JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 38, No. 4, July–August 2001

Design and Testing of Reduced-Stiffness Umbilicals for Space Station Microgravity Isolation

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We detail efforts on minimizing power electrical umbilical stiffness on the International Space Station active rack isolation system to improve system performance. The effects of wire conductor material, winding configurations, electrical insulation materials, and umbilical geometry were investigated. Dynamic sine-sweep measurements were made on a special test rig having an extremely low coefficient of sliding friction value of $\mu = 5 \times 10^{-6}$. Transfer function analyses were used to assess the stiffness of current configurations and various alternates. Because of the very low stiffness of some candidates, the effect of 1-*g* umbilical sagging on the measurements had to be considered. A detailed comparison is provided of the properties of the different umbilical candidates tested. Several candidates provided dramatic dynamic stiffness reductions.

Nomenclature

F_{com}	=	commanded force, N
f	=	natural frequency, Hz
g	=	acceleration caused by gravity, m/s^2
k	=	spring constant, N/m
k_u	=	umbilical spring constant, N/m
m	=	slider mass, kg
m_i	=	mass of ith slider, kg
n	=	number of cycles
$\ddot{x}$	=	acceleration, m/s^2
x_0	=	initial displacement, m
Δx	=	displacement, m
μ	=	coefficient of sliding friction (N/N)

Introduction

ONE-HALF of the scientific mission of the International Space Station (ISS) is to host microgravity research. Analytical predictions of vibration environments (Fig. 1) indicate that required levels at experiment locations can potentially be exceeded.[1] Two potential ways to reduce these vibratory disturbances are to reduce the levels of the disturbance sources, and to isolate sensitive payloads. Both of these methods are being pursued by the program.

The ISS program has made the decision to isolate science experiments by mounting them on racks utilizing an active rack isolation system (ARIS) to minimize disturbances and provide a true microgravity environment. The performance of the vibration isolation system is dictated by several factors: the ambient vibration environment, sensor quality, control system dynamics and bandwidth, and the stiffness of umbilical connections attached to the isolated platform.

Methods of Disturbance Reduction

The operating principle of the ARIS rack is to allow the sensitive payload to float freely, not connected to the base structure. Because of practical needs for power, data transfer, cooling, etc., the payloads on the rack must be connected to ISS with umbilicals providing these services. In addition, biases in the umbilicals and disturbances from outside require the addition of a control system that nullifies platform motion and keeps it from bumping into support structure. The reader interested in microgravity vibration isolation control systems is referred to multiple references in the literature.[2,3]

The components of a generic isolation system are shown schematically in Fig. 2. Even though the rack is allowed to "float" away from supporting structure, space station disturbances may still reach the isolated payload through the umbilical connections, air currents, acoustics, and via the control system. Of these paths only the umbilicals are addressed in this work.

The umbilical cables are critical to the isolator's performance. They can serve as an "energy conduit" to transfer vibrations from the support structure to the floating isolated rack, and their stiffness resists commands from the control system, potentially worsening performance. Reduced umbilical stiffness leads to a lower passive natural frequency and less control system "work." Higher gain levels can offset the effects of stiffer umbilicals and provide similar isolation performance, but they may not be available (as in the case of the ARIS, where bandwidth is limited as a result of other considerations).

Although the work presented here is focused on the reduction of umbilical stiffness, performance is also affected by bias force and linearity. Bias force is a quasi-steady force produced by umbilicals whose natural equilibrium position is not the desired platform position. Bias forces consume power necessary to keep the platform nominally centered within its sway space and affect the dynamic range that the control system must be capable of producing. Bias force is a byproduct of the umbilical manufacturing process and storage scheme, but one can infer that reduced stiffness is likely to reduce its magnitude. Linearity affects the control system's design and analysis.

Early measurements carried out for the ARIS program[4] showed interesting force vs stiffness characteristics. Onboard each ISS equipment rack, the two electrical power umbilicals contribute about half of the total umbilical stiffness. The purpose of this work was to measure and reduce this stiffness.

An illustration of the ARIS rack and its umbilical system is shown in Fig. 3. The ARIS housing on the right is allowed to float away from its support structure (not shown) but is connected with actuators and umbilicals. The numerous umbilicals provide disturbance paths; the composite stiffness of the umbilicals is dominated by the two power umbilicals. These umbilicals must transfer high power levels (up to 6 kW each) and their associated high currents, so heavy-gauge wire is required. These cables contribute half of the composite stiffness and thus are targets for performance improvement by stiffness reduction.

