SPRING PROBE CONTACT SOLUTIONS FOR SOLDERLESS INTERCONNECTIONS, BASIC DESIGN CRITERIA AND OVERVIEW OF CASE STUDIES AND DEVELOPMENTS

Don Marx [(1)], Richard Johannes [(2)], Pierangelo Bozzo [(3)]

[(1)] Smiths Connectors
5101 Richland Ave.
Kansas City, KS 66106
USA
Don.Marx@smithsconnectors.com

[(2)] Smiths Connectors
1550 Scenic Ave., Suite 150
Costa Mesa, CA 92626
USA
Richard.Johannes@smithsconnectors.com

[(3)] Smiths Connectors
Via P.D. da Bissone 7A
16153 Genova
Italy
Pierangelo.Bozzo@smithsconnectors.com

Introduction

In reply to an increasing demand of solderless interconnections (interposer), Smiths Connectors has developed, tested and deployed a number of interposer solutions based on spring loaded probe contacts. These solutions have proven to be able to withstand space application requirements, including typical vibration, shock and climatic testing and offer a reliable way to implement high density interconnections with high speed signal transmission requirements. This technology facilitates parallel PCB to PCB and cable to PCB connections, giving new options for electronics packaging in light weight, volume constrained satellite applications.
The scope of this paper is to present some typical design considerations in the development of spring loaded contacts and connectors for space duty. Typical contact and connector construction, material selection and plating requirements, high speed design approach through simulation and design validation and testing procedures will be also presented.

Typical Spring Contact and Connector

A spring loaded contact element, often called "spring probe", in its most basic form consists of (Fig. 1.):

- One or more contact members normally called "**plunger**"
- An helical coil **spring**
- A conductive tube often called "**barrel**"

The **plunger** is the moving contact member in the spring probe and makes the interconnection against the mating side or **target**. The **target** typically is a conductive pad on a circuit board, or a flat headed pin acting as a landing zone

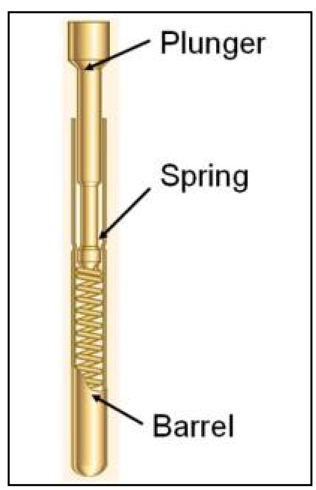


Fig. 1. Basic spring contact construction, single ended

for the spring probe in a mating connector (which is then called “target connector”) or a device to be tested. In some cases, spring probes can be used to terminate the conductive housing of a device for ground / shielding purposes. A typical spring loaded contact has one or two plungers.

In the first case, called **“single ended configuration”**, the electrical connection to be established is between the target and another conductor connected to the barrel, usually by means of soldering, crimping or by press fitting.

In the second case, called **“double ended configuration”,** both plungers are sandwiched between targets. There is no need of soldering or crimping, hence this configuration is called “solderless”. A “solderless” configuration can also be created by assembling a single ended probe in a “floating mount” fashion, as shown in Fig. 2.

A helical coil spring provides the force against the plunger. Pushing the plunger towards the target compresses the spring, which reacts according to Hooke’s Law: *“ut extensio sic vis”* (as the extension, so is the force). The barrel is the conductive component that encloses and retains the spring and the plunger and provides the path for the electrical current to either a second plunger, rear target, crimp to wire or solder joint to wire or PCB.

<u>Biasing techniques</u>

One of the main limitations of the traditional spring loaded contact is the inconsistence in contact resistance, which may vary greatly, if the plunger does not make a good contact with the barrel. This results in the current flowing intermittently through the spring, resulting in a significant increase in resistance.

A number of different solutions to this problem have been developed. The most common solutions to this problem involve “biasing” of the plunger. The spring probes have design features that force the plunger to make contact with the inner side wall of the barrel (biasing the plunger from the centreline of the barrel). Typical methods of inducing a bias include:

- Bias spring
- Bias ball
- Bias plunger
- Capsule design

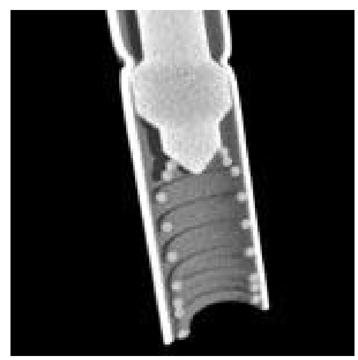


Fig. 2. Bias spring

The “bias spring” design (Fig. 2.) uses a conventionally wedge-shaped plunger tail. The spring is cigar-shaped, tapering at each end. The small, closed coils of the spring cause the plunger tail to seat poorly. As the plunger is compressed, the spring causes the plunger tail to angularly deflect. This is the least effective biasing method in terms of stability of resistance. This design provides the best performance in terms of low wear during high mating and unmating cycles.

A bias ball probe (Fig. 3.) construction involves a plunger with an angular face on its tail. A metal ball, typically a stainless steel ball bearing, is interposed between the plunger and spring. The ball acts as a fulcrum and the angle as a lever, causing the plunger to tilt radically within the barrel. This is the most aggressive biasing technique, and as such is typically the most successful in controlling internal contact resistance during the initial life cycle of the probe.

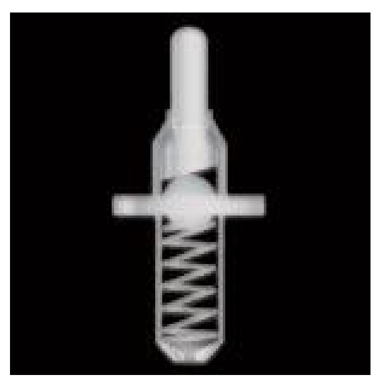


Fig. 3. Bias spring

A variation, and in many respect a simplification, on the bias ball design is the “bias plunger” technique (shown in Fig. 4.). This is basically the same concept of the bias ball solution, that is to force the plunger to tilt through the use of a specialize spring geometry rather than a bias ball. This design is relatively new, since advanced coil spring manufacturing techniques are necessary. The spring must have miniaturized features at the coil end tapered geometries, so that it is possible to properly control the tilting of the plunger with little or no risk that the spring wire jams the plunger motion for sitting in an improper position. The bias plunger design reduces the severity of the angle on the plunger's tail, eliminates the ball, and carefully closes the ends of the spring to ensure good mating with the plunger.

