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SIGNAL AND POWER ROLL RING TESTING UPDATE

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ABSTRACT

The roll ring was developed as a long-life, low-torque alternative to the slip ring. Roll rings showed significant advantages in two orders of magnitude lower torque, low debris generation, and transfer efficiencies well in excess of 99 percent (including high-power applications). Roll rings have also shown little sensitivity to storage and operating environments, minimizing handling problems and service requirements. A variation of the slip ring, the signal roll ring, was developed to achieve a low transfer-noise factor. Life tests of signal roll rings have accumulated 15 million revolutions with signal noise levels still below the requirements of other programs. Data on these life tests are presented, along with test results from the most recent signal roll ring design. The latest design operates at speeds of hundreds of rpm, with demonstrated life in the tens of millions of revolutions. Power roll rings were later developed, meeting the needs of large power transfers across a rotating joint (as in the space station application). Power roll rings have been tested by NASA Lewis to the equivalent of 200 years of space station operation and have carried currents of 200 A per circuit and 500 Vdc. In addition, alternating currents have been applied at frequencies of 20 kHz, with 440 V and 60 A current. Detailed results of these tests are presented, indicating that roll rings are ideal for low-noise requirement applications.

INTRODUCTION

The roll ring has been under development since mid-1970. Ryan Porter [1] presented a paper to the 19th Mechanisms Symposium entitled "A Rotating Electrical Transfer Device" in which he described the design and development of the roll ring concept in detail. Since the paper's publication, there has been considerable development and testing of both signal and power roll rings. This paper summarizes the life and performance test data for both signal and power roll rings after presenting a brief history of roll ring development, which is covered in more detail in Mr. Porter's paper.

ROLL RING DESIGN

A roll ring consists of one or more circular flexures captured by their own spring force in the annular space between two concentric conductors or contact rings. These inner and outer contact rings are rigidly mounted to the rotating and fixed sides, respectively, of the rotating axis.

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Three basic roll ring configurations are presently under development: a single flexure, 0- to 15-A configuration; a single flexure, 0- to 3-A, high-speed (200 rpm) configuration; and a 2- to 200-A, high power configuration. Figures 1 through 3 show photographs of each configuration.

The single flexure circuit, shown in Figure 1, is typical of over 400 circuits with a cumulative test history of approximately 900,000 circuit hours.

The high-speed, single flexure circuit (Fig. 2) is the most recent development. With inner and outer rings manufactured by plating onto plastic molded parts, 20-ring sets are contained in one pair of inner and outer rings. Up to six of these modules are designed to fit into a single housing that is 20.3 cm (8 in.) long and 7.6 cm (3 in.) in diameter. Besides its ability to operate at speeds of at least 260 rpm and fit into a small package, these single flexure circuits have incorporated a thicker nickel barrier under the gold outer plating on both rings and flexures and are expected to introduce less noise into the signal than in previous designs.

At present, four high-current designs have been fabricated and partially evaluated. Figure 3 is a plan view of one circuit in an 8-circuit module that was designed and fabricated with research funding. It has undergone extensive testing at NASA's Lewis Research Center.

Roll rings have several key advantages over other types of electrical transfer devices:

- o Extremely low drag torque
- o High transfer efficiencies in high-power configurations
- o Extremely low wear debris generation
- o Long life
- o Low weight for high-power applications.

DEVELOPMENT HISTORY

Signal

Initial development work on the roll ring concept was done on IR&D funding in 1975 for use in a vertical gyro gimbal. Three-amp signal roll rings were then developed for the Galileo program in the 1979 to 1980 time frame. This application had stringent noise requirements and necessitated the development of improved geometrics, plating matrices, cleaning procedures, and long-life flexure design. Other signal applications involving roll rings similar in size to the Galileo units advanced the state of the art through the early 1980s. The focus turned to power roll rings in the early 1980s and signal development was slowed until 1987 when a small, long life (107

revolutions), high-speed (100 rpm), 120-circuit roll ring unit was designed for Holloman AFB for use in a precision rate table.

