Spiral Orbit Tribometry

Introduction

A method of tribometry developed at the NASA-Glenn Research Center relies on an aspect of the motion of a rolling ball that has come to be known as Spiral Orbit Tribometry. The spiral, to be described more fully below, is an aspect of the motion exhibited by a ball loaded between two coaxial parallel plates that are rotating with respect to one another. This ball's spiral motion has been exploited to measure the coefficient of friction and other tribological phenomena inherent to the operation of the usual angular contact ball bearing, but in a highly simplified geometry. The tribometer to be described here is, in fact a retainerless thrust bearing with flat races and one ball. It functions as a credible mimic of the usual multiball angular contact ball bearing with curved races and a retainer to separate the balls. This site will first describe the early work on the spiral that has lead to the present development. The principles of the tribometer will then be described. The construction and some details of the tribometer at NASA-GRC will be outlined. Then the manner in which the tribometer has been used for research will be described. Finally, references to the literature both from the early work that lead to the present development as well as research results from NASA-GRC with this approach to tribometry will be provided.

Early Work Leading to Spiral Orbit Tribometry

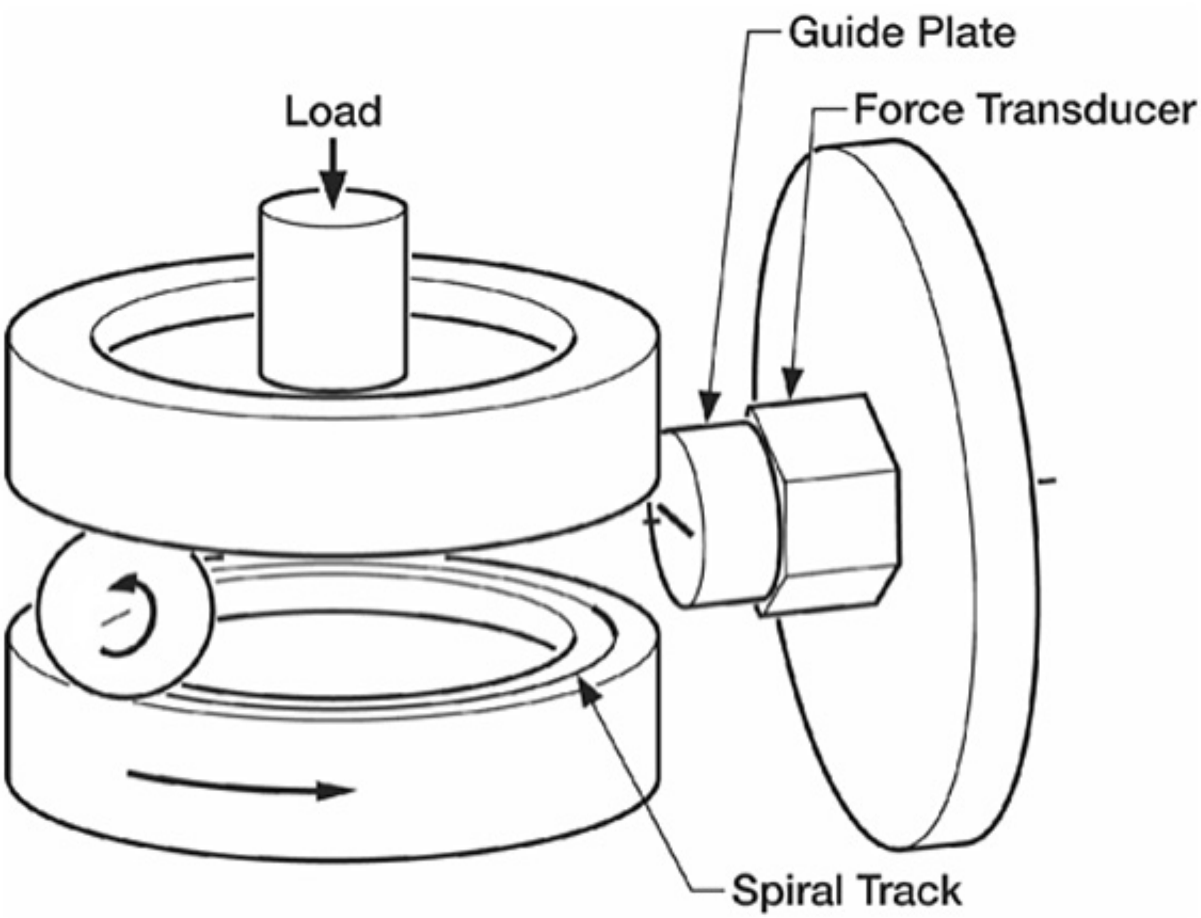
A. Palmgren. Arvid Palmgren of the SKF Co. of Philadelphia, PA was the first to report in 1928 what is referred to here as the spiral, although he did not use this term (1). Quoting K. L. Johnson (2), "The effect (the spiral) is mentioned casually by Palmgren (1) in connection with his rolling experiments with tangential forces, but is dismissed as insignificant, since he states in conclusion (3) that 'the ball is always, while rolling, seeking surfaces which are exactly parallel, if such exist in the path of the ball.'" It appears that Palmgren neither analyzed nor made use of the spiral after observing and reporting it.