Reducing the stiffness of just these two umbilicals would help to enhance performance considerably. Hence, the goals of this performance improvement effort were set as follows: 1) accurately measure the stiffness of existing umbilicals; 2) examine ways of reducing stiffness, including wire construction (materials, winding, insulation) and geometry; 3) design and fabricate candidate low-stiffness umbilicals; and 4) test and evaluate candidates vs baseline designs.

Received 30 June 2000; revision received 2 February 2001; accepted for publication 10 February 2001.

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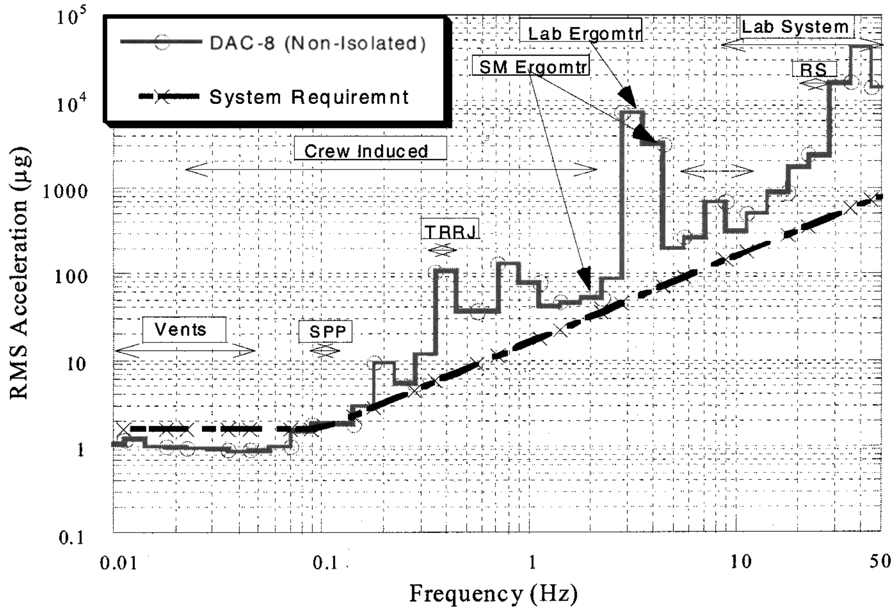

Fig. 1 Predicted ISS vibration environment.

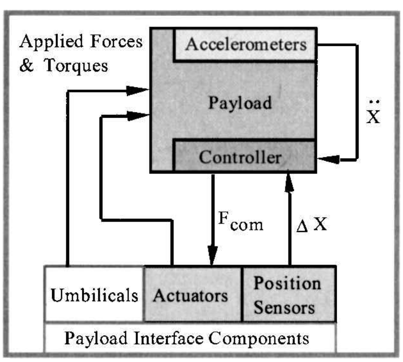

Fig. 2 Disturbances can be reduced by decoupling from base structure.

Table 1 Existing cable types and possible replacements

Wire type	Existing configuration	Lower stiffness replacement
4 gauge	SSQ21652 NSFW-SIL-4 05973: 1064 strands of #34 gauge[a] nickel-plated copper; pressure extruded insulation	1666 strands of #36 gauge[b]; loose "hosed" insulation (silicone or expanded Teflon)
8 gauge	SSQ21652 NSFW-SIL-8 34157: 665 strands of #36 gauge[b] nickel-plated copper; pressure extruded insulation	1666 strands of #40 gauge[c]; loose "hosed" insulation (silicone or expanded Teflon)

[a]0.1601-mm diam. [b]0.1270-mm diam. [c]0.0799-mm diam.

Umbilical Stiffness Considerations

The mechanical stiffness of an umbilical is a function of many parameters, including the wire's conductive material; the cable's internal twisting schedule; insulation; and umbilical geometry (whether looped or unlooped, how the cable routes between the two ends).