Fig. 4. Bias plunger

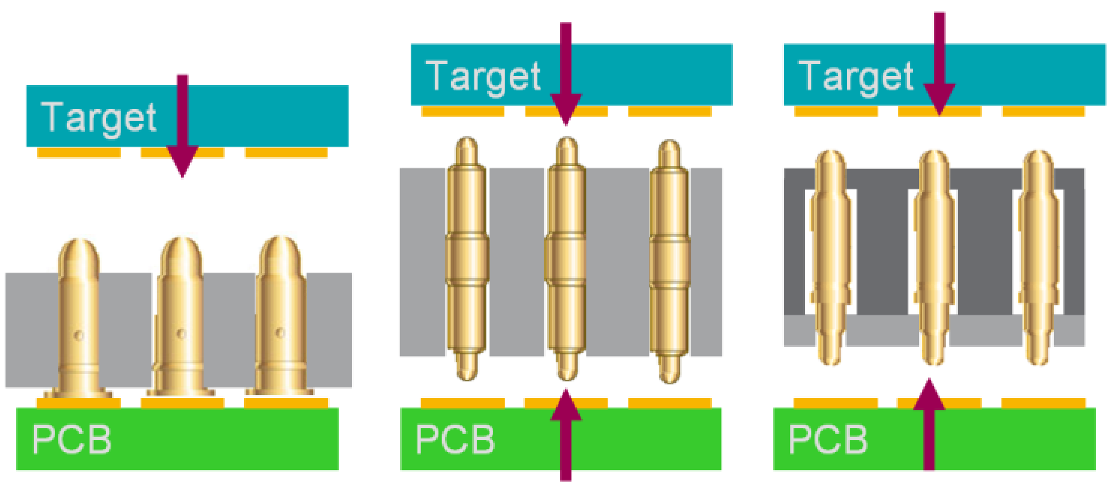
A different approach to probe design is the "capsule" (Fig. 5.) design. The idea in this case is to use a hollow plunger, creating more available space for the spring and more contact travel with respect of the overall length. As the spring settles between the two components, some biasing effect is generated. If the cavity in the plunger is eccentric with respect to the contact main axis, the biasing effect is enhanced.

Fig. 5. Capsule design

These are not the only methods to stabilize the electrical resistance. Other methods exist, and, while they differ in the details, the basic principle is to establish an alternate current path through the spring probe by completely separating the electrical path from the spring mechanics, usually by forcing some sort of internal "wiping" contact through an elastic element (e.g. bifurcated designs, hyperboloid-based biasing such as the Hyperspring contact or similar methods). These approaches have a number of benefits, but decrease the durability of the contact and can dramatically increase the mating forces.

Typical Interposer Connector Construction

Board to board interposer connectors based on spring loaded contacts are usually built in one of three fashions shown in Fig. 6. Contacts can be soldered onto one of the two boards, but can also be arranged in solderless solutions either employing a double ended probe (Fig. 7.) or a single ended contact kept "floating" between two insulators.



a) (b) (c)

Fig. 6. Examples of typical usages of spring-loaded connection (left to right): a) single ended probes (depicted with SMT solder terminations); b) double ended probes used in a "solderless" solution; c) single ended probes, kept "floating" between two insulators in order to create a "solderless" connection

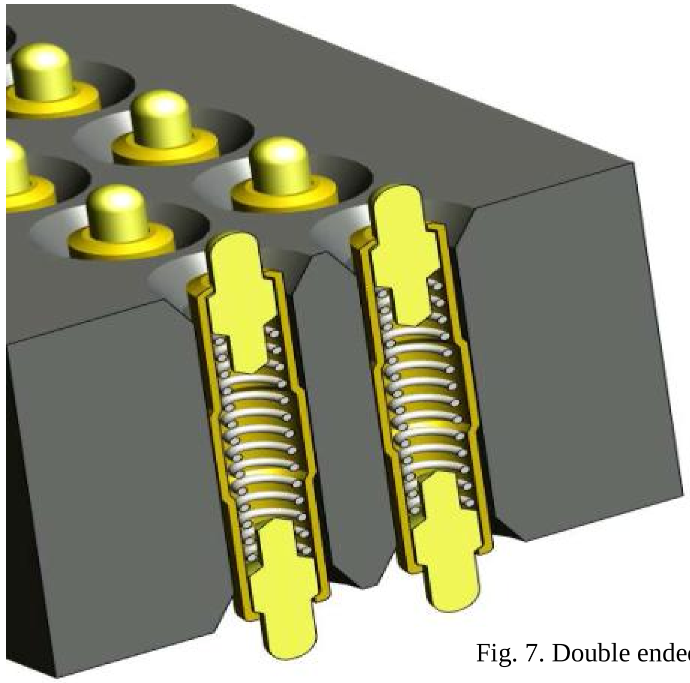


Fig. 7. Double ended spring contact

Advantages of Spring Loaded Solutions

The biggest difference between spring loaded connectors and pin/socket connectors is that the latter is self-retaining, while the former does require a force continuously applied to contrast the springs. Connection is not maintained if there is no compression force.

Also, basic, unbiased construction of most spring loaded contacts has a number of issues in the consistency and general reliability of the electrical connection, which is also prone to higher contact resistance with respect of other contact technologies. It is therefore, essential to employ properly biased contacts.
On the other hand, employing spring loaded (or otherwise compliant) connections may offer significant advantages for some applications, especially for Board to Board connections. The advantages usually sought in employing such connectors are:

- **Compact dimensions:** since there is no male/female contact engagement, spring loaded connections can be manufactured with higher contact density and smaller connection lengths than traditional pin/socket connection.

