Reliable Microwave Electromechanical Switches

Electromechanical switches offer loss, isolation and linearity performance unmatched by solid state switches which use semiconductors or ferrites, but customarily have not provided comparable life, reliability and repeatability. With appropriate design and rigorous testing and analysis in production these desirable qualities are obtainable, too.

Bob Alman
John Prouty
Hewlett-Packard Co.
Santa Rosa, California

Electromechanical switches find widespread use in test and measurement systems. They possess performance characteristics that are unmatched by solid state switches which have no moving parts, but customarily electromechanical switches have fallen short in providing comparable life, reliability and repeatability. Designing and manufacturing an electromechanical switch which delivers long life, high reliability and repeatable electrical performance requires a special switch architecture, appropriate selection of materials, and a rigorous program of testing and analysis during production.

The motivation for defining switch lifetime in terms of repeatability was the introduction of the vector network analyzer.

A very important application for electromechanical switches is in automated measurement systems. Automating RF and microwave measurements requires not only automating the instruments for stimulating and recording the responses from the devices under test, but often requires changes in the routing of RF and microwave signals between the measurement equipment and the device under test.

Because of their linear, low loss, low noise, high isolation and reproducible behavior, electromechanical switches, which can be controlled using off-the- shelf or custom switch drivers, are the most commonly used for such signal routing. Unfortunately, electromechanical switches suffer from a bad reputation for poor life and reliability, as well as repeatability. This view is sufficiently prevalent that electronic switches have been substituted in many of these applications. But solid state switches do not provide the performance of the electromechanical switch, which typically provides the performance listed in Table I.

The electromechanical switch offers an unique performance combination — loss, isolation, SWR, bandwidth, noise and linearity are unmatched by any other approach.

Table I. Performance advantages of the electromechanical switch compared with semiconductor or ferrite solid state switches.

Performance advantages	
Bandwidth	dc to 40 GHz
Insertion Loss	<0.5dB to 18 GHz
SWR	<1.5 to 18 GHz
Isolation	>60dB to 18 GHz
Nonlinearity	none
Excess noise	none

Electromechanical switches routinely provide useful lives of about one million switching cycles, but this rating is misleading for test set applications because it usually does not take performance repeatability into account. Customarily, the operating life for electromechanical switches has been defined simply as the number of cycles before the switch becomes inoperative. For precision measurements, repeatability is the more basic lifetime defining characteristic.

In the 1970s our firm introduced the first automatic vector network analyzer, which provided measurement accuracy and speed well beyond what had previously been practical for everyday design and production measurements. This system, and those which followed, required switching and other components having specifications previously unavailable from the common sources of supply, such as insertion loss repeatability for electromechanical switch life. For this reason our firm set out to design and manufacture the critical network analyzer components, and microwave switches were one such component.

Today, the need for high performance switching is all the more critical, as measurement systems are expected to improve in speed, accuracy and bandwidth. Further advances in measurement capability continues today, as the computational power built into these instruments gives them the ability to calibrate out and, in real time, compensate for systematic measurement errors. But notwithstanding the increase in computational capabilities, such as their capacity to easily and speedily handle 12 term error correction algorithms, nothing short of improving the repeatability of the basic components, such as the electromechanical switches, can compensate for random measurement or repeatability errors.

No matter how much computer correction is used, there is no way to recover the measurement uncertainty of switch repeatability.

Repeatability errors present themselves as variations in insertion loss, reflection, isolation or phase performance. Ideally, in a perfect switch, these parameters would not change over time, or among switching cycles. But in reality, over time, contact surfaces corrode or flake and mechanical parts wear, causing them to fall out of tolerance as well as contribute debris to interfere with subsequent switching cycles.

These performance deterioration events generally are random. Consequently they may or may not be present during calibration, and cannot be compensated computationally. During measurements, the results obtained may include the effect of random variation; for example, the insertion loss through the switch may be more or less than it was during calibration. To account for these possibilities, the test engineer must add an allowance for repeatability to measurement uncertainty, and thereby decrease the known accuracy of the measurement.

The random error contributed by a tolerance for switch repeatability can be quite appreciable in a moderately sized switching system (in which four or more switches may operate in tandem) unless switches with a low repeatability tolerance are used. As a result, we have expended a great deal of effort in the design and manufacture of switches which are both highly repeatable, to insure measurement accuracy, and which have long operating life, to lower the overall cost of system ownership.