Conductive Material

The umbilical cable's electrically conductive material affects the overall stiffness: two critical parameters are the modulus of elasticity and cross-sectional area. As one might expect, a reduction of conductor area yields less bending stiffness (the stiffness can be shown to be roughly proportional to the fourth power of the conductor's radius). However, the conductor's cross-sectional area is determined by power requirements and the wire material's electrical conductivity, which sets a minimum area for a given material.

Wire conductors are normally made from copper or silver. It appeared that the higher conductivity material (silver) had the potential for reduced cross-sectional area, and so we looked at silver conductor strands to replace copper ones. This idea was later rejected for several reasons, including a lack of a source of fine-stranded silver conductor and potential electrochemical problems with existing connector hardware.

Internal Twisting "Schedule"

A wire's bending stiffness depends on the number of strands in the wire and how the strands are twisted. A solid conductor is obviously much stiffer than a group of finely stranded wires bundled together with the same total cross-sectional area. If conductor area is held constant, it can be shown that the cable bending stiffness is inversely proportional to the number of strands in the cable.

Electrical wire is manufactured in a manner similar to rope, where bundles of small fibers are systematically wound into larger bundles and twisted together. The number of bundles in the cable, the twist direction of bundles, and the twist direction of rope all affect ultimate stiffness but were not addressed in this study.

Parameters of the ARIS baseline 4-gauge wire (all gauges given here are American Wire Gauge, or AWG) and a potential replacement wire with equal cross-sectional area (same current capacity) are listed in Table 1. (Note that a numerically higher gauge value indicates smaller internal strand diameter.) A similar replacement with finer stranding was found for the 8-gauge wire used on some lower-power umbilicals. The increased strand count was expected to produce a 44% stiffness reduction utilizing the parameters shown in Table 1.

The power umbilical cables provide functions similar to U.S. residential wiring, with "hot," return or neutral, and ground connections. The umbilicals are configured in one of two ways. The ground is always of 8-gauge wire; the hot and neutral may be of either 4- or 8-gauge cabling. Hence we had to test both 448 (referring to two 4-gauge and one 8-gauge wire) and 888 (three 8-gauge wire) cable configurations. The 448 configuration was designed to transfer 6 kW of electrical power, whereas the 888 configuration transfers 3 kW.

Insulation

The baseline standard ISS wire has pressure-extruded, silicone insulation. When the insulation is extruded onto the cable, its material fills voids between adjacent wire bundles resulting in increased cohesion between the wire bundles and insulation (Fig. 4), especially

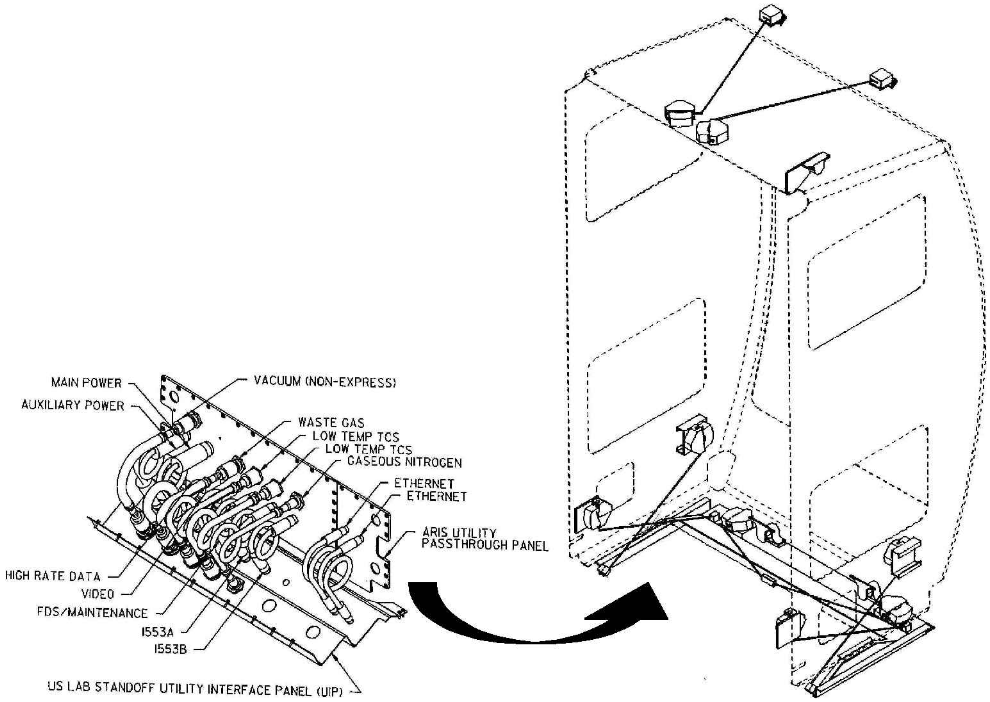

Fig. 3 ARIS housing and umbilical details.