- **Lightweight:** following the compact dimensions, and, in many cases, the absence of a mating counterpart, spring-loaded connections can be lighter than other connection technologies, and this is a critical factor in many aerospace applications.

- **Ease of assembly:** some applications require the concurrent assembly of a large number of connectors coming from separate mechanical subassemblies. This creates alignment and tolerancing problems, which could be easily solved with spring loaded connectors. The primary negative involves the force necessary to make and sustain a large number of spring loaded connections.

- **No solder joint:** the possibility to create solderless stacking connections in a very important benefit especially in space applications, where the cost of the soldering inspection is critical and very expensive.

Space Flight Connector Requirements

The peculiar challenges of space flight components must be carefully taken in account when designing a spring-loaded connector. The main requirements can be summarized as follows:

- **Shock and Vibration:** Requirements from ESA ESCC-3401 are 20 G sine and random vibration, and 50 G shocks with no micro interruption longer than 1 microsecond. Mission requirements exceed these values more often than not with the use of explosive bolts and latches. This can drive the shock accelerations into the thousands of G's.

- **Thermal cycling:** -55°C to 125°C (or up to 150°C) are most common requirements, although some application may require a wider range of temperatures.

- **Cycle Life:** In most application the connector is mated / unmated just a few times (during testing or device assembly) – movement of the plungers may be dictated during shocks or thermal cycling.

- **Vacuum conditions:** This limits the selection of the insulation materials as well as the plating process and poses requirements on general cleanliness of the manufacturing process.

- **Absence of debris / loose particles:** Material, design and processes must be selected in order to minimize the risk of having loose particles.

- **Contact resistance:** Contact resistance requirements may vary significantly with the application. A low and stable contact resistance is ideal, although, for signaling application, may not be strictly mandatory.

- **Current rating:** Depending on the application – usually current intensity for signaling application is low (less than 1A), but higher currents may be required in some cases.

General Design Considerations

One of the main requirements for space components is to comply with outgassing limits, but this is easily addressed with the right choice of materials and processes. Materials and plating commonly employed for the construction of spring-loaded probes are compliant to such requirements and a correct selection of the insulating material is sufficient to grant the compliancy. There are some important points that need to be kept in mind in order to minimize the risk of debris and loose particles:

- **Avoid pre-plated components**: drawn parts, most commonly barrels, could be made out of pre-plated sheets; however, the drawing process will stretch the plating layers and create voids and "orange peeling" conditions. Pre-plated components will fail the gold-plating porosity test and should not be used. Plating must be applied at the end of the manufacturing cycle of any component.

- **Cleanliness of parts and assembly process**: assembly operations should be performed in as clean an environment as possible. Insulators should be ultrasonically cleaned before assembly and processed in order to minimize burrs and flash. Springs should not be lubricated.

- **Floating contact vs. double-ended contacts:** in principle, non-floating designs are preferred in order to reduce debris being generated in use, in favour of a true double ended probe. If the application requires it, single ended floating probes can be used, provided that the insulators are well controlled for burrs and flash and the gap between the contact and its cavity is large enough.

Assuming there is no corrosion in space due to the vacuum (satellites only), then the thickness of gold should not be an issue. It must be thick enough to resist wear through caused by cycle life/fretting/thermal cycles. Satellite builds can take months, if not years, to prepare for launch and if the probes are exposed to regular atmosphere during these times, then nickel migration/oxidizing might become a concern for thin gold.

In designing for shock and vibration, it is essential to have a good understanding of the application requirements. ESA-SCC-3401 requires no contact disturbance longer than 1 microsecond during sine and random vibrations (20 G) and shock (50 G, 11 milliseconds). While the accelerations are definitely not low and electrical continuity is required, the length of the allowable interruption is much bigger than in MIL/Aero standards (usually 2 nanoseconds), which in turn usually mandate lower vibration levels. In reviewing the requirements of many recent missions, it is evident that the requirements at the connector level are not in line with the needs of some applications. In particular, for what concerns payload application, the shock and vibration levels are usually much higher (often about 30 G's for vibration and requirements of hundreds or even thousands G's) although continuity during test is not strictly required at application level. It must also be noted that if the connector must have a continuous signal during the extreme shock or vibration and the signal is above 500 MHz; even discontinuities of 2 ns are not acceptable. At higher speeds, signal integrity must be monitored through Bit Error Rate testing or Eye Pattern and mask measurement must be used.
In any case, when designing for shock and vibration, general criteria are as follows:

- **Spring Force:** in principle, spring should be designed to have the strongest possible force, especially if the application requires no micro interruptions. The higher the ratio between the spring force and the mass of the plunger, the greater the probe's immunity to shock.

- **Floating contacts vs. double-ended contacts:** for the same reasons of the previous point, double ended contacts are preferred over single-ended, since the greater mass of the barrel can more easily force movement under high accelerations vs. the mass of the plunger.

- **Biasing techniques:** bias ball designs provide the best performance during vibration, by providing a more stable (and lower) contact resistance. Unfortunately the mass of the ball is a negative in high accelerations or shock environments. Most of the existing designs employ the bias plunger approach successfully; however, it has been proven that a number of designs with different biasing techniques (including bias spring and capsule design) are able to pass ESA-SCC-3401 requirements.

Smiths Connectors performed vibration tests to both MIL and ESA standards on a variety of contacts with different (bias spring, bias plunger, bias ball and capsule design – typical test setup shown on Fig. 8.). Provided that boards and connectors are properly fastened, spring loaded contacts did not show continuity issues longer 1 microsecond, and most designs did not show issues even at 2 nanosecond detector settings.
Vibration tests confirmed that the bias spring has a higher and more variable contact resistance, even during vibration, while bias ball technology offers the lowest and most stable contact resistance values (Fig. 9. shows a summary of a test performed on 4 different types of connectors).

Although not strictly required by specification test procedure, Smiths Connectors employed accelerometers strategically placed to monitor accelerations on different axis and different points on the fixture, in order to identify resonance phenomena.