Performance Goals

Contact corrosion, contact wear and the presence of debris account for most switch failures.

In order to produce both a repeatable as well as a long life switch, it is appropriate to consider the factors that contribute to non-repeatability. It is our experience, having performed extensive evaluation of various switches to their destructive limits, that two factors principally determine repeatability and/or operating life performance: 1) Contact degradation through corrosion and wear, 2) Interruption of the switched path by debris generated from material wear and mechanical failure.

Designing the switches to reduce or eliminate these failure modes involves selecting the best switch architecture, using materials and processes which minimize the occurrence of these destructive factors, or in the case of debris and corrosion, providing a self healing mechanism. There are many factors which in turn influence contact degradation and interruption of the switched path. Understanding them can lead to an improved design.

Manufacturing and Wear Debris

Debris inside the switch can lead to premature failure if the debris material can migrate to the contact surfaces. Such material between the contacts even can result in an open circuit, and certainly can induce variations in insertion loss.

Debris inside the switch can come from two possible sources: contamination during manufacturing and material wear. Manufacturing debris are minimized by constructing the switch in a clean room, using laminar flow hoods for air circulation, as well as by thorough cleaning of the microwave switch cavity before closure.

Reducing wear debris requires the selection of both a suitable switch architecture as well as appropriate materials for the switch's construction. Wear debris are generated as two surfaces come in contact during motion of an electromechanical switch's contact(s). The amount of debris generated is dependent upon the surface area of the sliding contact, the amount of frictional force on them, and the contact material's tendency to shed.

Figure 1 shows a common design which uses a large center plunger and four dielectric rods positioned near the ends of the jumper along the cavity wall to provide center guides, maintaining alignment of the jumper by preventing its rotation relative to the center conductor contacts with which it mates.

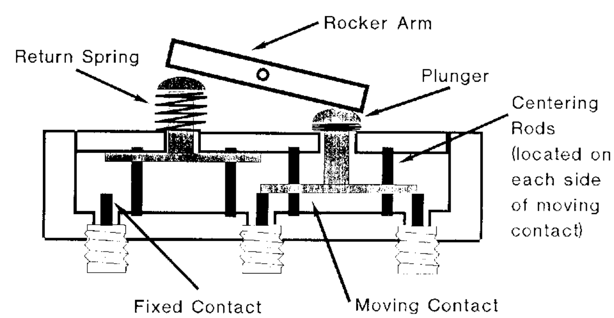


Figure 1. A common switch design.

A self aligning mechanical design reduces the number of sliding surfaces and accordingly switch wear.

By contrast, Figure 2 shows our design wherein two thin push rods move each jumper. The two push rod design inherently inhibits rotation, without the introduction of additional sliding surfaces to accommodate that purpose. The elimination of additional centering rods as well as the small surface areas of the two push rods significantly limits the potential amount of debris that can be generated compared with the common design shown in Figure 1.

Contact Force

Contact force between the contacting surfaces is critical both to the performance and life of the switch. Figure 3 represents qualitively the relationship between contact force and contact resistance. As can be seen, at the low end of the force scale, small changes in contact force translate into very

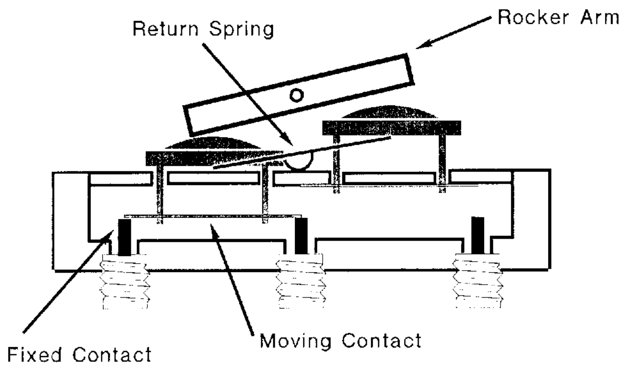


Figure 2. The proposed switch design.

large changes in contact resistance. At the other end of the scale, as force increases, contact resistance decreases, but at a much reduced rate, ultimately limited by the bulk resistance properties of the contacting materials.