Power

The multiflexure power roll ring was developed in mid-1980, primarily for space station application. Units of 4, 8, and 12 circuits have been delivered. Extensive testing has been performed at NASA Lewis on the 4- and 8-circuit modules.

SOME OBSTACLES OVERCOME

Flexure Fatigue

Early in the development of the 15-A flexure, a fatigue failure at 30×10^6 reverse bending cycles indicated that either the stress model or the allowable stress limit was incorrect. After the stress model was carefully scrutinized and exonerated, the material properties were investigated. It was empirically determined that the grain orientation for flexures (machined from rod stock) was nonoptimum for the direction of strain in operation. Published fatigue data were obtained from cantilevered strip stock or rotating beam testing, both of which stress the samples in a favorable axis along the grain. The difference in stress limits was nearly 20 percent. Figure 4 shows data for the rod, compared to published data. Once this lower stress limit was used, flexure fatigue problems disappeared.

Noise

The most difficult problem encountered in the development of the roll ring has been signal noise. The noise produced by a roll ring is different from that associated with a slip ring in that the signal is clean for most of the time with occasional resistance spikes. Figure 5 shows an example of noise from an ongoing life test originally begun for the Galileo program. While the noise spikes continue to be the principal concern of signal roll ring development, there has been considerable progress toward minimizing them and postponing their onset. Three areas in which significant noise reductions have been made are: (1) plating matrix development, (2) plating purity, and (3) surface cleaning.

Several different plating matrices have been evaluated on the contact rings and flexures in an effort to minimize electrical noise and wear. Most of these matrices consisted of a copper flash for adhesion, followed by either sulfamate or electroless nickel as a copper migration barrier and a hard underlayer of one of several types of gold outerplatings. The most recent surface analyses, performed using AUGER, indicated that a principal source of noise is from copper and lead oxides on the surface. One of the potential sources of these oxides is the migration through the plating matrix of active substrate metal. As a result, the thickness of the nickel layer was increased from a minimum of 2.5 microns (100 microinches) to a minimum of 5 microns (200 microinches). The type of nickel was also changed from sulfamate to

electroless to provide a denser barrier. The final gold layer is either a hard gold alloy, used particularly on the flexures and sometimes on the rings as well, or pure soft gold, often used on the rings to provide a relatively compliant track for the harder flexures. The gold-plated layers are typically about 125-microns thick. If the hard gold alloy is used on both the flexure and ring, very little wear is evident; however, the contact resistance is somewhat increased. This outer gold layer is also a potential source of contaminating oxides, due to impurities in the plating itself. Extreme care is required in the plating process to minimize the potential for contaminants, particularly copper and lead, which are commonly present in plating equipment. Careful monitoring and scavenging of the plating baths are required to minimize contaminants, particularly when other specimens are plated in the same bath.

Once the plating is applied with great care and purity, contamination from outside sources must be avoided. Primary sources of outside contaminants include organic films, silicone and metallic oxides. Outside sources of metallic oxides include migration from nearby components, such as solder used to attach the lead wires. For that matter, the lead wires themselves provide a potential source of copper contamination. The location of solder lugs for the rings in the Holloman signal roll ring design reduces the potential for noise. These lugs were molded into the inner and outer rings. When the curvature of the raceway was subsequently machined into the ring, it also cut into the lug, therefore, when the raceways were plated, the lugs were part of the substrate. The result is that the soldering operation is separated from critical surfaces by the plastic ring.

A high correlation was found between the presence of silicones in the system and resultant electrical noise. Although the exact form of the nonconductive silicone-containing film was never identified, several sources of silicone contamination were eliminated from the test system. The primary source was silicon grease used to lubricate gearheads in the test fixture drive located in the vacuum chamber with the roll ring. Elimination of these silicone sources resulted in greatly improved electrical performance.

