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6. IN-FLIGHT FRICTION AND WEAR MECHANISM

By E. J. Devine and H. E. Evans

Goddard Space Flight Center

SUMMARY

A unique mechanism has been developed for conducting friction and wear experiments in orbit. The device is capable of testing twelve material samples simultaneously. Power, weight, volume, mounting, cleanliness, and thermal designs were particularly critical requirements that were successfully met. The device performed flawlessly in orbit over an eighteen month period and demonstrated the usefulness of this design for future unmanned spacecraft or Shuttle applications.

INTRODUCTION

It is well recognized that the increased tendency of cold welding (friction) and wear in vacuum are potentially serious hazards to mechanical devices operating in space. When exposed to the space environment, conventional lubricants rapidly evaporate, oxide films disappear once disrupted, and chemically clean metal surfaces can come into intimate contact. The result is drastically increased friction and wear due to adhesion (cold welding). (Reference 1) This cold-welding phenomenon in space is of great interest to unmanned spacecraft instrument and equipment designers and especially to the manned space effort because such procedures as repeated orbital docking and assembly may be affected by cold welding.

A very widespread and costly effort was undertaken to investigate this problem under laboratory simulation of the space environment. At one time, a count showed that approximately 100 groups (both government and industry) had been or were studying cold welding and wear. Most of these studies involve vacuum effects.

In contrast to the extensive laboratory investigations and in view of the recognized importance of the friction and wear

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problem, it was surprising that very little data had been, or were planned to be, obtained in the actual space environment. The only previously planned experiments were carried out by the Jet Propulsion Laboratory (Reference 2) on the early Ranger flights and the Air Force Rocket Propulsion Laboratory using the Experimental Research Satellite (Reference 3).

OBJECTIVE

The major objective of this program was to determine the effect of the actual space environment on friction (cold welding) and wear of widely used spacecraft materials. In addition to verifying or disproving laboratory results, this experiment was planned to establish a better definition of the degree of vacuum required for an adequate simulation of the space environment.

APPROACH

It was decided that the disk and rider technique would be used for measuring cold-welding tendency and wear. Welding tendency was determined by measuring the strain induced in a cantilever beam supporting the rider. Semiconductor strain gages mounted on the beam were selected for this measurement. Seven disks and twelve riders were picked as a realistic sample size.

Cleanliness is mandatory when conducting experiments involving material surface effects. (Reference 4) Great care was required in designing the experiment to minimize the possibility of contaminating the material couples. Design of the drive train, instrumentation, and material selection had to be made with the objective of minimizing outgassing. The drive train had to be hermetically sealed and materials with vapor pressures less than 10^{-13} torr had to be used.

To minimize contamination by outgassing from the satellite and at the same time to give maximum exposure of the experiment to the space environment, it was necessary to mount the experiment on the outer surface of the spacecraft and to baffle it from any potential outgassing source.

Most of the laboratory test work was done at pressures of 10^{-8} to 10^{-9} torr; therefore, it was required that the orbit chosen for this experiment have an apogee that would expose the spacecraft to a pressure less than 10^{-10} torr, preferably 10^{-12} torr. This condition would shed light on the degree of vacuum required for adequate simulation.

The materials selected for study are commonly used in spacecraft and also have properties that enable the effects of mutual solubility and hardness to be studied. Materials were:

- Gold and silver
- 7075 anodized aluminum and 440C stainless steel (Rc60)
- 440C stainless steel (Rc60) and 440C stainless steel (Rc60)
- 440C stainless steel (Rc60) and nitrided Nitralloy 135 mod steel
- 440C stainless steel (Rc60) and 1020 carbon steel
- Be-Cu alloy 25 no. 190 heat treat and 440C stainless steel (Rc60)

Two samples of each of these combinations were tested with the experiment module.

INSTRUMENTATION

The basic friction-test mechanism consisted of a hemispherical rider sliding on the flat face of a disk rotated at constant velocity. This geometry is simple and has been widely used in past investigations of vacuum effects on friction phenomena.