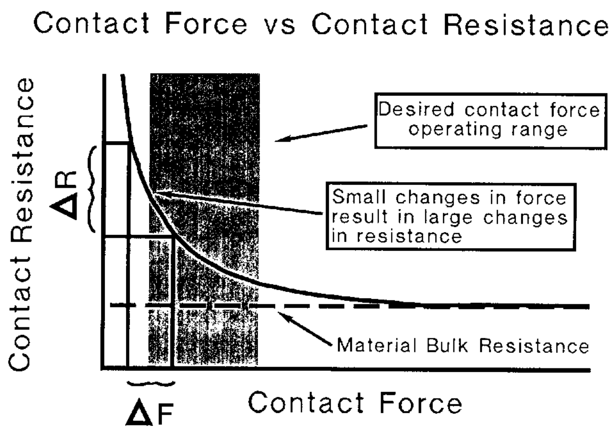


Figure 3. Contact force versus contact resistance.

A springy contactor minimizes wear. It also produces a wiping action to remove debris and surface corrosion, making the switch self healing with each cycle.

In addition, too low a contact force will not provide adequate contact surface pressure to break through surface films and soft debris. Figure 4 is a representation of the contacting surfaces. As noted, the contact resistance is a function of contact force, but the effective contact force is less than that applied because of the presence of foreign resistive films and debris. The applied force is shared among the desired contact surfaces as well as the surfaces of any debris (which may be non-conducting), as shown in Figure 4.

Nor is it appropriate to compensate for this reduction in applied force through excessively high contact pressures. Very high forces lead to surface deformation as well as to creation of wear debris which can embed themselves along with corrosive products into the contacting surfaces. Rather, the optimal contact pressure is that which does not damage the surfaces but is adequate to break through surface films, renewing the contact surfaces with each switching cycle.

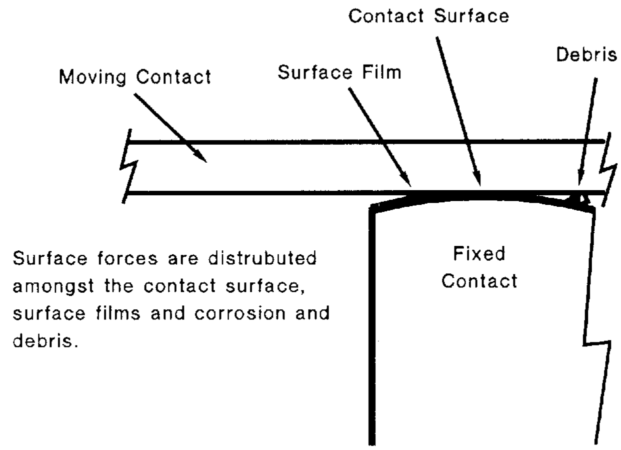


Figure 4. Surface contact force distribution.

Controlling contact pressure requires that the drive and latching circuit deliver just the right amount of force. Figure 2 illustrates the use of a thin center conductor rectangular coax structure. The 0.05mm jumper of our design is allowed to flex, like a spring, limiting force and impact. This is in contrast to the customary design shown in Figure 1, in which a 0.5mm thick jumper is used.

Contact Wiping Action

The concept of contact wiping action is well understood and has been used in relays and keyboard switches in order to break through surface corrosion and debris on contacting surfaces. In electromechanical RF and Microwave switches it plays a critical role in the achievement of long and repeat-

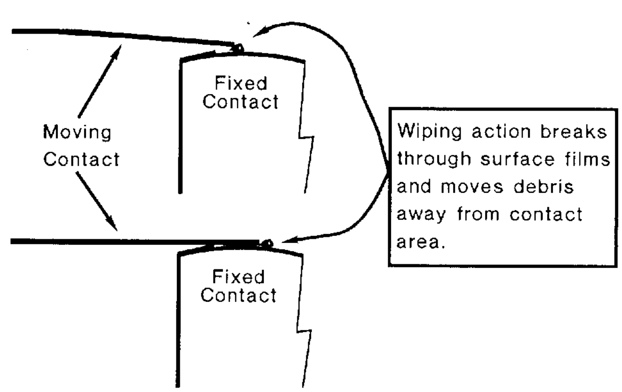


Figure 5. Example of wiping action.

able life. Just as with contact force, little or no wiping action does not allow the contacts to wipe through surface films and corrosion. If debris are present, the wiping action can push the material out of the contact zone, allowing the switch to "repair itself". Of course, too much wiping action, coupled with high contact pressures, will actually generate debris by flaking off material. Additional problems are created through the generation of frictional polymers on the contacting surfaces. To achieve adequate wiping action requires one of the contacting surfaces to move relative to the other. The design of Figure 2, with its flexible jumper, is so specified as to provide up to 0.01mm of wiping action. The jumper in Figure 1 is much more rigid due to its thickness and consequently does not provide significant wiping, failing to remove debris and contaminating films.