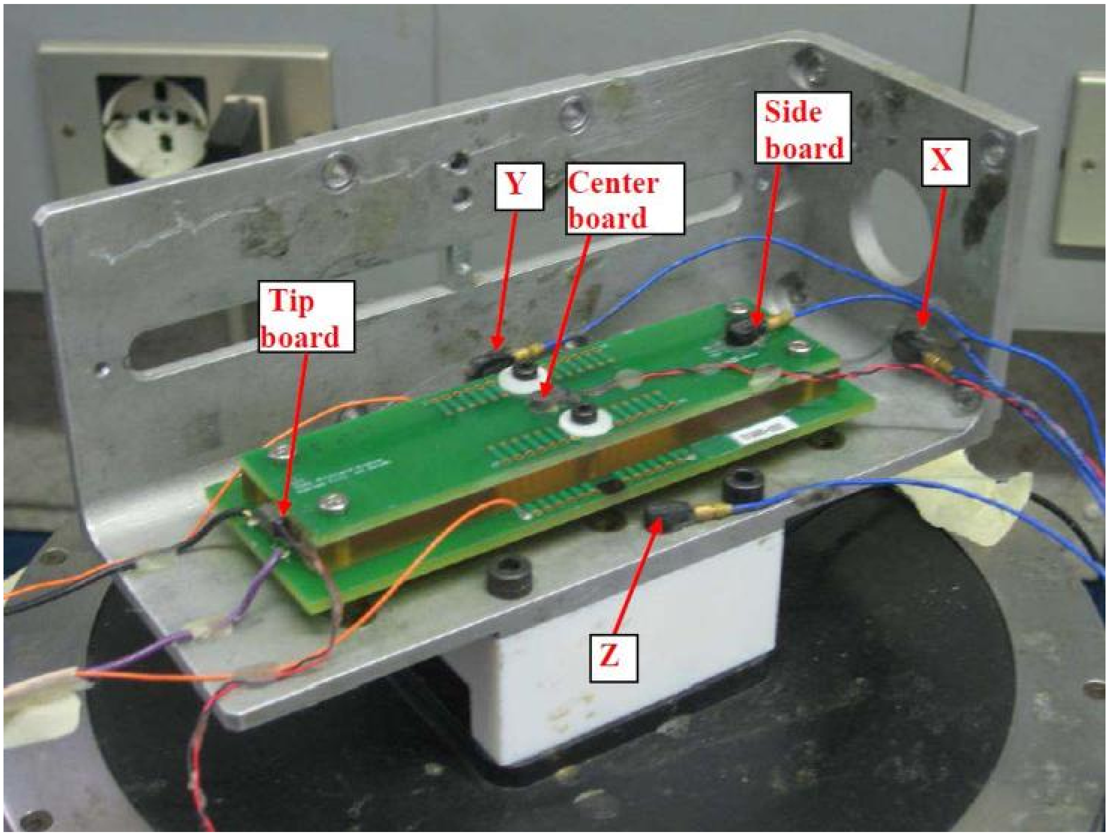


Fig. 8. Typical connector vibration test setup for an interposer connector. Apart from the feedback, additional accelerometers are placed on the fixture itself (along 3 axis), on the centre of the top PCB and at its edges (on two different axis) in order to monitor resonances.