It is believed that, for a roll ring, the presence of an organic film does not cause electrical noise under most conditions. Indeed, the presence of a large quantity, as in an oil film, actually benefits the electrical performance for signal current levels. Although organics are by nature primarily nonconductive, their viscous properties permit a flexure with sufficient mechanical preload to make electrical contact, either by complete displacement of the film or by partial displacement to a thickness that will permit conduction by tunneling. However, there are exceptions. In the presence of large quantities of a viscous organic, experience has shown that currents exceeding 3 A may cause breakdown of the organic into less viscous insulators that will not permit efficient conduction. Also, viscous films result in hydroplaning of the contact at elevated rotational rates. The speed at which transition occurs is a function of both flexure preload and film viscosity. These results were compiled during testing of contacts intentionally lubricated with a variety of organic substances. While specific

organic compounds may be used for specific applications, stringent cleaning procedures have been developed to avoid surface contamination by unknown and unwanted compounds and particles.

Circuit Isolation

Particularly important in signal roll ring applications is the isolation of adjacent circuits. The latest isolation system, used on the Holloman signal roll ring unit, consists of 0.025-cm thick copper barriers located between each adjacent ring. The barriers are molded into the plastic, which electrically isolates them from the rings. All inner ring barriers are connected, as are all outer ring barriers. These may then be grounded to the housing, depending on the application. Circuit-to-circuit isolation is typically greater than 50 Db up to a frequency of 300 kHz, reducing to 33 Db at 1 MHz.

Multiple Flexure Design for High-Power Transfer

When the high-power transfer requirements for space station first became a goal for roll ring technology, the element limiting the design was the flexure. Single flexures were not capable of transferring the high-current loads (up to 200 A), and multiple flexures in the same circuit eventually caught up with each other, causing failures. The solution was a multiple flexure design in which the flexures are separated by rolling idlers. The design, shown in Figure 3, has idlers contacting two adjacent flexures and a rail that rotates with the inner ring. If the diameters of all of the elements are selected correctly, there will be theoretically, pure rolling at each of the contact locations. The idlers have a curvature along the axis where they contact the flexures, which causes them to self center on the flexures upon which they ride. This design has minimized sliding contacts and thus minimized friction and wear. The result is a mechanism that is capable of transferring 200 A per circuit with extremely high efficiency and ultra-low drag torque. (Refer to Figure 6 for test results.)

Corona Generation

One of the problems encountered during the development of the power roll ring was the generation of corona. This effect was first observed during high-voltage testing of the four-circuit test unit for NASA Lewis. Fortunately, the current level was low for these tests and no significant damage occurred. A significant redesign of the insulation system was then undertaken. Emphasis was placed on eliminating all line-of-sight between conductors of different electrical potential as well as providing adequate ventilation to prevent pockets of critical pressure. Corona will most readily form at voltages above 250 V with pressures of approximately 1 Torr. No further corona problems have been encountered.

SUMMARY

A great deal of progress has been made in the development of the roll ring for power and signal transmission. Power roll rings are now fully capable of transferring hundreds of kilowatts of power, either ac or dc, for many years with minimum drag torque and extremely high efficiency. Signal roll rings are very suitable for all but the most noise sensitive applications, and research is continuing in an effort to achieve even lower noise levels.

REFERENCES

1. Porter, R. S.: A Rotating Electrical Transfer Device. 19th Aerospace Mechanisms Symposium, NASA, 1984.
2. Renz, D. D.: Multi-Hundred Kilowatt Roll Ring Assembly Evaluation Results. 23rd Intersociety Energy Conversion Engineering Conference, 1988.

TABLE 1. POWER TRANSFER EFFICIENCY DATA [2]

| 8-Circuit Roll Ring Assembly | | 4-Circuit Roll Ring Assembly | |
|------------------------------|------------|------------------------------|------------|
| Rolling, SS Years | Efficiency | Rolling, SS Years | Efficiency |
| 20 | 99.995 | 20 | 99.977 |
| 40 | 99.987 | 40 | 99.970 |
| 60 | 99.987 | 60 | 99.975 |
| - | - | 80 | 99.974 |
| - | - | 100 | 99.966 |
| - | - | 114 | 99.966 |