Plating and Corrosion

Plating can inhibit corrosion, but too much changes the spring in the contactor, increasing wear.

The materials used for plating contacting surfaces plays an extremely important role in switch performance and life. Gold is the choice material for the contact plating due to its intrinsically low resistance and resistance to oxidation and environmental corrosion. However, since gold is soft, consideration must be made for contact pressure and wiping action. Balancing the needs for these characteristics with the mechanical properties of gold necessitates the use of gold alloys which are more resistant to wear, but still possess the desirable electrical and chemical properties.

Most often, jumpers are made from beryllium copper or other copper alloys. The design in Figure 2 utilizes beryllium copper to take advantage of its spring properties. This choice of base material presents additional problems, as it requires the use of a barrier material between the copper based substrate and the gold contacting surface to prevent metal migration. Nickel and nickel alloys are the most common barrier materials in use. But, nickel presents further complications, as the fabricator first must lay down a nickel barrier which is pore free, to prevent copper migration, but is not so thick that it either affects the spring properties of the substrate or becomes so brittle that it cracks and consequently allows metal migration to take place.

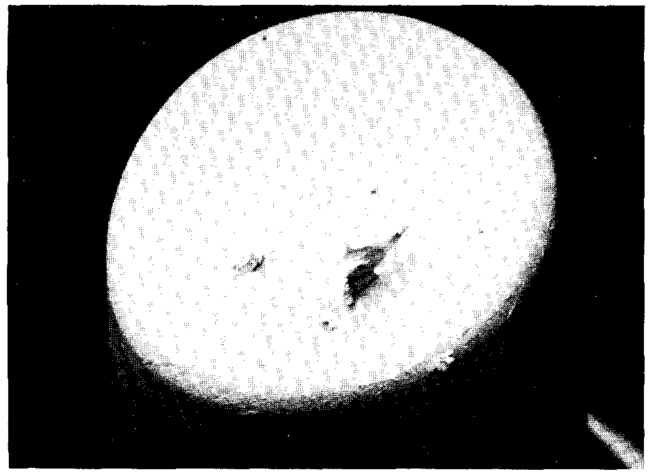


Figure 6. SEM photo of damaged contact surface after less than 1,000,000 cycles, evidencing poor plating and high contact forces.

Figure 7. SEM photo of contact surface from the Figure 2 design after more than 7,000,000 cycles.

Process Control and Monitoring

No matter how well designed and manufactured, sample switches must be tested to failure routinely to insure reliability.

Producing a long life switch requires some means for verifying on a periodic basis that the switch is meeting the life goals. No design, no matter how robust, is immune from variation in materials and processes that can compromise the long-term operation of the switch. Therefore it is important to have in place a monitoring process that will evaluate the long term switch performance and analyze sources of failure. Sacrificial switches should be included in every production run in order to run life and repeatability tests.

To do this we cycle the switches and test them for electrical performance and dc repeatability until they fail. We define that a failure has occurred when the switch no longer operates or when the dc insertion loss variability exceeds 0.03 dB, whichever comes first. DC repeatability is the preferred production test for several reasons. 1) It can be checked on every cycle more easily than RF/Microwave repeatability. 2) It is far more sensitive to variations in contact force, debris and contact corrosion than RF repeatability, and 3) The time required for DC test is a small fraction of the time necessary to test for S-Parameters.

