The *MillSOT*—A Spiral Orbit Tribometer on a Milling Machine

Stephen V. Pepper
Glenn Research Center, Cleveland, Ohio

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to *help@sti.nasa.gov*

- Fax your question to the NASA STI Information Desk at 443–757–5803

- Phone the NASA STI Information Desk at 443–757–5802

- Write to:
  STI Information Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076–1320

The *MillSOT*—A Spiral Orbit Tribometer on a Milling Machine

Stephen V. Pepper
Glenn Research Center, Cleveland, Ohio

Level of Review: This material has been technically reviewed by technical management.

The *MillSOT*—A Spiral Orbit Tribometer on a Milling Machine

Stephen V. Pepper[1]
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

A spiral orbit tribometer (SOT) intended to characterize friction and wear phenomena has been constructed on a milling machine. The instrument, essentially a retainerless thrust bearing with one ball and flat races, is exceedingly simple and inexpensive to construct. The capabilities of the tribometer to measure both the coefficient of friction and contact electrical resistance are demonstrated with clean specimens as well as with well known lubricants such as molybdenum disulphide and Krytox oil. Operation in a purged environment of inert gas is also demonstrated. The results with these lubricants are quite close to what is obtained by other methods. Suggestions for extending the capabilities of the tribometer are given. This arrangement may find use in university mechanical engineering laboratories to introduce and study rolling contact motion as well as for research in contact mechanics and tribology.

1.0   Introduction

Tribometers are fundamental to the study of friction, lubrication and wear. Most tribometers rely on simple sliding, either in a back and forth reciprocating mode or in a circular mode as in the popular pin on disk geometry. The spiral orbit tribometer (SOT) has been introduced as a rolling contact tribometer that is a credible mimic of the ubiquitous ball bearing (Ref. 1). The first version of the SOT was constructed in a vacuum chamber to provide information on tribological issues related to mechanisms in the vacuum experienced by spacecraft. However, such a construction employs hardware that is expensive and thus limits its use to well funded laboratories. This paper reports on a version of the SOT that is mounted on a milling machine (mill) of the sort found in all machine shops and mechanical engineering laboratories. It is exceedingly simple and inexpensive to construct and mounts and demounts from the milling machine in a few minutes, thus permitting the mill to be used alternately for both its usual machining operations as well as the host for the SOT. This tribometer may find use in laboratory courses in university mechanical and materials engineering departments that study rolling contact ball motion as in a ball bearing.

The basics of the SOT are described in the Section 2.0, while its construction and mounting on the mill is described in Section 3.0. The data obtainable from this tribometer will be demonstrated in Section 4.0. Final remarks and suggested extensions of the SOT's capabilities will be found in Section 5.0.

2.0   Basics

The basic geometry of the SOT is indicated in Figure 1. A ball is captured under load between two flat coaxial parallel plates, one of which rotates with respect to the other. The ball is driven in a near circular path which is actually an opening spiral—hence its use to describe this instrument. The ball would eventually fall out from between the plates if not for its contacting the flat "guide plate" which guides the ball back to its original orbital radius. A short scar, s, is established on the guide plate and the stationary plate. A stable orbit is established by the ball, which traverses the track multiple times. A transducer on which the guide plate is mounted senses the force of the ball on the guide plate. An analysis (Ref. 1) of the system's kinematics shows that the ball actually slides on the rotating plate when being

---
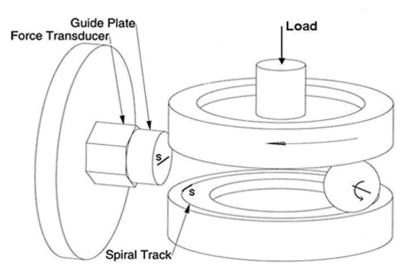
[1]Distinguished Research Associate.

Figure 1.—Basic geometry of the spiral orbit tribometer.

guided back to its original radius and the force sensed by the transducer is this sliding friction force. This sliding friction force can thus be related to the coefficient of the friction during this brief sliding segment of the ball's orbit. Thus the arrangement can be termed a tribometer because it measures sliding friction.

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 (Ref. 2), who has used 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 retainerless thrust bearing with one ball and flat races. 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: a ball, being driven under load, and undergoing all the motions it would undergo in the usual angular contact ball bearing. So this tribometer functions as a credible (albeit 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 shows that the ball *rolls* on the guide plate when in contact. This disruption of the ball path encourages the contact point of the ball to shift, and in doing so the entire surface of the ball (as opposed to a single equatorial ring) is eventually 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. A rare exception to this scenario is the observation of "ball banding", in which an equatorial ring of degraded lubricant is, in fact, observed to develop on the ball. This is analogous to ball banding observed in the usual ball bearing and has been attributed to inadequate lubrication.