Parameters measured and telemetered were friction force, normal force, and displacement of the rider because of wear. These were measured by strain-gage transducers.

The rider-support arm was designed with two flexible sections: one sensitive to friction force and the other sensitive to normal force. The sections were instrumented with epoxy-bonded, diffused silicon strain gages. The gages were arranged in a half-bridge configuration to increase the output signal and to cancel the apparent strain due to thermal expansion mismatch of the gage and substrate.

Normal load was applied by means of an independent, adjustable spring as shown in Figure 1. Normal load for the gold versus silver samples was 4.45 N (1 lb); all other metal couples were loaded to 8.90 N (2 lb). The occurrence of a given amount of wear (0.12 cm) of the rider would result in a corresponding motion of the load rod that would bring the rod in contact with the wear transducer, giving a single-point measurement of wear.

Seven disks were stacked on a common drive shaft and 12 rider assemblies were equally spaced around the periphery, giving a capability for measuring 12 material combinations. Surface velocity between disk and rider was approximately 0.10 cm/s.

In the event that the friction force on a particular couple reached a level such that excessive power was required, the rider was removed from contact by means of a sealed pyrotechnic actuator. The electrical signal for firing the actuator was generated when the friction gage output exceeded a level corresponding to a coefficient of 3.3.

The drive train for the device incorporated two state-of-the-art devices. A brushless motor with solid-state commutation required only 3.5W to drive the fully loaded device. The motor drove an intermediate gearhead of 16.3:1. The motor and gearhead were enclosed in a hermetically sealed package to avoid contamination of the friction experiment and at the same time to maintain conventional lubricants on the high-speed drive elements. Transmittal of power through the hermetic package, together with an additional 72:1 gear reduction, was accomplished by a harmonic drive mechanism.

Considerable attention was given to lubrication of the few slow-moving parts exposed to the space vacuum. The spline (gear) of the harmonic drive mechanism was gold-plated and a light burnish of molybdenum disulfide was applied, run in, and the excess removed. Linear ball bushings, which float the transducer load rods, were in-situ coated with molybdenum disulfide. The drive shaft support bearings were equipped with a self-lubricating duroid retainer and shields.

The strain-gage transducers were designed to meet the following requirements:

Load range	Normal force: 0 to 13.3 N (3 lb) Friction force: 0 to 26 N (6 lb)

Maximum strain	5000 X 10^{-6} cm/cm (limited by the bond strength)
Natural frequency	2000 Hz
Sensitivity	Normal force: 13.5 mV/N Friction force: 6.8 mV/N

These requirements dictated the use of semiconductor strain-gages for the required sensitivity. Literature search (Reference 5) indicated that radiation exposure in a one-year orbit would not significantly affect the gage output. Silicon gages of p-type material are more radiation-resistant and were accordingly selected. The gages had a nominal gage factor of 100.

Experimental studies were conducted in a search for a bonding technique that would eliminate organic materials. Although two of these approaches (ceramic bonding and soft soldering) showed promise, neither could be flight-qualified in the time available. As a result, a high-temperature epoxy bond was selected for this application.

The transducer substrate chosen was 17-4 PH stainless steel. The gages were used in a half-bridge configuration with one gage in tension and the other in compression. The gage output as a function of load (strain) deviated only slightly from linearity within the desired range of operation; therefore compensation for this effect was not required.

The gages were compensated for temperature effects. First, the two gages in a half-bridge were tested for gage-factor change with temperature. Any mismatch was eliminated experimentally by a shunt resistor across the gage showing the larger change. Even with the gages matched for gage-factor change with temperature, the bridge sensitivity dropped with increasing temperature. This effect was compensated by a resistor in series with the voltage supply to the bridge. At elevated temperatures, the bridge resistance increased, causing the current and the voltage drop across the series resistor to decrease. As a result, the voltage across the bridge and the bridge output rose to compensate for the loss of sensitivity. The compensated transducers readily met the specification of less than ± 3 percent of full output drift over a temperature range of -20° to 60°C. Typical transducer linearity is shown by Figure 2.