K. L. Johnson. Kenneth Johnson in 1958 (2) was next to consider the spiral, denoted by him as "creep". He performed a detailed analysis of the slip within the region of elastic contact (Hertzian contact area) and derived expressions for the growth of the spiral (the spiral's pitch) over one ball revolution that contained an indeterminate functional dependence. An explicit expression for the spiral was not obtained. An experimental measurement of the spiral's pitch was obtained for the case of three symmetrically- placed balls between two flat plates, one of which rotated to drive the balls to one revolution. He was the first to measure the spiral's pitch, but his experimental arrangement did not permit continuous rotation of the ball set. There was also no measurement of the coefficient of friction in his experimental arrangement used to measure "creep". Johnson continued work that made use of the spiral (his 'creep') in subsequent publications (4, 5).

E. P. Kingsbury. Edward Kingsbury (6) was next to work with the spiral. His intent was to use a set of balls captured under load between two flat plates (as Johnson (3) did) to study wear in a lubricated, highly simplified tribological system. His experimental system used a set of twelve balls and a peripheral "bumper ball" that forced the balls back to their original radial position. Thus the ball set was capable, unlike Johnson's, of continuous rotation by driving one of the plates with an electric motor. The system did not provide for a measurement of the coefficient of friction. The system to be described below replaced Kingsbury's bumper ball with a flat guide plate and a force transducer so that the coefficient of friction could finally be measured. Kingsbury's study was also facilitated by the use of the measurement of electrical resistance between the plates and thus through the two contact points a ball makes with the flat plates to observe the development of electrically resistive friction polymer due to tribochemical breakdown of the organic lubricant.

Basic Description of Spiral Orbit Tribometry

Spiral orbit tribometry, as a method to measure the coefficient of friction, was developed at the NASA-Glenn Research Center in the late 1990s incorporating elements of the experimental work of both Johnson and Kingsbury. This approach to tribometry originally employed three symmetrically-spaced balls loaded between two flat plates (7), whereas a single ball was used thereafter. An outline drawing of the main elements of the tribometer as it is presently constituted is shown below. One of the plates is stationary while the other rotates to drive the ball into a track (orbit) that seems circular, but is actually an opening spiral. The ball contacts a "guide plate" during each orbit, which forces the ball back into its initial orbital radius. This contact with the guide plate is termed the "scrub" here. The ball establishes a stable orbit, repeatedly rolling over the track on both of the large plates and the guide plate. A piezoelectric force transducer supporting the guide plate senses the frictional force developed on the ball as it slides on the rotating plate during the scrub. A coefficient of friction, CoF, is obtained from the ratio of this friction force to the load and can be plotted as a function of time, or orbit number. A kinematic analysis of the ball's motions that leads to the method by which the coefficient of friction is measured in this system has been published as a NASA Report (7) and also in the open literature (8). Instruments that produce a plot of CoF versus time (a "friction trace") are usually referred to as tribometers, so this instrument is dubbed the Spiral Orbit Tribometer.