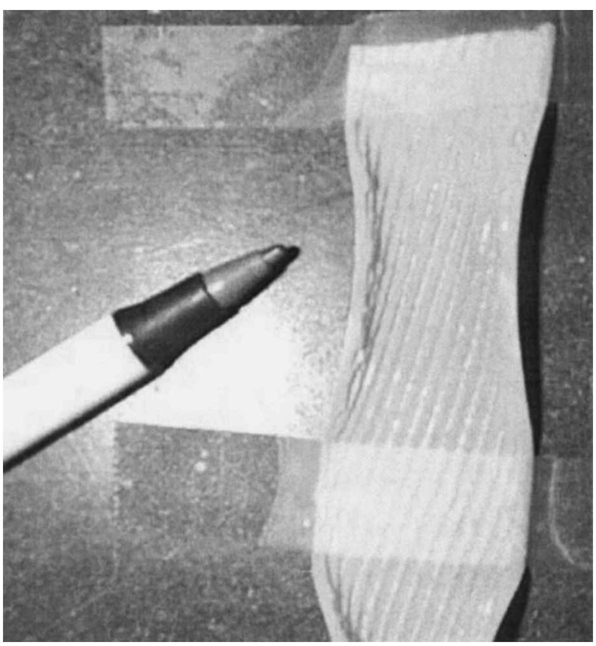

Fig. 4 Baseline wire's extruded insulation "grabs" the wire bundles, providing unwanted stiffness.

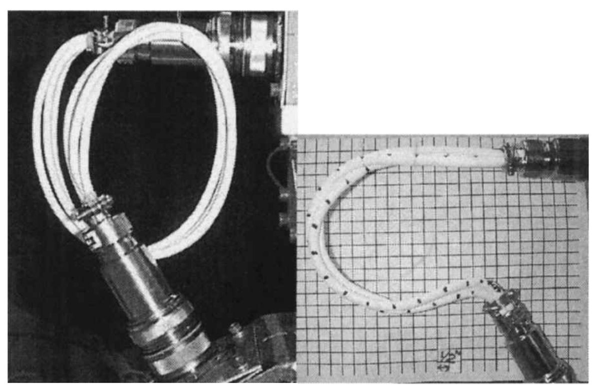

Fig. 5 Looped and unlooped umbilical configurations.

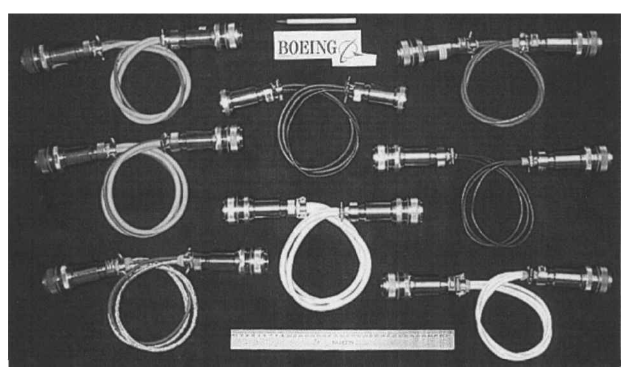

Fig. 6 Looped umbilicals tested.

at low amplitudes. Replacing this insulation material with looser insulation was expected to reduce stiffness further. Candidate wiring with sleeved silicone insulation and sleeved expanded Teflon® [polytetrafluoroethylene (PTFE)] insulation was procured for testing.

Geometry

In an effort to reduce stiffness, the baseline design connects the two ends with a complete loop, as shown to the left in Fig. 5. The looped umbilicals that were tested are listed in Table 2 and shown in Fig. 6.