3.0 Construction

The basic motion of the ball driven into an opening spiral orbit may be achieved by mounting on the bed of an ordinary milling machine as shown in Figure 2. The mill offers a convenient host in that the spindle is very stiff and the horizontal bed provides x y z motion to position the stationary SOT plate coaxially under the rotating plate. The callouts indicate the mill's spindle A, the rotating plate B, the ball C, the stationary plate D, the guide plate E, the piezoelectric uniaxial compressive-mode force transducer (Ref. 3) F and the mill's bed G. The load on the ball is provided by hanging a weight, H, on the arm that lowers the spindle, thus providing a deadweight load. A load cell provided for a one time calibration of the load on the ball in terms of the weight on the arm. The hardware shown is simple enough to be fabricated on the same mill on which the tribometer is eventually installed. Of course, such an arrangement can also be installed on drill press (DrillSOT), but without the convenience of the mill's robust x y z base table with which to position the hardware under the rotating plate.

A simple plastic box (not shown on the figure) on the tribometer's base permitted an environment purged with dry nitrogen gas to be established around the specimens. The rotating plate is electrically grounded while the stationary plate is electrically isolated from ground, thus allowing the measurement of the electrical resistance of the two tribological contacts (stationary plate/ball and ball/rotating plate) in series. The piezoelectric force transducer was connected to a charge amplifier (Ref. 4) and that signal was processed by a digital data acquisition system (Ref. 5) to produce a plot of the coefficient of friction and electrical resistance versus orbit number.
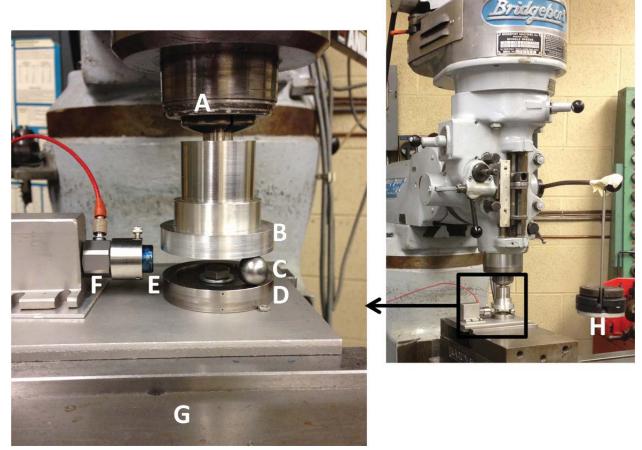

Figure 2.—The spiral orbit tribometer installed on a Bridgeport milling machine.

4.0   Demonstrations

The capabilities of the MillSOT are demonstrated with situations often encountered in practice, such as lubricating with oil or MoS$_2$, a solid film lubricant. All the tests reported here used 50.8 mm (2 in.) diameter 440C steel plates that were polished to a mirror finish, as was the 12.56 mm (0.5 in.) diameter 440C steel guide plate. The 12.56 mm (0.5 in.) diameter 440C ball was a standard Grade 25 bearing ball. The plates were all clean at the start of each test and only the ball was lubricated, except for the one test reported here in which it also was clean. All tests were performed with a deadweight load on the ball of 22.7 kg (50 lbf) for a Hertz pressure of 1.56 GPa, and at a spindle rotational speed of 80 rpm.

The results of three separate tests are shown in Figure 3 for 100 orbits of each test. The balls were either clean, lubricated with 50 µg of Krytox 143AC oil or lubricated with MoS$_2$ by rubbing the ball with the MoS$_2$ powder and gloved hands. The test with a clean ball and the oiled ball were performed in room air, while the test with MoS$_2$ lubrication was performed in a dry nitrogen purged environment. The test with a clean ball exhibited a coefficient of friction (CoF) of ~1, a typical value for an unlubricated clean system. The CoF for the oiled ball was 0.13, the same as that found in the vacuum version of the SOT (Ref. 6). Note how smooth and reproducible are the orbit to orbit friction values, typical of an oil-lubricated system. Inset into the figure is the profile of the force on the guide plate as the ball enters into contact with it on a typical orbit for the oil-lubricated system. The force abruptly rises, exhibits a fairly flat value while in the contact and then returns to zero as the ball exits the contact. The red portion of this profile indicates those data points that are averaged to give the nominal friction force which, divided by the load, gives the recorded CoF. The test with the ball lubricated with MoS$_2$ powder yielded an appropriately low value for the CoF of 0.02, again a value typical for this system. It is seen from the CoFs in these tests that this SOT exhibits a dynamic range of at least 50 for these coefficients of friction.
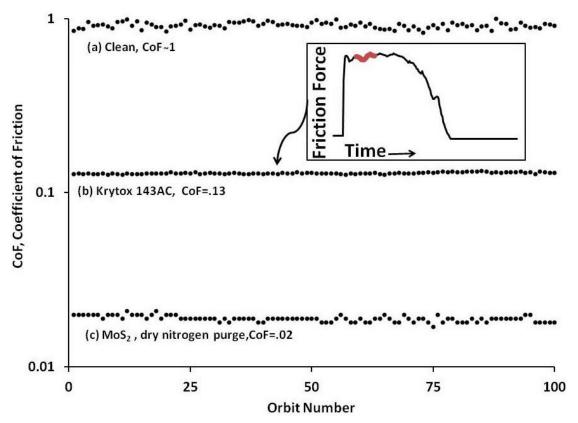