**NOTE: Lifetime (Rolling Station Years) and Average Efficiency
(500 V dc, 200 amp)**

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CURRENT TESTING STATUS

Signal

Over the years, numerous tests have been conducted to determine the performance and life characteristics of various roll ring configurations, including variations in geometry, plating, lubrication, cleaning procedures, and environments. Many of these tests were short-term in nature and provided the results in a matter of days or weeks. Some of the units, composed of the most promising of the candidate parametric variations, were placed in life testing. The longest running of these, for signal configurations, began as six circuits of a Galileo roll ring assembly. These six circuits were unique in that they were lubricated with tricrysil phosphate (TCP). The pitch diameter of the roll ring circuits is 9.27 cm (3.65 in.) and the flexure diameter is 1.33 cm (0.525 in.). With insulation and housing, the module is 14.42 cm (5.68 in.) in diameter with a 4.45-cm (1.8-in.) hole through the center. Each circuit is 0.51 cm (0.20 in.) wide, and, with bearings and structure, the module is 15.2 cm (6.0 in.) long. Individual circuits are physically separate, as shown in Figure 1, and are, therefore, stackable. Using this design, units have been built with 1 to 20 circuits, and, by stacking modules of 20 circuits, virtually any number of circuits can be accommodated.

The life test, started in January of 1981, now has over 15 million revolutions on it. The operating speed was initially 3 rpm and, after nearly five years, was changed to 7 rpm, following a period in which the test had to be shut down. Figure 6 shows the change in signal noise as a function of time for each of the six circuits. It should be noted that the plotted data represent the highest resistance transient observed during the measurement period. The noise, as described previously, was the primary reason for running the test. Other performance and life issues have been satisfactorily demonstrated with short term tests, but the effects of long term running on the noise performance required a real time life test. The operating speed was not increased in an effort to accelerate the test because of the potential for elastohydrodynamic films developing between the rings and flexures.

Power

Since the power roll ring was initially developed with the space station in mind and because of their superior facilities, NASA Lewis has been responsible for most of the performance and life test results. Two test units were provided to NASA for testing: a 4-circuit (200 kW) unit and an 8-circuit (400 kW) unit. In addition to life testing with both dc and ac power, thermal equilibrium and corona testing were performed. The results are summarized here from the NASA report by David Renz [2].

Initial test showed the onset of corona to occur in the 450- to 625-V range. This was unacceptably low for a unit that is to operate at 500 V. The sources of corona formation were traced and corrected as discussed previously and the 4-circuit unit was retested. The onset voltage increased to the 800-

to 1180-V range and after six months of testing at 440 Vac to 20 kHz, the maximum onset voltage increased to 1650 V. This improvement is attributed to run-in and longer time in the vacuum; current designs minimize this conditioning time. These values are acceptable for most applications.

Three types of power transmission tests were performed on the power roll ring units: accelerated life, high-voltage, and high-current tests.

Accelerated life tests were performed on both the 4- and 8-circuit assemblies. Each was run at 5 rpm with a 100-A load. This speed is approximately 450 times the normal operating speed of the space station rotary joint (16 revolutions/day). Electrical transfer efficiencies were measured at intervals during the testing as a criteria of acceptability. The 8-circuit unit ran for an equivalent of 60 space station years with a minimum transfer efficiency of 99.987 percent. The 4-circuit unit ran for an equivalent space station life of 114 years with a minimum transfer efficiency of 99.966 percent. Table 1 shows the intermediate efficiency data.

An additional 3.3 equivalent space station years of operation were added to the 8-circuit unit during the six months of high-voltage testing at 500 Vdc and 10 A in a $<1.0 \times 10^{-4}$ Torr vacuum. No problems occurred during this test. The 4-circuit unit received corona suppression modifications following the accelerated life test and was then subjected to high-voltage/high-frequency testing at 440 Vac, 20 kHz, and 1.5 A in a $<1.0 \times 10^{-4}$ Torr vacuum. The test was run at 5 rpm for an equivalent of 22 years of space station operation after which the speed was reduced to the real time 16 revolutions per day in October 1987, where it is still running without problems.