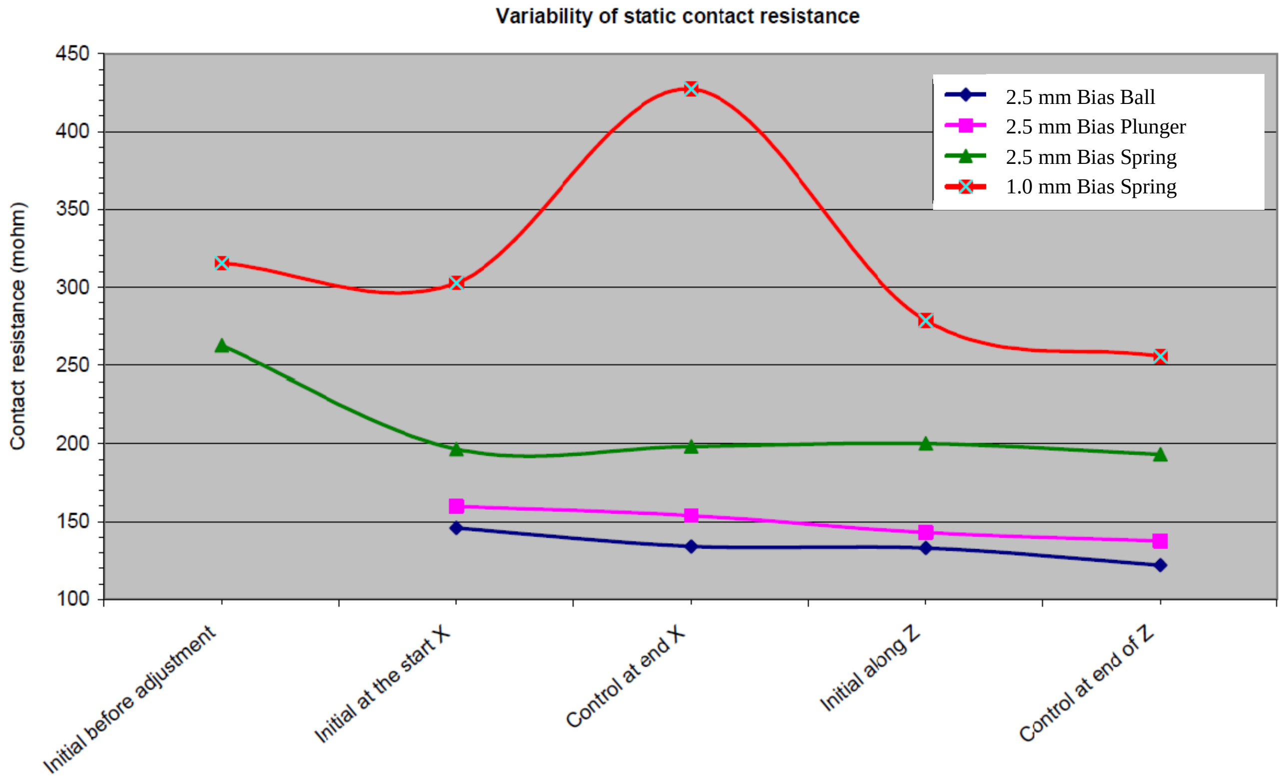


Fig. 9. Sample results during a comparative test of different board to board contacts (6mm board to board distance). On Y axis, contact resistance values for a series of 16 contacts, while the X axis, reports average values at different times during the tests (initial static test, and then at the beginning and at the end of X and Z axis). Red line is for a "bias spring" contact 1mm pitch, green line is for a 2.5mm pitch "bias spring" contact, purple line is for a 2.5mm pitch "bias plunger" while blue line is for 2.5mm "bias ball".

Designing for elevated temperatures, the spring material selection must address stress relaxation. Typical materials for the spring are Beryllium Copper, Music Wire and Stainless Steel. Smiths Connectors performed various tests exposing spring materials to high temperature storage per ESA-3401. Fig. 10. and 11. show test data for a 24 hours exposure to 260°C (for a Stainless Steel spring) and 120°C (for BeCu) Spring. Test results show that if stainless steel spring is used, temperatures up to 150°C should not be an issue, although for such springs, prolonged exposure to higher temperatures (e.g. above 200°C) are likely to generate a relaxation of the spring force and therefore, be detrimental to contact resistance and vibration performance. Music Wire springs can be safely used, if the application maximum temperature does not exceed 85°C, since the stress relaxation at 1000 hours exposure at that temperature is negligible. Beryllium Copper may be subject to significant relaxation and shall not be used.
Fig. 12. shows a partial summary of test conducted in Smiths Connectors.

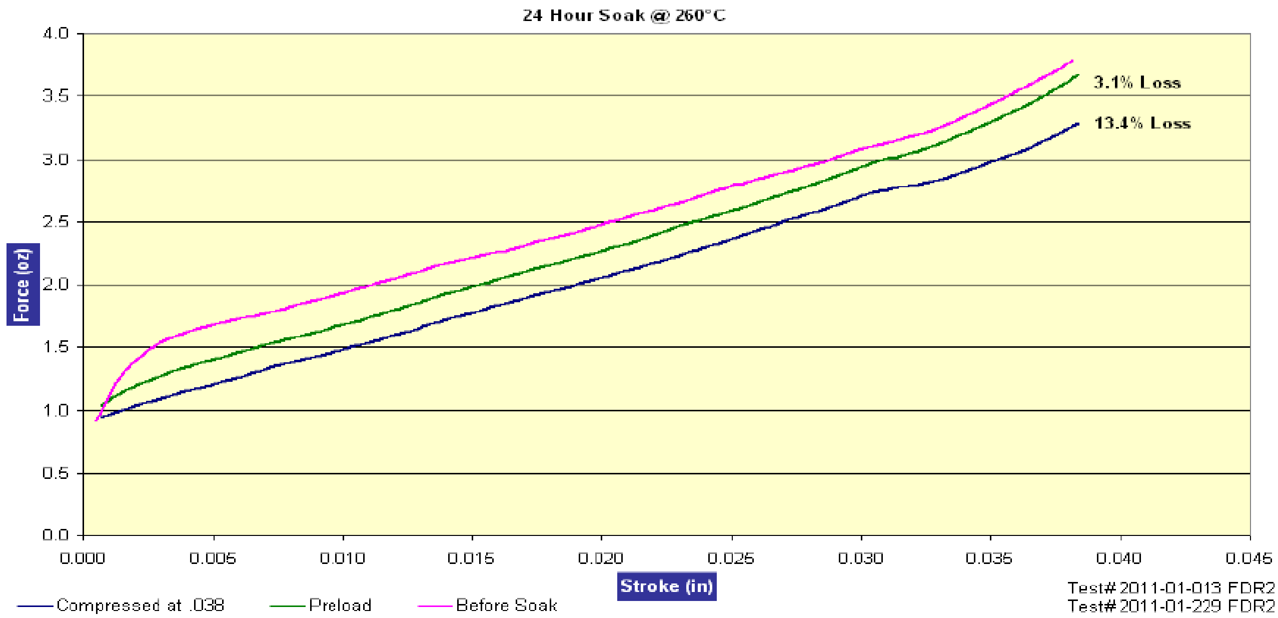


Fig. 10. Force loss for a Stainless Steel spring exposed to 260°C for 24 h (both with and without compression)