An unlooped configuration was also possible, as shown on the right-hand side of Fig. 5. Unlooped umbilicals were attractive in that more clearance was available between the different umbilical cables, and it was felt that it would be easier to maintain the shape of an unlooped umbilical to preclude contact. We investigated the possible stiffness reductions of unlooped umbilicals that would possess less total length. Details of the unlooped umbilicals tested are given in Table 3 and Fig. 7.

Umbilical Stiffness Testing

Because of the criticality of the dynamic performance of the isolated platform, it was decided to carry out dynamic measurements and use them to infer stiffness. Budget limitations and limited

Table 2 Looped umbilical configurations tested

Wire configuration	Baseline stranding, insulation, twisted	Baseline stranding, insulation, untwisted	Baseline stranding, insulation, removed	Higher stranding, hosed silicone	Higher stranding, hosed Teflon
448	✔	✔	✔	✔	✔
888	✔	——	——	✔	✔

Table 3 Unlooped umbilicals tested

Wire configuration	Baseline stranding, insulation	Higher stranding, hosed silicone	Higher stranding, hosed Teflon	Length variation
448	✔	✔	✔	✔(10–19 in.; 25.4–48.3 cm)
888	✔	✔	✔	——

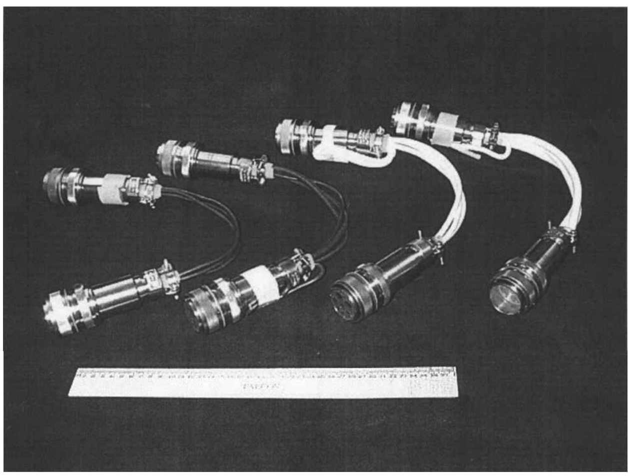

Fig. 7 Selected unlooped umbilicals.

hardware resources forced us to consider only single-degree-of-freedom testing, although it would have been preferable to obtain the full stiffness matrix.

As shown in Fig. 8, our test apparatus consisted of two sliding platforms, of mass 3.4 kg (8 lb_m) and 21 kg (50 lb_m). One accelerometer was mounted on each of the sliders. The smaller slider was connected to an ARIS electromagnetic actuator used to provide a disturbance input. The umbilical under test was used to connect the two sliders. By applying a known acceleration to one end of the umbilical and measuring the response at its other end, a measurement of acceleration transfer function and the dynamic stiffness could be made. The peaks of the transfer function were used to identify the natural frequency of the umbilical being tested and to calculate stiffness, which may be used to predict ARIS performance.

A custom electronic box converted acceleration to digital signals and to null out accelerometer dc bias (a 1-μrad tilt produces an acceleration of 1 μg on an accelerometer). A HP3566 structural dynamics analyzer was used to acquire data and compute transfer functions. Compressed dry nitrogen gas from six pressurized bottles was supplied to gas bearings in the sliders in order to provide an extremely low-friction surface.

With the low umbilical stiffnesses present in the design, the test apparatus' friction needed to be minimized as much as possible. A glass pane was placed under the larger air slider to reduce friction. To measure the actual friction coefficient, the umbilical cable was disconnected, and a spring was attached to the larger slider. After "plucking," the linear decay of the oscillations was used to calculate[5] the coefficient of sliding friction using Eq. (1):

$$\mu = kx_0/2nmg \quad (1)$$

These decay tests used a small initial displacement yet still took as long as seven to eight minutes to complete, indicating a very low effective sliding friction coefficient of 5×10^{-6}. Therefore as long as the slider motion exceeds a few microns, the friction force will be negligible compared to the umbilical force.

