Flex-Capsules for the Roman Space Telescope High Gain Antenna Gimbal

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ABSTRACT

The Cable Wrap mechanism has been traditionally used for feeding power and telemetry through each gimbal actuator exiting at the gimbal output flange. Such a mechanism had often utilized round wire bundles or a multitude of single insulated conductors woven together flatwise to handle the angular rotation. Though flexible printed circuit board (PCB) is not a new technology, it was decided to implement it for the Roman Space Telescope (RST) High Gain Antenna Gimbal in an effort to improve reliability with consistency of manufacture and to save mass and minimize required volume. This paper provides a description of what we term Flex-Capsule (a similar vendor flight development is termed Twist Capsule), discusses the reasoning behind choosing a new engineering development over maintaining heritage, and includes commentary pertaining to life cycle analysis, electrical performance, and flexible PCB lubrication. Lessons learned from the design, analysis, and test campaign are also included. The conclusion is that benefits of pursuing the Flex-Capsule over heritage Cable Wrap have been realized.

1 REJECTION OF HERITAGE CABLE WRAPS

Past in-house gimbals have all had Cable Wraps of varying types so there has been significant flight heritage. Nevertheless, there has been a history of operational anomalies arising during testing which we will reflect upon by addressing existing Cable Wrap design concerns.

The nature of Cable Wraps is such that bundle or wire flexing behavior can be inconsistent from one build to another and that bundling of conductors is a labor intensive process that is subject to variability. This is true of both the round wire bundle and flatwise ribbon cable wrap varieties. Round wire bundled Cable Wraps are typically of short length and large diameter while flatwise ribbon Cable Wraps are of slightly less diameter but of increased length. In the round bundle configuration, typically used for two-axis gimbal pointing systems, electrical service groupings are determined for each capability required on the far side (or down stream) of the articulated joint. For example, primary and redundant motor power twisted, shielded triplets can be grouped in an overwrapped round bundle. Similarly, sensors like optical encoders, resolvers, etc., as well as heater and temperature sensor services can be grouped into individual twisted, shielded subgroups and overwrapped. In each case, only a single bundled round wire cable is allowed per Cable Wrap "pancake" thereby requiring multiple slices to be built up to accommodate the required number of conductors (See Fig. 1). Flatwise ribbon unshielded Cable Wraps are most commonly used on single-axis pointing systems, typically solar array drives (See Fig. 2).

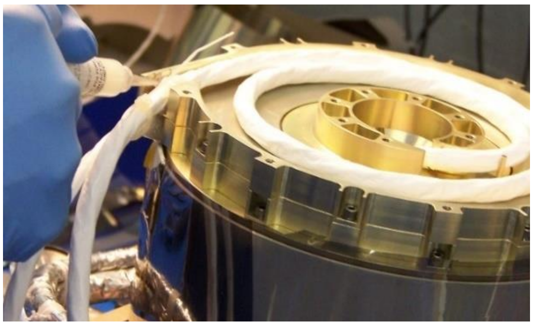

Figure 1. Lunar Reconnaissance Orbiter Flight Pancake Cable Wrap Assembly (In Process)

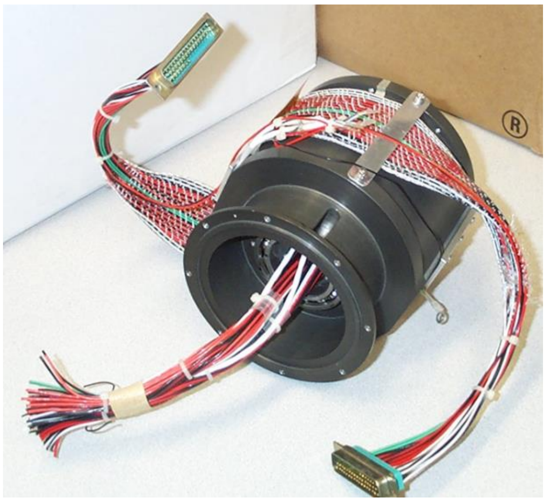

Figure 2. Heritage Flatwise Cable Wrap

The first reason for pursuing utilization of flexible PCB is the consistency of the flex element in that a single manufactured unit replaces a bundle of either variety. The expectation is that flex element behavior will be very consistent from one build to another, regardless of the number of conductors per element, improving reliability and increasing the credibility of a life test.