High-power tests were conducted to determine the voltage drop across the 4-circuit unit. With 52.5 A, 420 Vac, 20 kHz, the measured voltage drop was 563 mV (0.0014 percent). Most of the voltage drop was reactive and would not contribute to heating the assembly. The inductance was calculated at 0.08 microHenry per circuit, using dc resistance (0.45 milliohm). AC resistance at 20 kHz would be substantially less. Since the cable inductance is 0.032 microHenry per meter, the roll ring is electrically equivalent to approximately one meter of cable.

FUTURE PLANS

Noise Reduction

Efforts to reduce the noise of signal roll rings are now focusing on the elimination of metallic oxides from the surfaces. Increasingly stringent demands for high-purity plating, improvements in migration barriers, and elimination of external contamination sources will continue to be pursued. Additionally, new substrate materials that do not contain easily oxidized metals will be investigated. While progress has been made on cleaning procedures, more potential lies in this area once the sources of metal oxides are minimized.

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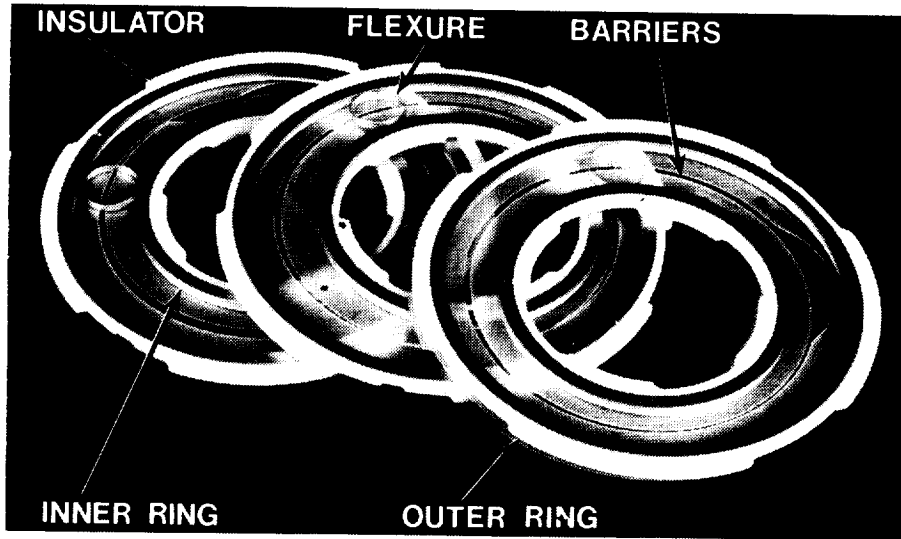


Figure 1. Single flexure roll ring circuits.