Figure 3.—Results of tests in which the ball is clean (plot a), lubricated with 50 µg of Krytox 143AC oil (plot b) and with MoS$_2$ powder (plot c). Inset is the force on the guide plate as the ball traverses one of the contacts in plot b.

The next demonstration of this test rig's capabilities shows the effect of exposing the MoS$_2$-lubricated system that had been running in a dry nitrogen purged environment to a room air environment. The purge box was simply removed while the system was running, exposing the system to room air with about 50 percent relative humidity. The results are shown in Figure 4. The friction immediately doubles to higher values from its previous lower value of 0.02. This is the expected result and the explanation for this behavior is by now classic: the low values are attributed to the MoS$_2$ crystal basal plane platelets easily sliding over each other, while in a humid environment this sliding is impeded by reaction of the crystal edges with water vapor to form sulfuric acid and oxides of molybdenum (Ref. 7). The cross-bearing electrical resistance, close to zero in the purged environment, starts to increase upon exposure to humidity. This increase is evidently due to the oxides which are electrical insulators being generated in the ball/plate contacts. Thus the behavior of MoS$_2$ as a lubricant observed in the MillSOT is just what is expected and provides confidence in its performance as a tribometer.
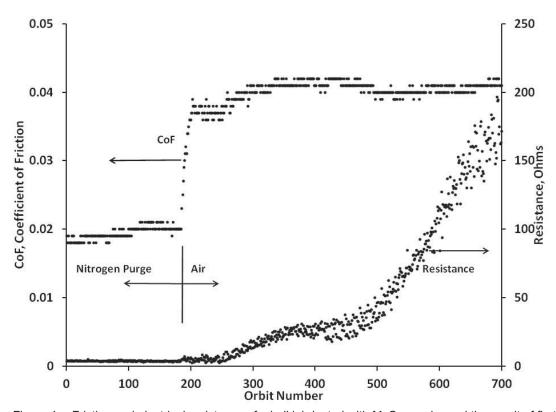

Figure 4.—Friction and electrical resistance of a ball lubricated with MoS$_2$ powder and the result of first running in a dry purged environment and then in a room air environment.
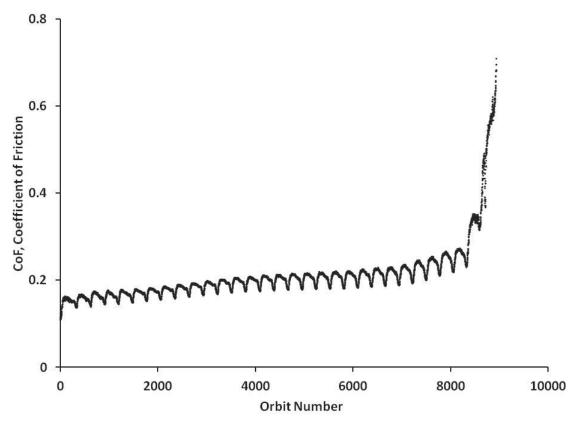
Figure 5.—Friction of a ball lubricated with 15 μg of Krytox 143AC oil.