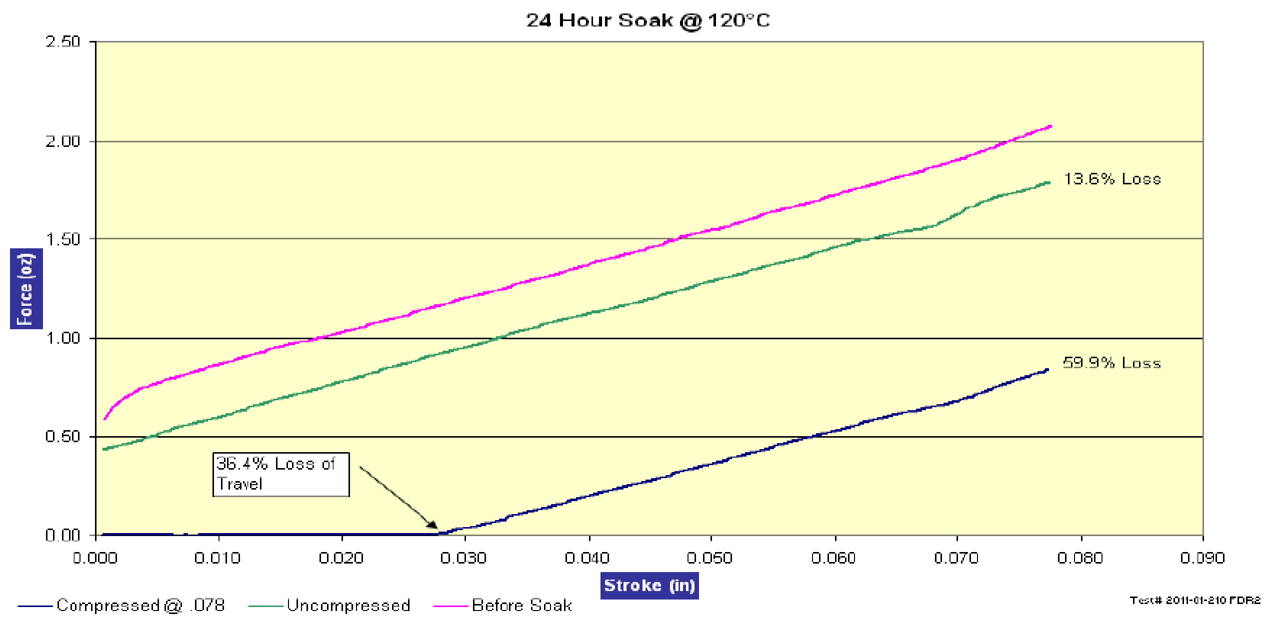


Fig. 11. Force loss for a Beryllium Copper spring exposed to 120°C for 24 h (both with and without compression). Under compression, the spring relaxes to a point in which a significant part of the travel is lost.

	Operating Temp (°C) 1 Hour	Percent Load Loss **Preload Condition** **Rated Compression**	Operating Temp (°C) 24 Hour	Percent Load Loss **Preload Condition** **Rated Compression**
BeCu Ø .005”	205	14.5	120	13.6
		64.4		59.9
S.S. Ø .004”	260	2.8	180	3.1
		12.4		13.4
Music Wire Ø .007”	120	0	85	0
		1.8		3.7

Fig. 12. Force loss for a Beryllium Copper spring exposed to 120°C for 24 h (both with and without compression). Under compression, the spring relaxes to a point in which a significant part of the travel is lost.

Space flight applications requiring high current, low / stable contact resistance and high durability must ensure that material selection, plating and biasing design is considered in detail. It should be noted that floating designs may indeed offer better performance than double ended solutions for special applications.

Contact Design:

In trying to fulfill the requirements of space flight, and address any potential issues, a good spring loaded contact design would include the following:

- Barrel:
    - Drawn barrels are preferred over machined one, as they have much smoother ID’s minimizing wear, very light as the walls are thin which also allow for a larger spring for a given outer diameter.
    - Pre-plated barrels not allowed. Barrels must be post-plated and include relevant flow-hole features.
    - Through holes for plungers need to be large enough such that the barrel edge does not scrape the plunger

- Plunger:
    - As short as possible to meet the stroke requirements, both externally and internally. The internal length needs to be devised, such that the play between plunger and barrel does not lead to excessive wear.
    - Plating: 1.27 micron gold over nickel thickness will aid in minimizing fretting/thermal cycling degradation and reduce the amount of nickel bleeding through prior to launch.

    - Biasing selection will depend on the application: if allowable micro interruptions are really short (e.g. less than 10 nanoseconds) bias plunger design is recommended. If regular ESA-SCC-3401 requirements are to be met (1 microsecond) most biasing techniques can be safely employed, as long as the spring force vs. contact resistance ratio is high enough (about 500 minimum).

- Spring:
    - Material shall be stainless steel in order to comply with full temperature range requirements.
    - Designed to be as strong as possible if continuity is required for high shock applications.
    - Plating: standard gold is needed only if used with bias plungers to minimize impact of fliers induced by interference.
    - No lubrication.

- Overall Probe Design:
    - If the connector has non-floating contacts, the barrel must be made as long as possible to meet the amount of plunger extension needed for the travel range. The plunger is kept as short as possible with all available room left for spring design and internal plunger features.
    - If a floating probe is used, the mass of the contact shall be minimized. Drawn shell versions are preferred, but must include bleed holes.
    - Cleanliness of parts and during the assembly process is essential.

<u>Connector Design and Integration Criteria:</u>

Spring loaded connectors are, by their nature, different from pin/socket connectors in the area of mating force. Pin/socket connectors require that a mating force is needed to mate the connector, but after the contacts are engaged, little axial force is required to keep the connector mated. Spring loaded contacts require that a force is constantly applied during connector operation. Connectors may or may not be equipped with fastening features, which may engage the target components. It is essential that integration of the connector in the application device is carefully considered. Apart from common requirements for space applications (e.g. the proper selection of insulator material in order to avoid outgassing issues), it is important to consider what follows:

- “Hard stop” features must be included in the connector: connector shall be designed in such a way to prevent over compression of the contact (i.e. plunger going beyond its maximum travel) and mechanical stop feature should be included to prevent that from happening, even by chance or during testing.

- Fastening features: it is important that they are designed to minimize the relative movement of the plungers and targets (usually gold pads on the PCBs), especially if continuity is to be maintained during shock and vibration. Note that, in many cases, disconnection on the Z axis (mating direction) is a rare event, while slippage of the plunger off the target pad in the X/Y plane is a possibility, if the pads are small.

- Maximize pad dimensions in the target hardware. In order to avoid or minimizing slippage or alignment problems, the target hardware should feature pads which are as large as possible.

- Guiding features / dowel pins: if possible, the design should include alignment features to ease the assembly and reduce relative movement along the X/Y plane. If alignment features cannot be included, it is mandatory to perform a Tolerance Analysis to check if the system design allows for that.

- Connector fastening shall be such that the connector is “bolted” onto the printed circuit and the stiffening elements of the device. In some cases, separate stiffeners may be required.

- Mechanical resonances on the application device / PCB may result in the connector being exposed to accelerations much higher than its intended (or tested) operating conditions. This shall be taken in account in the design of the device.

- It is advisable that a finite-element analysis is performed upfront to check that during shock and vibration the displacement keeps the spring loaded connectors within their working parameters. This analysis must include the possible over compression of the probe, which could result in the plunger being fully compressed into the barrel causing sticking of the probe.