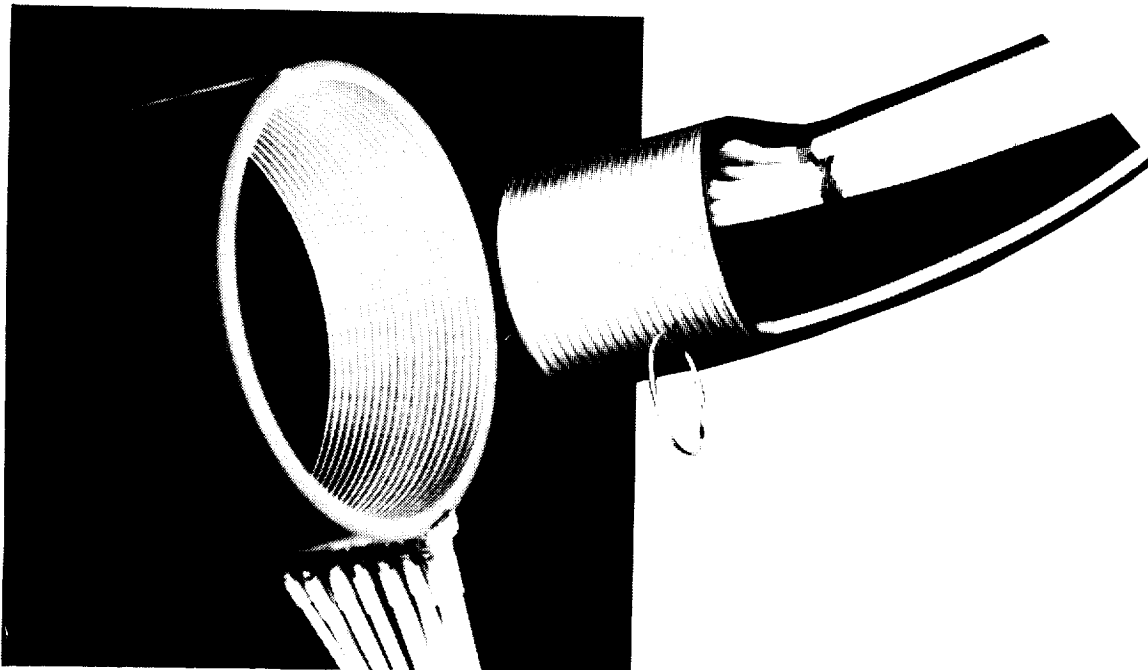


Figure 2. High-speed signal roll ring.

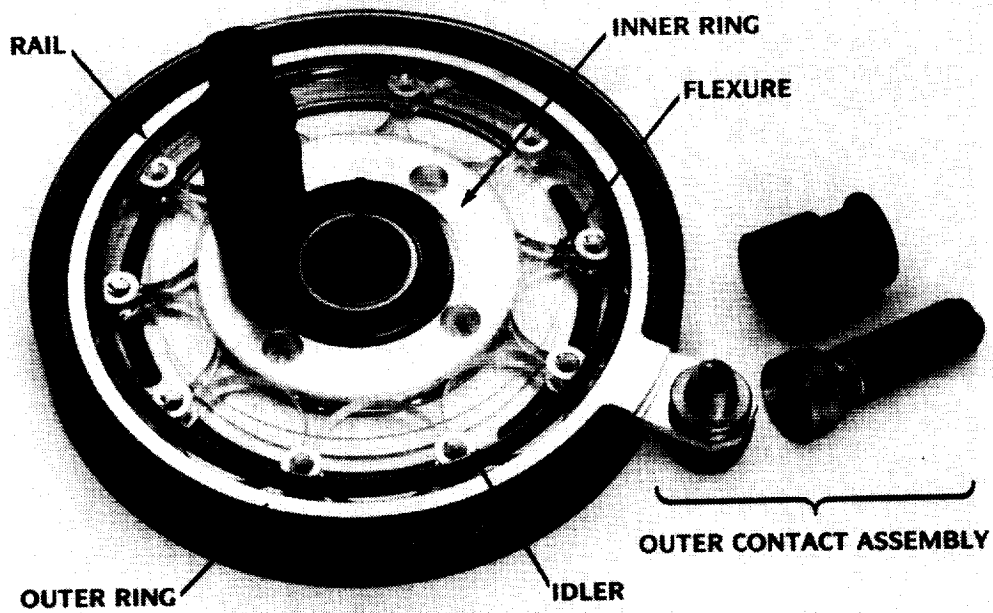


Figure 3. Multiflexure power roll ring.