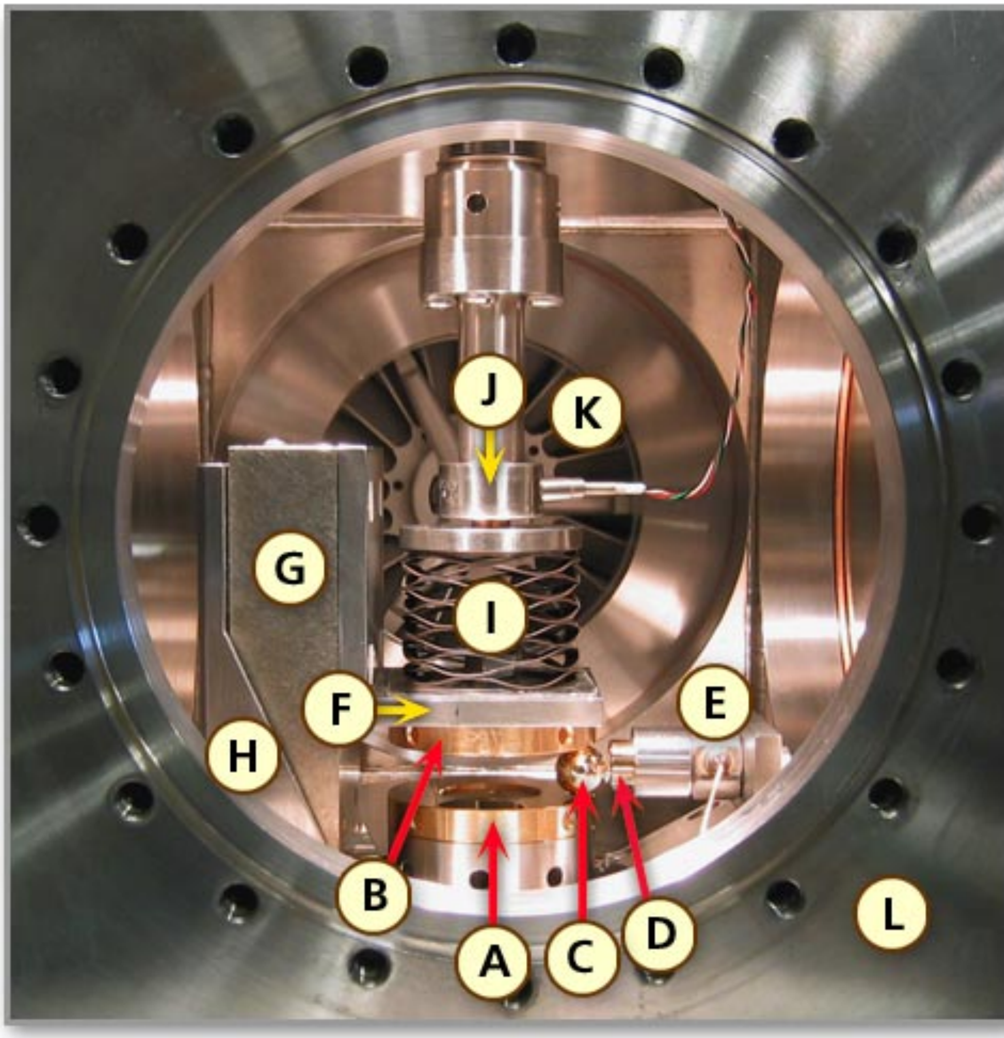
The term "spiral," used here to describe the growth of the ball's orbit as it is driven by the rotating plate, should be taken advisedly. The path of the ball appears to be a spiral in its orbit. But in fact, the orbit is not necessarily a mathematical spiral. The current understanding of the ball’s motion is due to K. L. Johnson, who hasused the term "creep" for the growth of the ball’s orbital radius. At present there seems to be no simple mathematical description of the orbit, so the term "spiral" will be used here for descriptive convenience.