The relatively high output of the semiconductor strain-gage transducers made feasible the use of individual linear integrated-circuit amplifiers. Thus the complexity of commutation was avoided and redundancy was attained. Some penalty in power drain was inherent in the individual amplifier approach. It was desired that the amplifier stability and temperature drift performance would at least equal that of the transducers. This was, in fact, achieved by careful burn-in and selection. A sample of 500 commercial μA709 amplifiers was burned in over a temperature range of -40° to 100°C; 250 were selected because of minimum change in offset current.

The schematic for the strain-gage half-bridge, the series-shunt resistor-type temperature compensation, and the integrated-circuit amplifier is given by Figure 3.

Ancillary circuits are required for the following:

- Converter regulators for supplying -3 V (± 0.5 percent) for the strain-bridge excitation, ± 9 V for unregulated amplifier power, and 5 (± 0.5 percent) V for temperature sensors

- Thermistor temperature sensors for in-flight temperature monitoring

- Shaft rotation sensor for status monitoring of the drive train

- Timer for turning the experiment on and off at a 10 percent duty cycle to extend the lifetime of the material couples

The experiment was wired with solid conductor, teflon-insulated wire to minimize trapped gasses and to provide a control of the outgassed materials (Figure 4). Teflon and the minute amount of epoxy bonding material for the gages are the only organic materials permitted in the friction-measurement environs.

TEST PROGRAM

The instrument was qualified for launch vibration at the following levels:

	Prototype	Flight Qualification
Sine vibration	8g vector	5g vector
Random vibration	6g	6g

The prototype disclosed large displacements of the normal load rods when the vibration was parallel to the rod (thrust axis). As a result, vibration stops were incorporated to limit the excursion of the rod and thus prevent overstressing of the normal load strain-gages. Two units were subsequently qualified at flight levels with no significant shifts in the strain-gage transducers.

The experiment was qualified for thermal vacuum over a temperature range from 0° to 60°C and vacuum from 10^{-9} to 10^{-7} torr. These tests were conducted in an oil-free, ionization-pumped system and are the source of the vacuum-friction data discussed in the next section.

The instrument was integrated and tested on the OV-1-13 Satellite with the following results:

- Electrical, RF, and magnetic interference tests showed no interference with the satellite systems or the other sensitive experiments.

- Thermal-vacuum (including solar-simulation) tests established the worst-case condition as the cold temperature and demonstrated the capability of the passive temperature control to maintain a predicted range of 0° to 15°C.

- Satellite vibration test with a 1g vector input resulted in no degradation. The vibration test demonstrated that the strain-gage transducers maintain remarkable stability under mechanical abuse. The other unknown factor was the stability with time. Table 1 gives stability data for a complete set of transducers measured at the beginning and end of an 8-month interval. The drift figures shown include both the transducer and integrated-circuit amplifier circuit. In only one case did the drift exceed the design specification. the drift in this instance being in the amplifier circuit.

IN-ORBIT OPERATION

The friction-and-wear device was operated in orbit throughout the 18-month life of the OV-1-13 Satellite. The experiment was turned on and data recorded on an average of one orbit per week. Because the duty cycle was designed for 3 minutes of operation out of 30, this schedule resulted in an average of 6.5 turn-on intervals per week. This totals approximately 500 intervals of 3-minute duration for a total running time of about 25 hours. Instrument performance was flawless throughout the mission.