The second reason for utilizing flexible PCB is to reduce the size of the Cable Wrap to the more compact Flex-Capsule. The geometry of the flex element includes conductors that are thin and wide, which is a characteristic of PCB conductors. This is ideal for the need to flex in terms of minimization of stress since trace thickness is thinner than wire diameter. The same total conductor area of a standard circular stranded bundle covered with insulation will see higher stresses, reducing the number of life cycles to flex a given radius, or would require a larger flex radius to match the number of life cycles of the flexible PCB conductors.

2 FLEX-CAPSULE BENEFITS

Expected benefits are numerous including increased reliability from consistency of manufacture, elimination of labor-intensive custom harness manufacture, reduction of the parts count, much more compact design, reduction of mass and volume, lower running torque, especially when cold, and much simpler assembly. With less likelihood of anomalous behavior arising during testing, potential associated schedule slip is mitigated. Though there was some uncertainty regarding shielding effectiveness of flexible PCB and the "unknown unknowns" pursuing any new development, a trade study indicated that the weight of the benefits along with the fact that the technology is nothing new led us to choose to develop the Flex-Capsule.

3 FLEX-CAPSULE REQUIREMENTS

There were several key or driving requirements associated with the devlelopment of the Flex-Capsule to meet RST mission requirements. The most significant environmental and performance requirements are given in Tab. 1.

Table 1. Key Requirements

Operating pressure	Ambient and 0.0013 Pa
Thermal Operating Qualification Survival	 -40 C to +40 C -50 C to +50 C -55 C to +50 C
Mechanical loads Random vibration Quasi-static Sine vibration	Qualification 14.1 G RMS 43.5 G sine burst 12.5 G (5 Hz to 100 Hz)
Range of motion	196° (3.42 rad)
Power	7 traces 1A A&B sides each
Signal	18 traces low current A&B sides each
2x Life cycles	6768 fully reversing

4 PREVENTION OF FLEXURE BUCKLING

Keeping conductor stresses to a minimum allows for highest cycles along with minimal size. Flexible PCB layers need to be kept to a minimum. Our application has three conductive layers, the outer conductive layers for shielding and the inner conductive layer for traces.

In looking at a particular aerospace flexible PCB application, that configuration combined multiple flexible PCBs together to achieve the desired number of conductors. Each flexible PCB is termed "leaf" and are manufactured attached together at one end connecting into a single connector. The other ends of the multiple leaves attach at fixed locations. The inherent problem is that when flexing the group of leaves, buckling of the PCBs occurs. It is logical that each leaf needs to bend at a different radius since any leaf cannot reside in the same location as another. All being a particular length, they must buckle as the group of leaves changes radii.

To prevent buckling, each flexible PCB must be independent. The Flex-Capsule utilizes up to four flexible PCBs, each clocked 90 degrees (1.57 rad) from one another. Though they are wound one upon one another, the clocking puts them in different locations from one another, thus allowing them to bend in an identical manner. There is however some sliding of the flexible PCBs against one another.

5 FLEX-TAPE PHYSICAL ATTACHMENT

The PCB vendor has the capability to merge the flexible PCB layers into a rigid board. Each flexible PCB has a rectangular rigid PCB at each end. We term the flex/rigid PCB assembly "Flex-Tape."

Each rectangular rigid PCB has four holes that accept fasteners to provide physical attachment within the Flex-Capsule. Each board also has solder pads for connection to conventional harnessing and additional holes for lacing cord. Thus mechanical fastening and interfacing with harnessing is easily accomplished using standard processes.

6 ACTUATOR DESCRIPTION

The Flex-Capsule is designed to interface with a Honeybee P35 actuator with an accessory shaft interface located at the rear of the actuator which drives the Flex-Capsule rotor. The accessory shaft is tubular such that harnessing can be fed through the actuator shaft exiting at the actuator output flange. There is also a fastener interface to accomplish attachment of the the Flex-Capsule fixed housing.