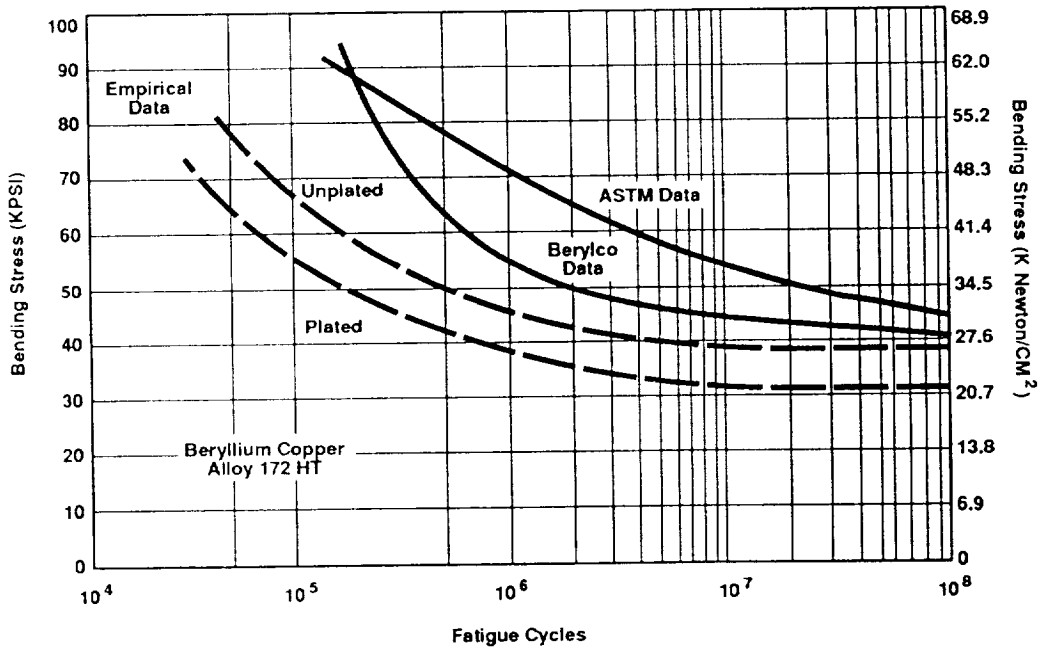


Figure 4. Fatigue characteristics of beryllium-copper alloy 172.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Typical Roll Ring Noise Trace
(After 14000 Revolutions)
GALILEO Life Test-Circuit 1