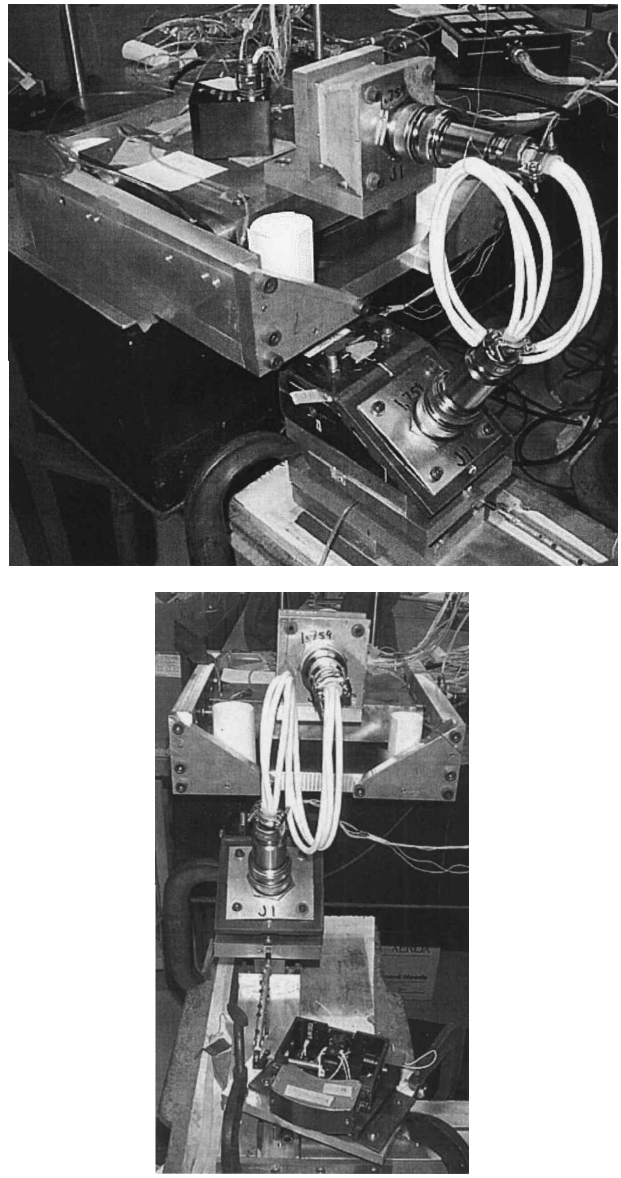

Fig. 8 Typical test setup.

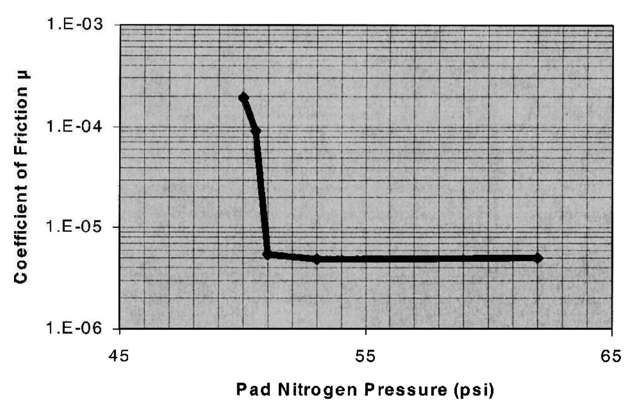

Fig. 9 Effect of supply pressure on friction coefficient.

Tests were run with varying regulator pressure to see the effect of pressure depletion on friction. This resulted in the data presented in Fig. 9, giving an effective lower-end pressure for low friction. The abrupt transition is where the slider "bottoms out."

One major problem area was the effect of gravity on the more flexible umbilical cables. The baseline cables possessed enough internal stiffness that gravity presented little problem, but the sagging of the more flexible umbilicals (Fig. 10) became very noticeable, and it was believed that the sag would significantly affect the cable dynamics.

The left-hand photo in Fig. 10 shows the extreme sag present in an unsupported PTFE-jacketed cable. We developed a simple support to suspend the loop as shown on the right photo of Fig. 10 and in Fig. 5. The support removed the sag so that the shape of the umbilical approached that achieved in orbital conditions.

The support cable was tied to the high-bay room's ceiling and contributed negligible stiffness to the system because the restoring force caused by cable stiffness dominates that caused by pendulous displacement of the suspended cable mass. The equivalent stiffness of the support cable can be shown to be on the order of 0.3 N/m, much less than the effective stiffness of the umbilicals (on the order of 50 N/m). Thus, the effects of the suspension will be negligible in these measurements, and the behavior of the umbilical under these tests is expected to approximate those likely to occur during orbit.