7 FLEX-CAPSULE SIZING

The Flex-Capsule was designed to integrate with the 102 mm (4.0 in.) diameter Honeybee P35 actuator, which incorporates redundant motor windings plus motor and output encoders. The Flex-Capsule was sized to match the diameter of the actuator, which was accomplished, thus minimizing the size and mass of Gimbal bracketry.

The Flex-Capsule rotor appears to form a square cross section since there needs to be attachment of four Flex-Tapes. Envisioning the four Flex-Tape inboard rigid ends attached to and recessed into the rotor with each Flex-Tape extending linearly throughout its 609 mm (24 in.) length, rotating the rotor will wind the four Flex-Tapes one upon another while retracting each Flex-Tape as if onto a spool. This method is performed to install the Flex-Tapes into the housing. Once the Flex-Tapes are appropriately retracted, each rigid Flex-Tape outboard end is fastened to the housing, clocked 90 degrees (1.57 rad) from one another.

A Flex-Tape 609 mm (24 in.) length was selected being the larger dimension of a standard PCB panel, and happened to be enough length to meet our angular rotation specification. If longer Flex-Tape lengths would be needed, the PCB vendor can manufacture using larger panel sizes up to 914 mm (36 in.) and 1000 mm (39.4 in.). Remember that the Flex-Tape length includes the rigid ends, so the flexible portion is shorter.

Sizing the Flex-Tape length and housing diameter is not complex. Each Flex-Tape acts like a spring restoring force and wants to remain flat. Thus before each Flex-Tape is wound onto the rotor, the active portion of the Flex-Tapes will reside at the inner diameter (ID) of the housing.

The active portion of the Flex-Tape used to compute angular rotation does not include the Flex-Tape length from the outer rigid board to the tangential contact with the housing ID, the Flex-Tape length from the inner rigid board to the tangential point at the outer diameter (OD) of the rotor, and the section of Flex-Tape that transitions from the inner housing Flex-Tape grouping to the rotor Flex-Tape grouping. In our case we found that 17% of the Flex-Tape length was not active in terms of computing angular rotation.

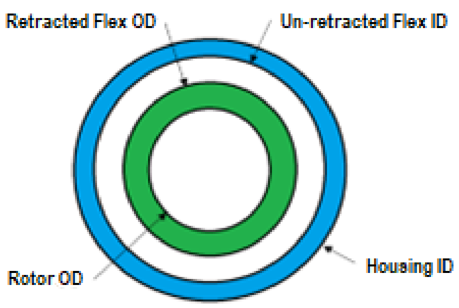

Figure 3. Un-retracted and Retracted Flex-Tapes

Designing for the required angular rotation of the Flex-Capsule rotor is easiest to solve iteratively. Pick both the ID of the housing and the OD of the rotor. Assume the active flex length is coiled inside the ID of the housing, which is the un-retracted case indicated by the blue region (See Fig. 3). Next, determine the number of circumferences achieved for a single Flex-Tape active length using the housing ID. Determine the thickness of the blue region from the combined thickness of four Flex-Tapes times the number of circumferences of a single tape. Using the average diameter of the blue region, recompute the number of circumferences. Use the same process to determine the number of circumferences for the retracted condition, which is the green region. Take the difference between the number of circumferences for the two conditions, multiply by 360 degrees (2π rad), and angular rotation capability is determined. Perform additional iterations such that angular rotation is achieved and adequate space is available for harnessing.

8 FLEX-TAPE CONSIDERATIONS

We had a requirement for redundancy and we desired to separate power from signals. To minimize coupling between power and signal Flex-Tapes, we included shielding edge traces and layers. There were two designs for Flex-Tapes: power and signal. With redundancy, there are four total Flex-Tapes in a Flex-Capsule.