High Speed Connector Design

Spring loaded interposers provide strong signal integrity performance as compared to traditional pin and socket systems. This is due to the shorter path length required by spring probes and the great uniformity of the spring probe cross section minimizing the variation of the impedance. A major consideration in using spring probes for high speed and RF applications is the requirements for grounding. This affects both the impedance of the system through the inductance and capacitance and the amount of EMI radiation into and out of the connector.

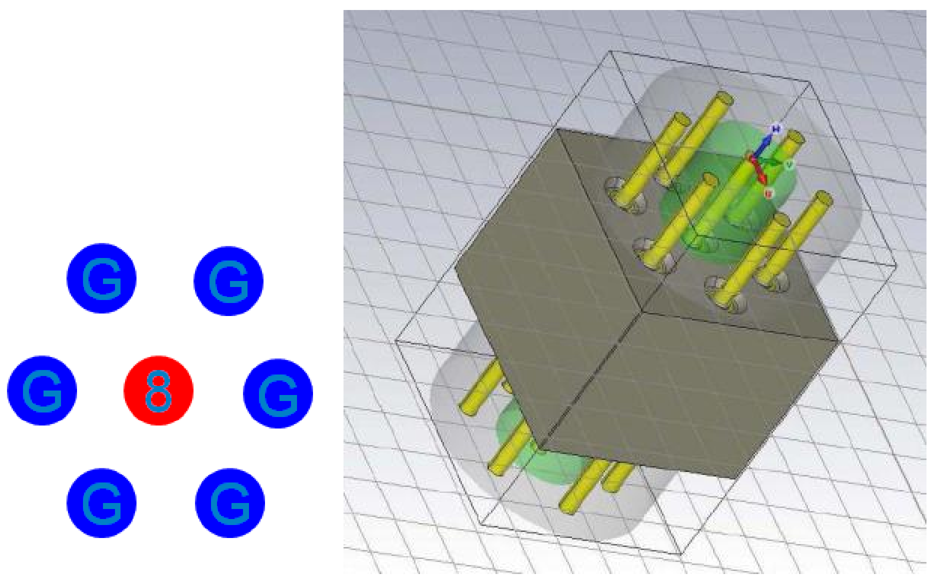


Fig. 13. Example of design of a 50 ohm single ended design – a signal contact is surrounded by a number of return pins. Once the contact selection is frozen, distance of the return is first calculated with an approximate formula – design is iterated through finite element simulation and finally baked into the connector design once the project criteria is met.

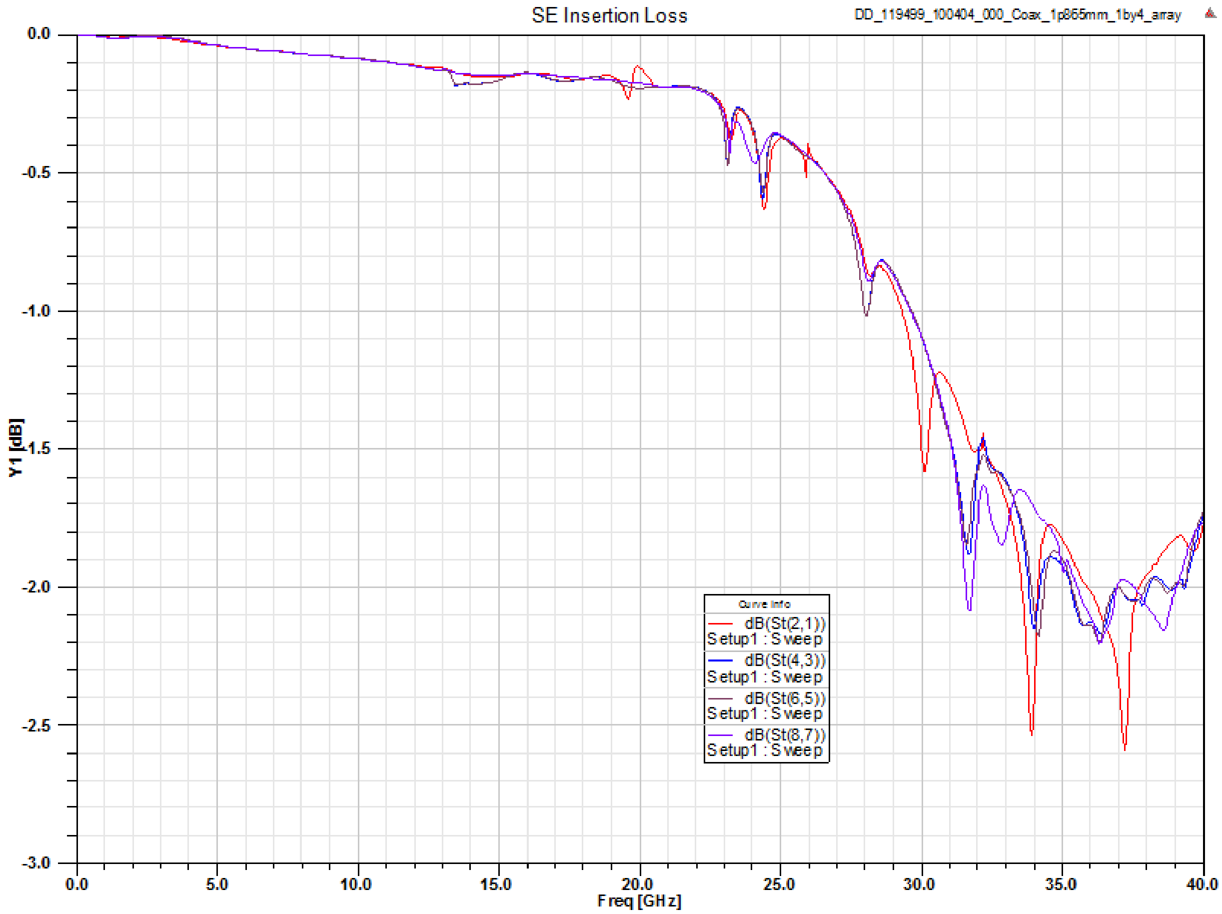


Fig. 14. Single Ended RF Interconnection Simulation

Fig. 13. shows a quick summary of the design process for a single ended RF interconnection, in a so-called “pin field” arrangement (that is a number of spring loaded pins are arranged to mimic a “coaxial” line – with a number of return pins strategically placed at a given distance from the signal pin). After the contact has been selected, on the basis of its mechanical characteristics, and insulator material has been identified, single ended line design starts with an approximate formula then a draft 3D model is created and design is iterated through finite element simulations as demonstrated in Fig. 14. Once the design criteria are met, the design is finalized into the connector drawings.