The last demonstration of the MillSOT presented here is that for a long term test of Krytox 143AC. The ball was lubricated with 15 μg of Krytox 143AC and run in air under the above conditions. The results are shown in Figure 5. The initial value of the CoF is the same as that in Figure 3 but then exhibits a gradual increase, modulated by an interesting minor oscillatory behavior. Eventually at ~8700 orbits, the friction undergoes a dramatic increase, marking the end of lubricated behavior. Such finite "lifetimes" of liquid lubricants, expressed in orbits to failure divided by the lubricant charge in micrograms or orbits/μg, have been observed under vacuum conditions and have been attributed to the chemical reaction of the organic molecules that constitute the oil with the metal of the bearing elements. This tribochemical process gradually depletes the supply of lubricant, leading to an unlubricated state characterized by the observed high friction (Ref. 6). The lifetimes of these liquid lubricants when run in air (Ref. 8) have been observed to be much greater than the lifetimes in run in vacuum (Ref. 6). In the case for Krytox 143AC, the lifetime in vacuum is about 73 orbits/μg (Ref. 6), whereas in air found here it is 8700 orbits/15 μg = 580 orbits/μg. This difference has been attributed to the effect of water vapor, although the chemical mechanism for this "protection" is certainly not understood. What is important here is that the behavior reported for tests in both air and vacuum performed in the original expensive tribometer is found in this simple MillSOT.

5.0   Concluding Remarks

Further developments of the MillSOT may be considered. A more complete characterization of the forces on the tribological elements, as recently reported (Ref. 9), may be obtained by replacing the single axis force transducer behind the guide plate with a 3-axis transducer (Ref. 10). Also, the stationary plate may be mounted on a 4-component transducer (Ref. 11) that provides torque information in addition to three components of force. This transducer will thus provide a record of the actual load during operation

instead of relying on the calibration of the dead weight load. Such additional information from multi-axial transducers may aid in developing a more complete theory of the SOT.

Another development may be operation at elevated temperature to explore the properties of oils. The open geometry permits the installation of a simple electrical band heater (Ref. 12) around the plates. Such heaters can expand to accommodate the guide plate in its holder. The transducer supporting the guide plate may have to be moved back to prevent operation above its temperature limit.

The open geometry of the MillSOT also permits consideration of chemical analytic probes such as infrared spectroscopy to characterize the tribochemical degradation process in situ. The confined geometry of the vacuum version of the SOT does not so easily permit the use of such optical probes.

The results presented in the above demonstrations with this rolling contact tribometer are totally in accord with values obtained in more usual tribometers. With a high level of confidence established in this arrangement as a tribometer, it may be put to use in a variety of modes. It has been mentioned already that it can function as a teaching tool at the university level. With upgraded sensors and chemical analytic instruments, it may also be a platform for basic research into such diverse areas as the mechanics of rolling contact (Ref. 9) and tribochemistry. However, the basic motion of the ball driven into an opening spiral is extremely robust. Although the simple flat guide plate was one way of stabilizing the orbit and using it to construct a tribometer, there may be other uses of this relatively unexplored phenomenon of a driven ball. The mount offered by a milling machine offers a platform to explore many possibilities.

References

1. Pepper S.V. and Kingsbury E.P. (2003) "Spiral Orbit Tribometry—Part I: Description of the Tribometer" Tribology Trans., 46, pp. 57–64. A picture of the vacuum tribometer may be viewed at http://www.grc.nasa.gov/WWW/StructuresMaterials/TribMech/highlights/spiral.html
2. Johnson, K.L. (1958), "The Effect of Spin Upon the Rolling Motion of an Elastic Sphere on a Plane," Trans. ASME, 80, pp. 332–338. Johnson, K.L. (1958), "The Effect of a Tangential Contact Force Upon the Rolling Motion of an Elastic Sphere on a Plane," Trans ASME, 80, pp. 339–346. Johnson, K.L. (1959), "The Influence of Elastic Deformation Upon The Motion of a Ball Rolling Between Two Surfaces," Proc. Inst. Mech. Engrs., 173, 34, pp. 795–810. (.pdf)
3. Kistler Corp. Model 912
4. Kistler Corp. Model 5016
5. National Instruments Corp. Model USB-6215 data acquisition module with National Instruments Corp. LabVIEW Version 8.2 software. The LabVIEW data acquisition program is available from the author upon request.
6. Pepper S.V. and Kingsbury E.P. (2003) "Spiral Orbit Tribometry—Part II: Evaluation of Three Liquid Lubricants in Vacuum," Tribology Trans., 46, pp. 65–69.
7. EW Roberts, 2012 J. Phys. D: Appl. Phys. 45 503001
8. Pepper S.V. (2011) "Effect of Test Environment on Lifetime of Two Vacuum Lubricants Determined by Spiral Orbit Tribometry," NASA/TM—2011-217002.
9. Shareef I., Gilles M and Pepper, S.V. "Capturing Ball bearing Interactions From a Spiral Orbit Tribometer," STLE 69th Annual Meeting & Exhibition, May 18–24, 2014, Control ID: 1258388.
10. Kistler Corp. Model 9017 triaxial piezoelectric force sensor
11. Kistler Corp. Model 9272 4-component dynamometer
12. Tempco Electric Heater Corp., Mi-Plus Band Heaters