his writings, strongly individual. He was conscious of the value of his work, but was content to leave it to the mature judgment of the scientific world. For advertisement he had no taste, and undue pretension on the part of others only elicited a tolerant smile. To his pupils he was most generous in the opportunities for valuable work which he* *put in their way, and in the* share of cooperation." Osborne Reynolds died in 1912 at the age of 70.

James Watt (1736-1819) studied the properties of latent heat and steam at the University of Glasgow. Employed as an instrument maker, Watt was asked to repair the university's model of the Newcomen steam engine. That design was very inefficient and while working to fix it, Watt decided he could improve it.

Considering the properties of steam, especially how density relates to temperature and pressure, Watt designed a separate condensing chamber for his steam engine. This prevented massive steam loss within the cylinder, enhancing the vacuum conditions. A patent for this and other improvements to Newcomen's model was awarded in 1769. Watt's use of steam-jacketing, oil lubrication, and insulation of the cylinder helped maintain the high temperatures critical for maximum efficiency.

Watt added mechanical attachments that converted lateral piston movement into rotary movement, allowing it to power a variety of manufacturing activities. His steam engine became the first of the modern "prime movers" and was soon driving large factory machinery, speeding on the Industrial Revolution.

He devised a centrifugal governor in 1788 to automatically regulate the speed of the engine by controlling its steam output. The seed of automation, it exemplifies the feedback principle of a servomechanism linking output to input.

Watt is also remembered for his efforts to measure the power of his steam engine. He defined a "horsepower" as 550 foot-pounds per second and the metric unit of power, the watt (W), is named in his honor.

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[1]*Editor's Note: In 1974, Donald E. Bently correctly theorized that Emil Mathieu's equation could be used to describe the vibration response that was due to a partial rub. Dr. Ehrich was one of the first people to recognize Don Bently's innovative work on machine rubs.*