As there is no engaging counterpart for the contact, but just a pad on the PCB, contact placement has no significant restrictions and can be tailored to a high degree of accuracy. Also, in some pin/socket contacts, there may be significant difference between the male and female pins leading in a discontinuity in the signal impedance. In addition, with the spring probes interconnecting on surface pads of the PCB, small diameter blind vias can be used in the PCB rather than larger diameter plated through holes, which can add a large amount of capacitance in the transmission line. “Pin field” solutions generally offer good performance, but in some very demanding applications shielding is less than optimal as there may be leaks due to gaps between the connector and the PCB, and in between the return pins.

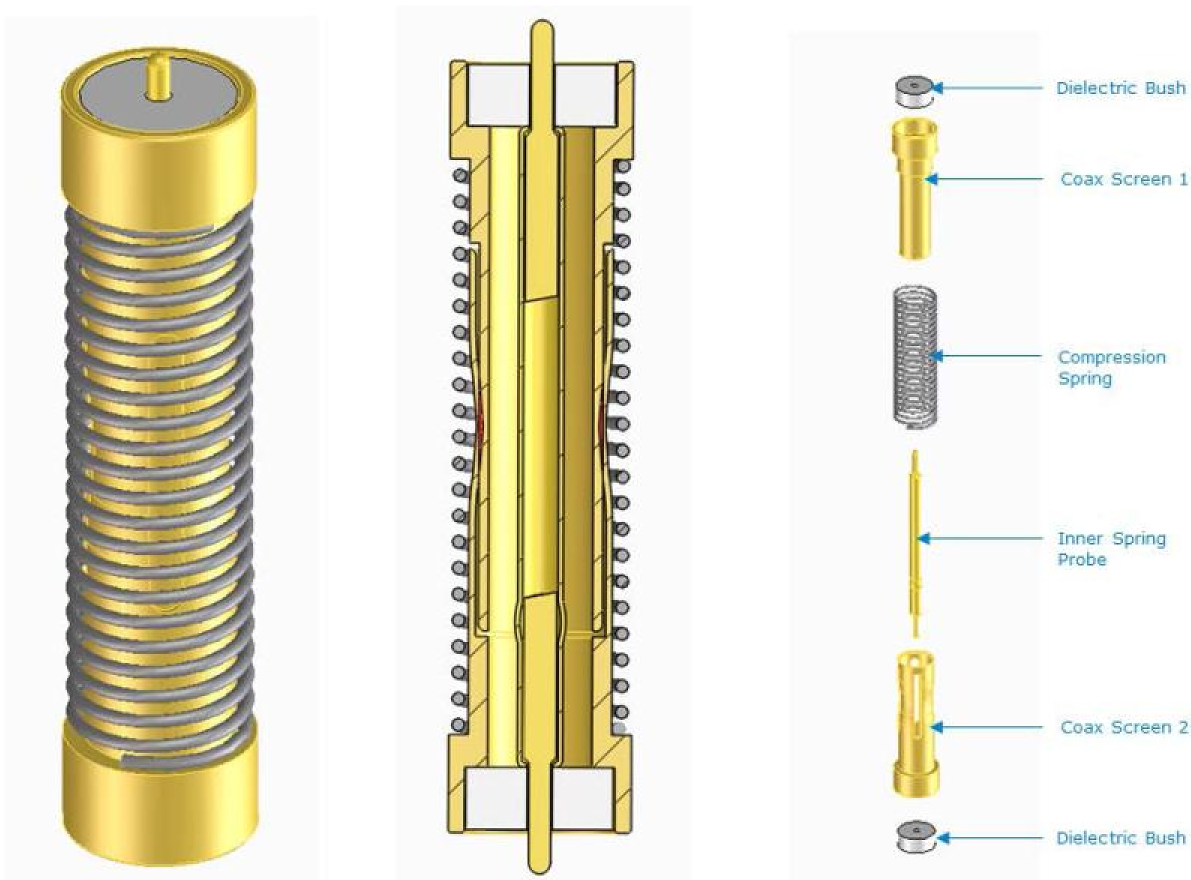


Fig. 15. Example of proper spring loaded coaxial design

For applications requiring 360º shielding for EMI or improved impedance control, proper shielding needs to be provided, with continuous metal shells. Spring loaded coaxial lines can also be obtained by press fitting spring loaded contacts into cylindrical insulators, which can in turn be inserted into continuous metal shells.

For other cases, Smiths Connectors has developed proper spring loaded coaxial contacts, in which the return path is provided by continuous, spring loaded metal shields.

<u>Conclusion</u>

Spring probe contact technology can provide significant benefits in space and satellite applications over traditional pin and socket connector systems. These benefits include the following: smaller packaging volumes, higher density of interconnect, higher speed transmission, reduced weight and rugged performance to meet the rigors of the launch and space environments. Smiths Connectors has developed, tested and deployed a number of solderless interposer connector solutions for many space flight applications. Based on this experience, it has been determined that an advanced level of knowledge and understanding of the technology is essential for its effective use in these areas. Proper selection of materials and biasing techniques are paramount for the correct selection and design of the contacts, and connectors for the space system. It is also critical to fully understand the application requirements to best balance the design trade-offs to make the best implementation of spring probe contacts and connectors to meet the reliability and efficient design needs of today's satellite and space craft challenges.