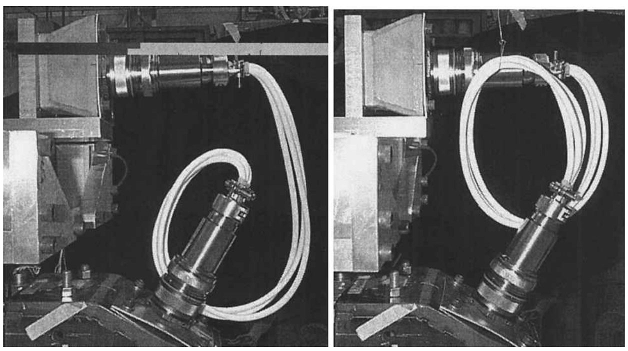

Fig. 10 Effects of gravity on loop.

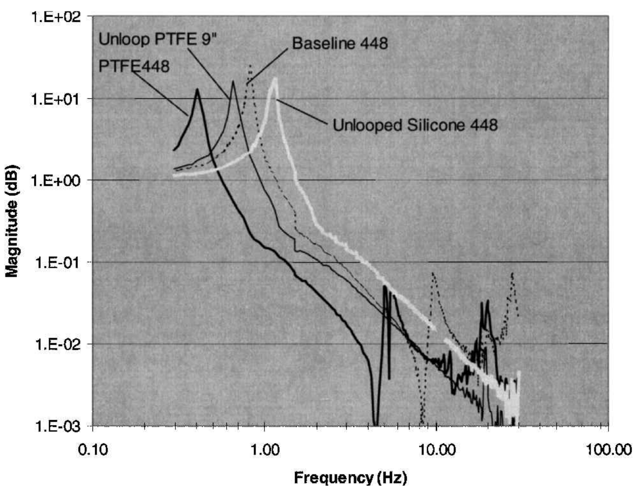

Fig. 11 Frequency responses of looped and unlooped umbilicals compared.

Results

Figure 11 shows some of the results of transfer function testing with both looped and unlooped umbilicals of various configurations. Some of the unlooped designs turn out to be stiffer than the baseline 448 umbilical design, whereas others turn out to be less stiff. All are stiffer than the looped PTFE 448, which showed the lowest frequency measured.

Natural frequencies are indicated by maxima of the response curves and can be used to calculate umbilical stiffness. To first order, the slider–umbilical–slider assembly can be considered a free–free mass–spring–mass system. If the umbilical mass is lumped into that of the sliders, the umbilical stiffness can be calculated[6] from Eq. (2):

$$k_u = 4\pi^2 f^2 \left(\frac{m_1 m_2}{m_1 + m_2} \right) \tag{2}$$

As shown in Table 4, the stiffness of the baseline 448 umbilical calculates to about 73 N/m, and the stiffness of the high-strand-count, PTFE-insulated 448 umbilical works out to be about 18 N/m. Because the higher strand count was expected to reduce stiffness by about a factor of two, we see that the insulation change reduced it by another factor of two.

The effect of insulation can also be determined by comparing the unlooped 9-in. (22.9-cm) PTFE and unlooped hosed silicone 448. These had the same high strand count and similar unlooped lengths. The stiffness was reduced by about a factor of three. Because

Table 4 Calculated stiffness for tested 448 cable configurations in Figs. 11 and 12

Configuration	Stiffness, N/m
Unlooped hosed silicone	143
Baseline	72.3
Unlooped 9-in. (22.9-cm) PTFE	47.3
Unlooped 10-in. (25.4-cm) PTFE	47.3
Unlooped 12-in. (30.5-cm) PTFE	31.0
Unlooped 14-in. (35.6-cm) PTFE	27.5
Unlooped 17.5-in. (44.5-cm) PTFE	25.2
Looped PTFE	18.1
Unlooped 19.5-in. (49.5-cm) PTFE	15.5