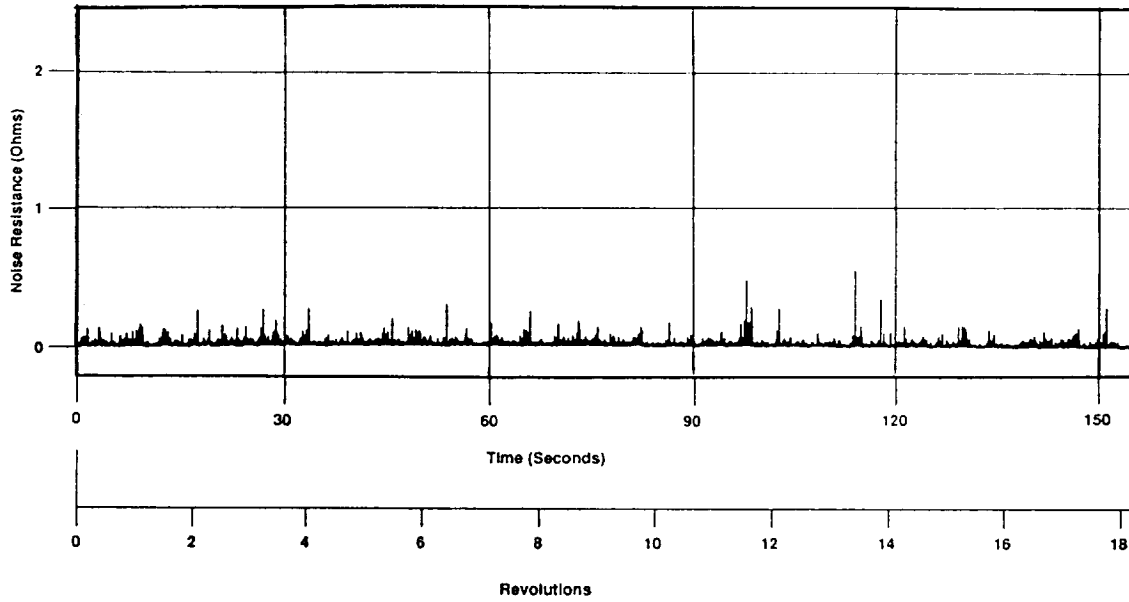
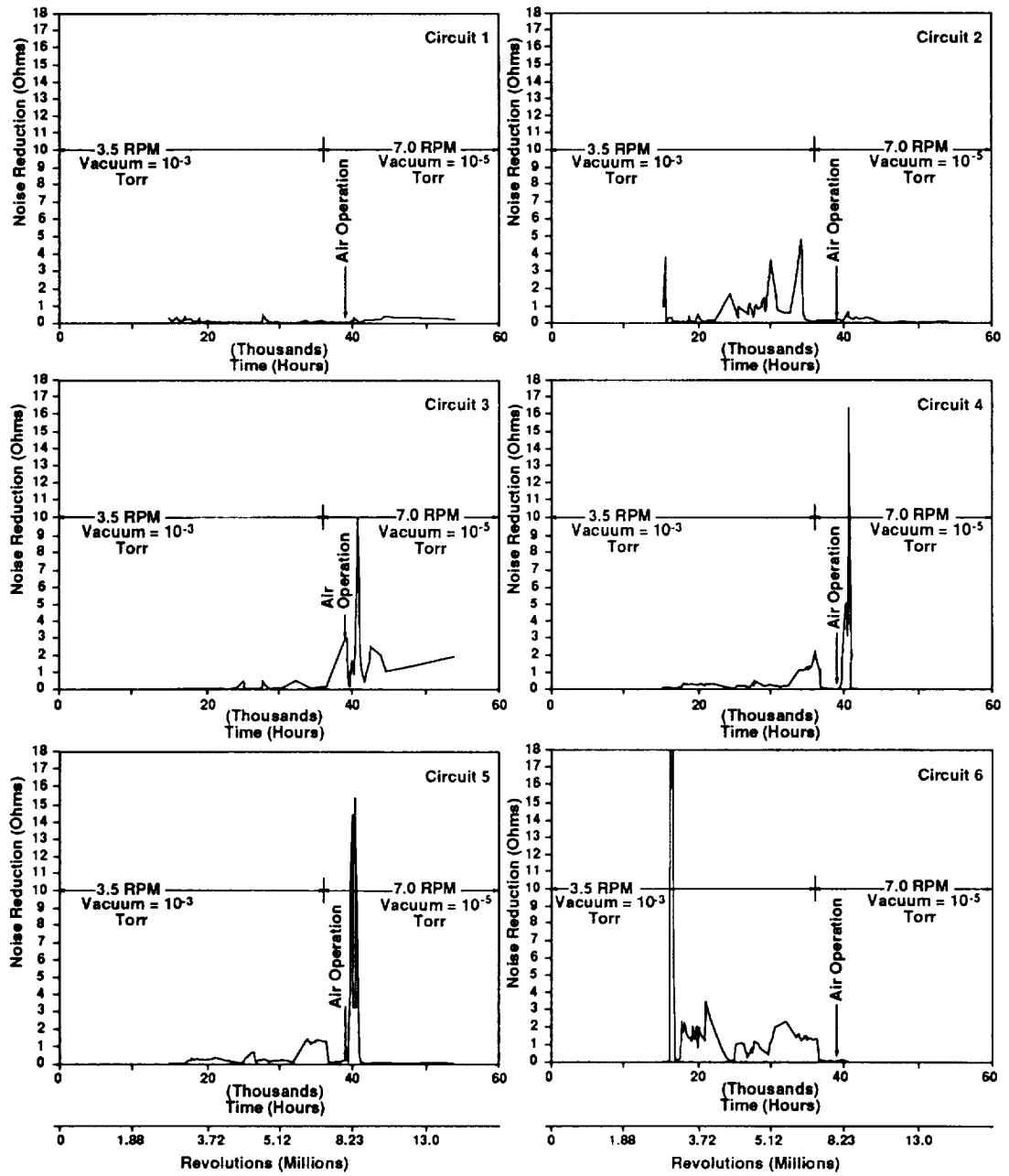


Figure 5. Signal roll ring noise characteristic.



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Figure 6. Six circuit LTU data.