The arrangement may be recognized as a thrust bearing with one ball, flat races and no retainer. It is a reduction of the usual angular contact ball bearing to its most basic elements and thus the simplest realization of a ball bearing. It is in fact a true ball bearing. It has been shown by Kingsbury (9) that the ball undergoes all the motions it would undergo in the usual angular contact ball bearing. So this tribometer functions as a credible (simplified) mimic of the familiar angular contact ball bearing.

In addition to the measurement of the coefficient of friction, there is another beneficial aspect of the contact of the ball with the guide plate. Analysis (8) shows that the ball *rolls* on the guide plate in the scrub. This rolling rotates the ball off the line of contact on the ball each time it passes through the scrub and allows the entire surface of the ball to eventually be brought into contact with the plates. Thus all lubricant that may be on the ball is eventually brought into the tribological contact and stressed. This motion is very different from that of the more usual ball on plate tribometer in which the same spot on the ball is continuously slid upon, generating a flat wear scar on the ball. No such wear scar is generated in this tribometer. Sphere on flat geometry is always maintained and the simple formulae of Hertzian analysis for a sphere loaded against a flat always apply in this tribometer.

The NASA-Glenn Spiral Orbit Tribometer

Description of the tribometer. There many ways to actually construct a tribometer based on the above principles. One such way is shown below. It is used at the NASA-Glenn Research Center to test lubricants for use on spacecraft in the vacuum of space.