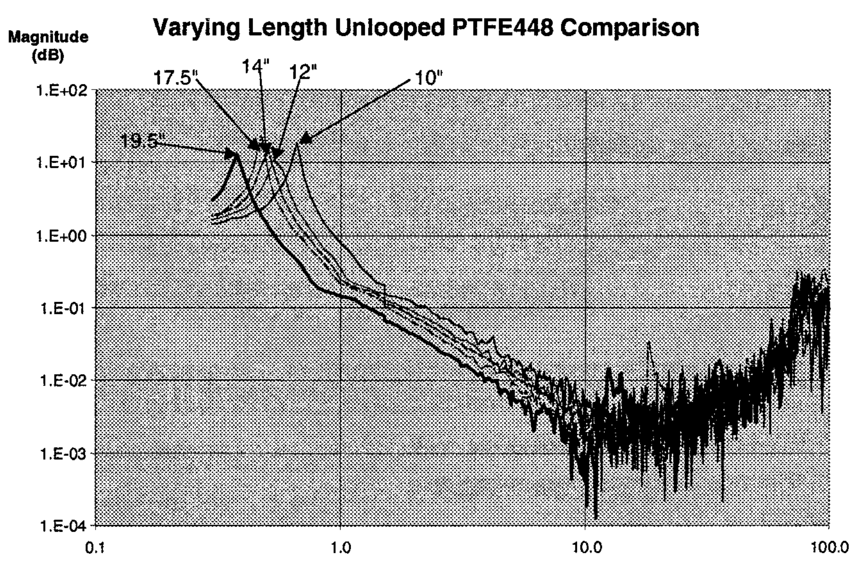

Fig. 12 Comparison of unlooped umbilicals with varying length.

the stiffness reduction as a result of the insulation change was the same order of magnitude as between PTFE and pressure-extruded silicone, it can be concluded that for small amplitudes the insulation stiffness is dominated by the "stiction" between the insulation and the wire.

Comparing the unlooped, 9-in. (22.9-cm)-long PTFE 448 with a (looped) PTFE 448 shows that looping reduces stiffness by about a factor of 2.6. Although this stiffness reduction is attractive, it introduces more dynamics in the cable. In 1 g a pendulous mode was observed in the baseline cable at about 10 Hz. This mode is the loop swinging into the loop axis. This mode would not appear in microgravity, but the potential for reduced dynamics and resultant cable-to-cable contact make an unlooped configuration worth investigating.

Figure 12 shows the results of transfer function testing of unlooped umbilicals. One can see a progression of decreasing stiffness with linear umbilical length increases. In this series of testing, the worst unlooped higher strand-count PTFE umbilical [10-in. (25.4-cm)] arc length still had less stiffness than the baseline 448. The longest unlooped umbilical, 19.5 in. (49.5 cm), attained a stiffness of 15.4 N/m, almost a factor of five reduction compared to the baseline.

In all cases the baseline wire stranding had higher stiffness than an equivalent length of the higher strand count of equivalent area. The baseline extruded silicone insulation possessed the highest stiffness, followed by the hosed silicone, whereas the expanded PTFE insulation had the least stiffness for a given cable size.

In Fig. 12 the noise above 10 Hz can be attributed to test fixture dynamics because it was observed in measurements made with no umbilical connecting the two sliders.

A comparison of Figs. 11 and 12 shows noticeable differences between looped and unlooped umbilicals. The unlooped umbilicals appear to have less dynamics at the higher frequencies. It is believed that the looped umbilicals possess dynamics in this range because of the looping itself having stiffness or pendulous modes as a result of gravitational forces. However, it is not clear that this behavior will be repeated on orbit.

Conclusions

Testing indicates that significant stiffness reductions can be obtained by a redesign of the ARIS power umbilicals. Stiffness was reduced by about a factor of two by increasing the cable strand count, and a lower-friction insulation was shown to reduce the stiffness by another factor of two. Umbilical stiffness was also shown to depend on cable length; depending on configuration and geometry, the unlooped umbilicals were found to be more or less stiff than looped ones.

The best umbilical candidate had about one-fifth of the stiffness of the baseline design, a significant reduction.

In our ground testing in a 1-g situation, unlooped umbilicals appear to possess less high-frequency dynamics. This appears to make them more desirable for an isolation system: the control system can be designed to have higher bandwidth for better high-frequency performance. They also have the potential for better control of configuration to minimize interference or contact with other umbilicals.

A flight experiment of the baseline and lower-stiffness umbilicals is planned to verify performance of ARIS with both the baseline and low-stiffness sets. Flight performance will be used to select best candidate for production of the flight articles.

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