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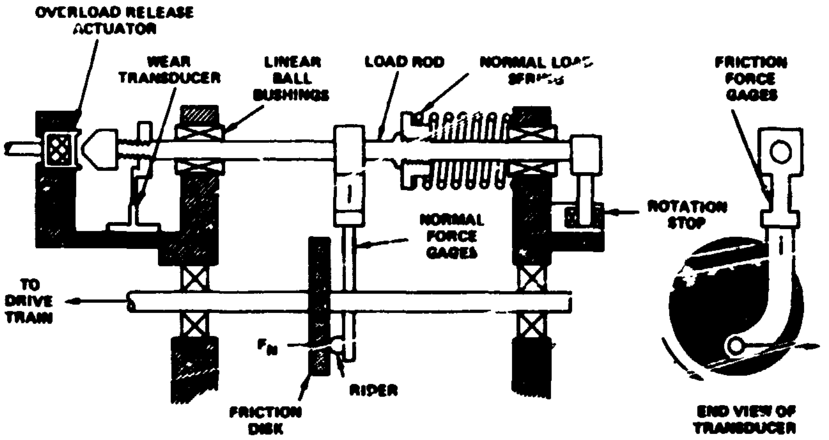

Figure 1 Schematic diagram of friction-test mechanism showing position of spring for application of normal load.

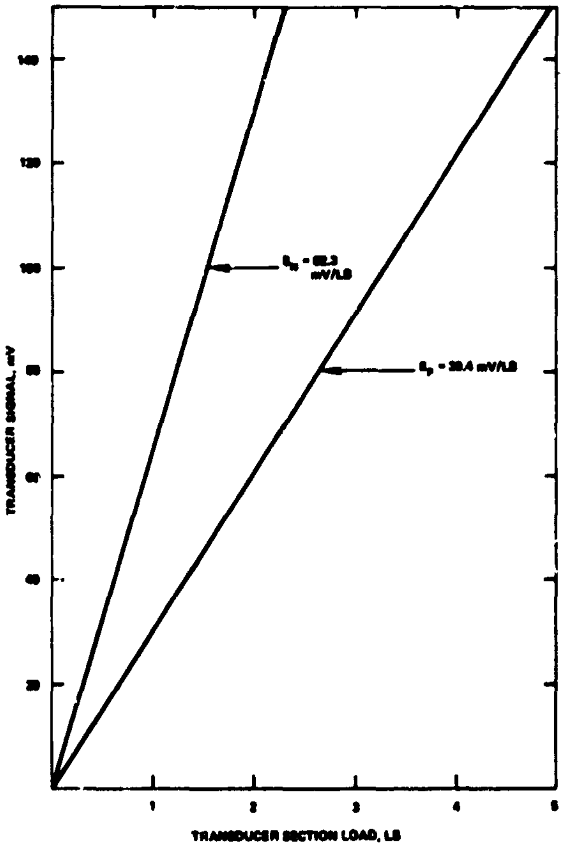

Figure 2 Transducer output as a function of load. Transducer substrate: 17-4 PH stainless steel; 3.00-V excitation; S_N = normal load; S_F = friction load.

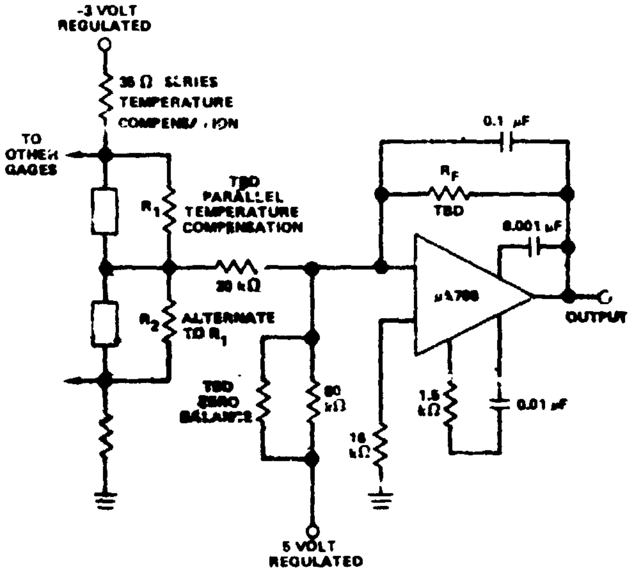

Figure 3. Schematic diagram of the half-bridge, the series-shunt resistor type temperature compensation, and the integrated-circuit amplifier of a strain-gage transducer.