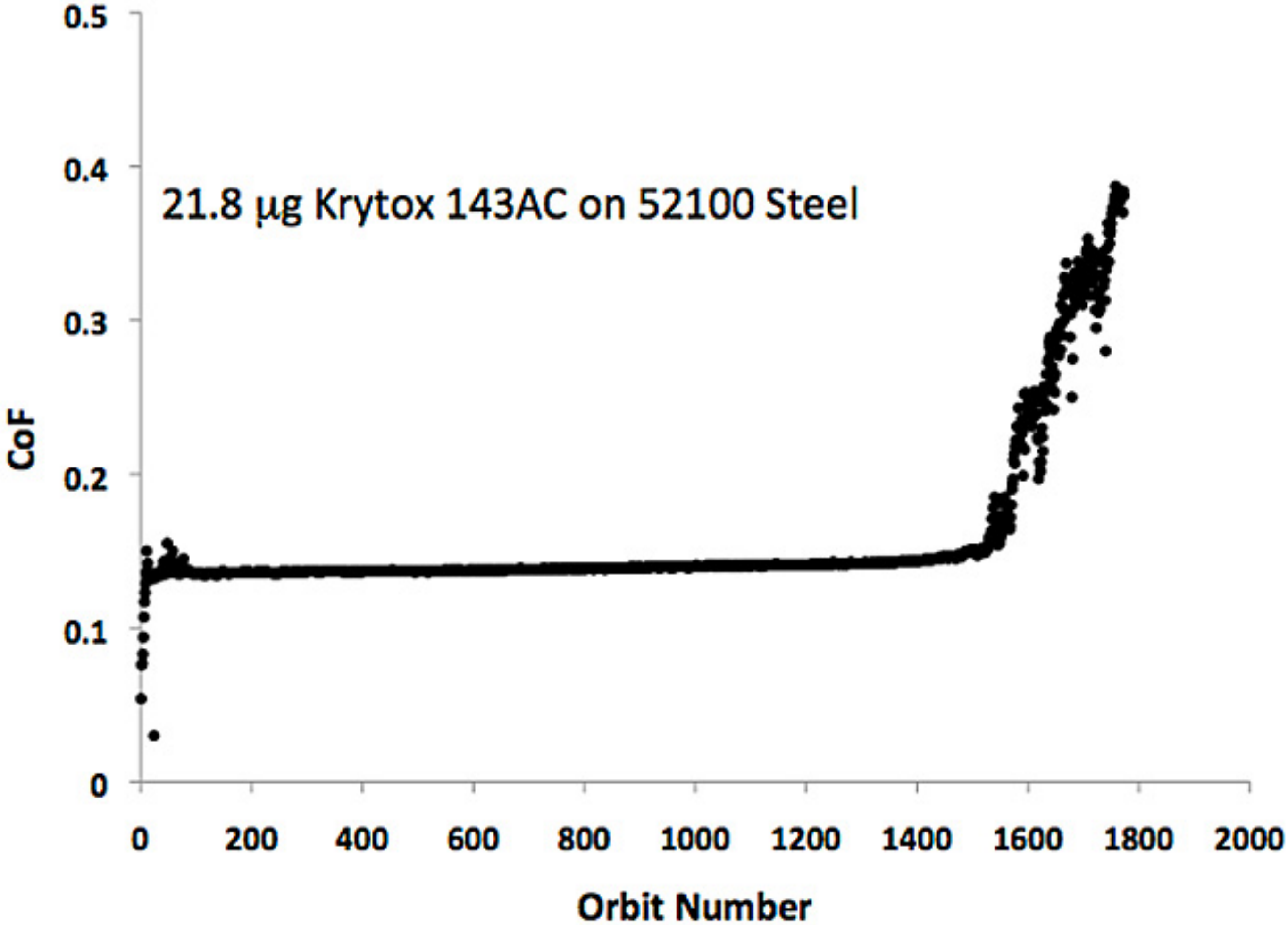
The elements called out in the image are as follows. There is a lower rotating plate A on the shaft of a rotary vacuum feedthrough, a fixed upper plate B and the driven ball C, all in gold. The guide plate D is in a holder attached to a piezoelectric force transducer E to measure the force developed when the ball in the scrub slides on the rotating plate. The fixed plate is attached to a stainless steel L-bracket F that is in turn attached to a crossed roller bearing slide G on the bracket H, thus restricting the motion of the fixed plate to a single vertical degree of freedom. The fixed plate and the L-bracket are electrically isolated from ground by plastic screws attaching the L-bracket to the slide, a mica sheet between the bracket and the slide and a mica sheet between the bracket and the wave spring I that bears down on the top of the L-bracket to provide the load on the system. A linear motion vacuum feedthrough compresses the wave spring I to provide the load which is sensed by the strain gauge load cell J in line with the linear motion feedthrough. The rotating plate is electrically grounded by a mercury-wetted rotating electrical contact on the air side of the shaft of the rotary vacuum feedthrough. The electrical isolation of the fixed plate permits the measurement of the electrical resistance between the two plates through the two contacts the ball makes with the plates. The tribometer is housed in a stainless steel 8" cubical vacuum chamber L that is evacuated by a 140 l/s turbomolecular vacuum pump whose turbine blades are visible as K. The chamber achieves base pressures < $1.5x10^{-8}$ torr as measured by a cold cathode vacuum gauge. A gate valve between the turbomolecular pump and the chamber can be closed to isolate the chamber from the pump. Selected gases can then be introduced into the chamber to permit the observation of the effect of ambient test environment on tribological properties.

Specimens. Typical specimen plates were 2" diameter, 3/8" thick. The balls were usually one-half inch diameter and the guide plates were one-half inch diameter. Metal, ceramic and polymer specimens have been successfully used, as have specimens coated with tribologically beneficial films. Most of the tests at the NASA-Glenn Research Center have used steel specimens whose preparation is described below.

Steel Specimen Preparation. The plates and guide plate were polished to an rms roughness of 15-20 nm with successively smaller diamond grit polishes, ending with 1 µm diamond grit size. The plates were repolished after every use and used multiple times. The balls (usually one-half inch diameter), obtained from commercial sources, were at least Grade 25 and were used as received without any additional polishing. The balls were used only once. All specimens were cleaned by gentle rubbing with nitrile-gloved fingers and silicon carbide polishing powder under deionized water. This was followed by ultrasonication in deionized water and blow-drying with nitrogen as described in *Specimen Cleaning* in the **Internal Unpublished Research Notes** in the References section.