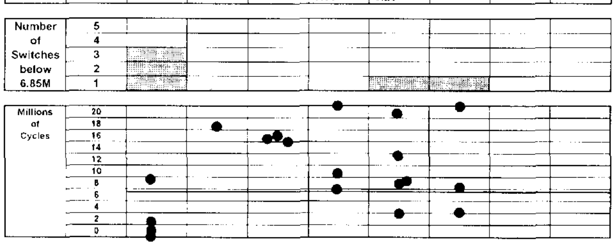
Some results of Test To Destruct (TTD) monitoring are presented in Table II. This type of testing helps identify material fatigue problems in RF, magnetic drive and actuation components. It can also help isolate problems with plating quality. The statistical process measures establish a lower control limit (LCL) for the TTD test. The TTD unit must exceed this LCL to ensure that the specified life is exceeded by approved lots of production switches (see Table III). Switches represented by the TTD sample are not shipped until the TTD sample exceeds the LCL. If the sample fails, all the units will be held back from shipment until the problem areas are identified and corrected, and the solution has been verified by additional TTD testing.

Switch #	Cycles @ Death	Repeatability		Comments
		Max Path Resistance	Range of Path Resistance	
Sample 1	889K	2569mΩ	2561mΩ	Path 6 Failed, debris from internal load
Sample 2	250K	OPEN	75mΩ	Path 6 Failed, Bad plating
Sample 3	0K	OPEN		Path 3 DOA from manufacturer
HP #987	12.15M	545mΩ	516mΩ	Path 1 Debris

Table II. Test to destruct evaluation of various common designs of switches.

Switch Test to Destruct Chart with Narrow-Limit Gaging

Date		1/28	2/1	2/15	3/24	4/29	5/21		
Sample	1	F 0.80	P 17.25	P 15.00	T	P 19.75	P 24.00		
	2	F 2.5	T	T	P 24.75	P 8.25	F 3.25		
	3	P 8.75	T	P 16.00	P 9.25	P 8.00	T		
	4	F 0	T	P 15.50	T	P 12.75	P 7.25		
	5				P 7.00	F 3.25			



Comments:

Customer Spec: 5.00 Million Cycles
Test Line Limit: 6.85 Million Cycles

Code: F = Fail Customer Spec T = Testing in Progress P = Passed Test Line Limit

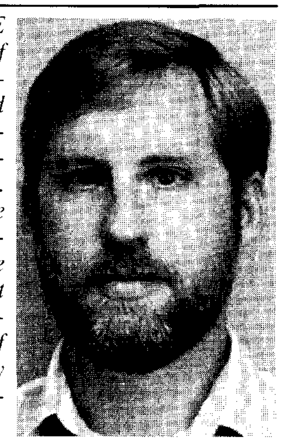
Table III. Test to destruct production data for the Figure 2 switch design.

Units that exceed the LCL are continued in the testing to provide feedback for design and process improvements. It is noteworthy that, in one case, a switch which first started TTD in 1989 is still functioning within specification, including repeatability, three years and 90 million cycles later. While this is not typical, it is an encouraging testament to the design and manufacturing approach.

While electromechanical switches may never realize the potential life expectation specifications of electronic switches, they can with proper design, selection of appropriate materials, careful process control and on-going evaluation and improvement meet the needs of system designers for components that last well over 5 million cycles, offering their uniquely high isolation, low loss, low noise, linear operation and very good repeatability.

References

1. Rytting, Douglas K., "Improved RF Hardware and Calibration Methods for Network Analyzers," 1991 RF & Microwave Measurement Symposium, pp 7.



Robert E. Alman *received the BSEE degree in 1984 from the University of Wisconsin in Madison. Upon graduation, he joined Hewlett-Packard Company, Microwave Test Accessories Operation as a production engineer for electromechanical switches. In 1988, Bob moved to R&D where he designed the HP 33314 line of electromechanical switches, for which he was awarded a patent for significant breakthroughs to increase the life, reliability, repeatability and isolation of the switches. Bob has most recently been designing HP's new line of multiport switches.*

John H. Prouty *was awarded the BSIE degree by California Polytechnic State University in San Luis Obispo in 1980. Upon graduation, he joined Tektronix, Inc. in Beaverton, Oregon. While with Tektronix, John worked as an Industrial Engineer within the Electromechanical Components Manufacturing Group, and the Instruments Division, supporting the TM500 and TM5000 line of modular measurement instruments. In 1982, John joined Hewlett-Packard Company where he has held positions in materials engineering and manufacturing engineering. In 1987, John helped start up the marketing department for the Microwave Test Accessories Operation where he has had responsibility for strategic planning and promotion for electromechanical products and systems.*