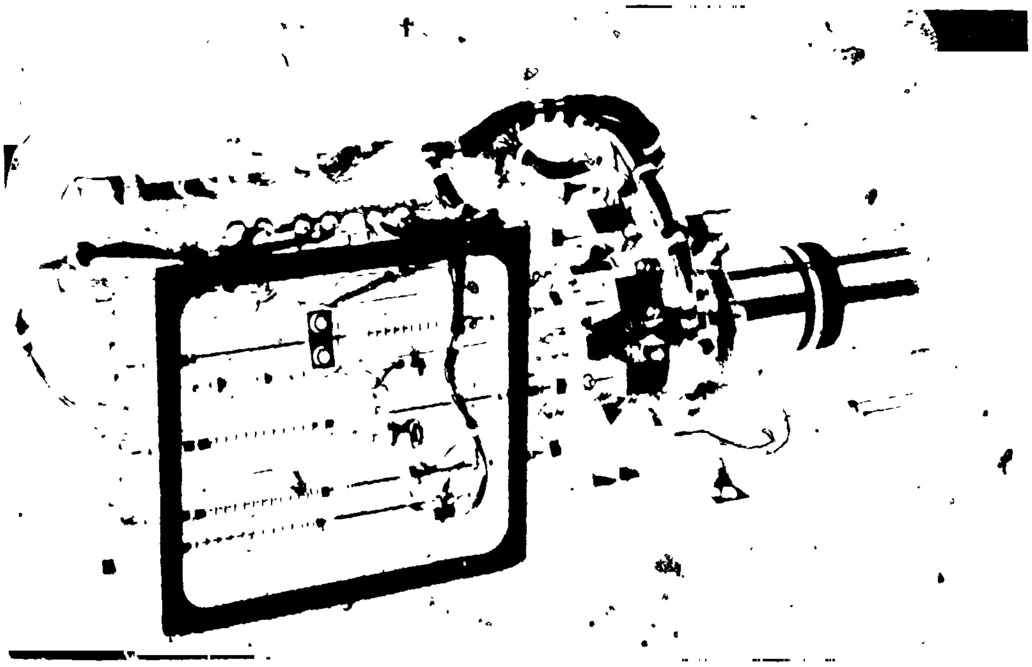

Figure 4. Friction-and-wear module.

Table 1
Stability of Strain-Gage and Amplifier Zero Levels at
Ambient Temperature.

Friction Force			Normal Force			Wear		
Initial	8 Months	Change*	Initial	8 Months	Change*	Initial	8 Months	Change*
–	–	–	0.340	0.378	0.8	2.529	2.486	-0.9
0.315	0.310	0.1	0.427	0.276	-3.0	2.506	2.496	-0.2
0.293	0.368	1.5	0.918	0.808	-2.2	2.574	2.516	-1.1
0.240	0.172	-1.3	0.442	0.385	-1.1	2.525	2.497	-0.5
0.322	0.352	0.6	0.282	0.238	-0.9	2.510	2.474	-0.7
0.240	0.188	-1.4	0.307	0.237	-1.4	2.463	2.479	0.3
0.210	0.233	0.5	0.329	0.343	0.3	2.536	2.520	-0.3
0.173	0.170	-0.06	0.439	0.419	-0.4	2.496	2.466	-0.6
0.154	-0.076	-4.6	0.503	0.400	2.0	2.515	2.471	-0.9
0.428	0.460	0.6	0.654	0.606	-1.0	2.416	2.403	-0.2
0.345	0.417	1.4	0.843	0.827	-0.3	2.484	2.422	-1.2
0.267	0.323	1.1	0.722	0.696	-0.5	–	–	–

*Percent of full scale.