Lubrication. The Spiral Orbit Tribometer has been used to assess the relative tribo-degradation rates of liquid lubricants as discussed below. This requires the use of extremely small amounts of lubricant to permit reasonable test times. In this method only the ball is lubricated and the plates are clean at the beginning of the test. The method by which only a few micrograms of liquid lubricant is applied to the cleaned ball is to first prepare a solution of the lubricant in a volatile solvent at a concentration of about 1 microgram/microliter or 1 milligram/milliliter. Then about 25 microliters of this solution is applied to the ball by dripping a few drops of the solution on the ball with a microliter syringe as the ball spins in a bench lathe. The volatile solvent evaporates, leaving about 25 micrograms of lubricant on the ball. The actual mass of lubricant on the ball was determined by the weight gained by the ball using a microbalance such a Mettler-Toledo Model AT-20. A few tens of micrograms of lubricant on a on-half inch diameter ball corresponds to a few tens of nm thickness of lubricant, assuming a uniform distribution on the ball. The distribution is not uniform, although multiple orbits of the ball will tend to even things out.

Typical Use. The figure below presents the results of a test on 52100 bearing steel with 21.8 micrograms of Krytox 143AC oil, one of the oils used to lubricate mechanisms on spacecraft.



The following characteristics of this typical test are noted. After a few orbits the coefficient of friction, CoF, is extremely steady and noise free, in contrast to the often noisy CoFs from other types of tribometers. Here, CoF=.13. Next, it is observed that after this period of steady CoF, it exhibits a sharp increase to values typical of a system lacking lubrication. This end of lubrication is considered due to the consumption of the organic lubricant molecules by chemical reaction with the steel bearing material, termed tribochemical reaction. See *Evidence for Liquid Lubricant Consumption* in the **Internal Unpublished Research Notes** below. At this point there is no more lubricant oil left to provide lubrication to the system. By assigning a value of CoF=.2 to be the end of lubrication and dividing the number of orbits at which this value is achieved by the initial lubricant mass in micrograms, a normalized "lifetime" L can be defined that characterizes the degree of robustness for a particular lubricant in such a chemically active tribological system. In the case above the lifetime is 1591 orbits so that L = 1591/21.8 = 73 orbits/µg. Four tests (10) were made with each of the three commercially available oils commonly used in the lubrication of space mechanisms. The average values for these four tests for CoF and L are presented below.

Lubricant Oil	CoF	$\mathcal{L}$, orbits/μg
Pennzane 2001A	.077	4113
Krytox 143AC	.13	73
Castrol 815Z	.12	44

The most tribochemically robust lubricant is a hydrocarbon multiply alkylated cyclopentane, commercially known as Pennzane 2001A. This oil also exhibits the lowest CoF. The perfluoropolyalkylether lubricants Krytox 143AC and Castrol 815Z exhibit much lower lifetimes and somewhat higher friction coefficients. More details on these tests have been published (10).

Many studies with this tribometer have been carried out and may be found in the list of references below.

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Additional Publications

- **Pepper S. V., "The MillSOT - A Spiral Orbit Tribometer on a Milling Machine", NASA/TM—2014-218312, June 2014 (.pdf)**
- **Della Corte C, Pepper S. V., Noebe R., Hull D. R. and G. Glennon, "Intermetallic Nickel-Titanium Alloys for Oil-Lubricated Bearing Applications", Power Transmission Engineering, August 2009, p26. (.pdf)**
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Internal Unpublished Research Notes Relating to Spiral Orbit Tribometry

- Additional Uses of the Spiral Orbit Tribometer (PDF)
- Ball Motions in the Spiral Orbit Tribometer (PDF)
- Construction of the Friction Trace in the Spiral Orbit Tribometer (PDF)
- Evidence for Liquid Lubricant Consumption in the Spiral Orbit Tribometer (PDF)
- Friction Measurement in the Spiral Orbit Tribometer (PDF)
- Origin of the Spiral (PDF)
- Residual Gas Analysis in the Spiral Orbit Tribometer (PDF)
- Specimen Cleaning (PDF)
- Triboelectrification (PDF)