The first actuator of the gimbal has power and telemetry connections provided directly to the actuator from the spacecraft bus. The Flex-Capsule of the first actuator passes power and signal connections to the second actuator. Some power and signal needs to go past the second actuator to the antenna bracket, so the Flex-Capsule of the second actuator makes those connections. Since the number of connections made by the Flex-Capsule of the second actuator are so few, we only populated two Flex-Tapes in that unit as required for heater power and temperature telemetry.

9 FLEX-TAPE STACK

The Flex-Tape layout work is not much different than that of typical rigid PCB. With three copper layers, there is some asymmetry, so the highest stress is in the uppermost copper shielding layer of Fig. 4 and Fig. 7, which is farthest from the neutral axis. If we added thickness to force the three copper layers to be symmetrical, it would balance the stresses in the shielding layers, though the result would lower middle layer stress, it would increase outer layer stress.

Layouts were developed and Flex-Tapes were ordered. Once Flex-Tapes were on hand, a preliminary electrical test was performed to measure coupling between power and signal Flex-Tapes to compare with twisted/shielded pairs. No differences in performance were observed.

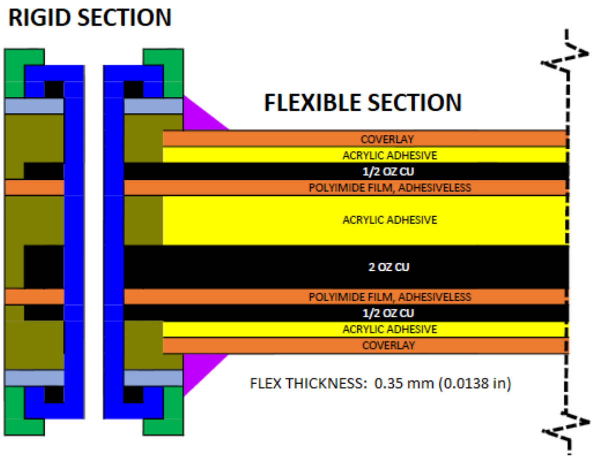

Figure 4. Flex-Tape Stack

10 FLEX-TAPE LIFE ANALYSIS

Flex-Tape strain, stress, and fatigue analysis is predominantly centered on evaluating if the Flex-Tape can successfully survive 6,768 (2x life) of 196 degrees (3.42 rad). (Due to the low number of cycles, we decided to analyze and test to 10,000 cycles). However, the rotational angle is not directly relevant to stress, but minimum and maximum flex diameter is, which is the rotor OD and the housing ID respectively (See Fig. 3).

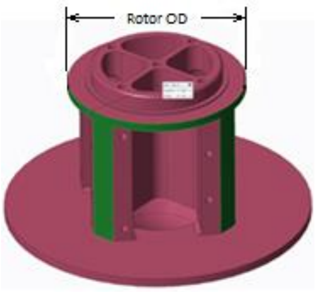

Figure 5. Rotor Outer Diameter

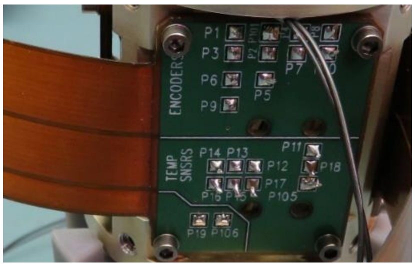

Figure 6. Smaller Flex Bend Near Rigid Board

10.1 True Material Strain

Flex-Tape distance to neutral axis a_n was calculated using Flex-Tape stack parameters of Fig. 4. The simplified version used in the analysis is Eq. 1 of which the parameters include modulus of elasticity E_i, distance to the centroid of each material layer a_i, and thickness of each material layer t_i (See Fig. 7).

Note: To solve for the neutral axis a_n, Institute of Printed Circuits, *Design Guide Manual*, IPC-D-330 [1] Eq. 7-10 was utilized, which is Eq. 1 of this document. Please be aware that there is an error in IPC-D-330 such that t_i and a_i definitions are reversed.

$$a_n = \frac{\sum E_i * t_i * a_i}{\sum E_i * t_i} \qquad (1)$$

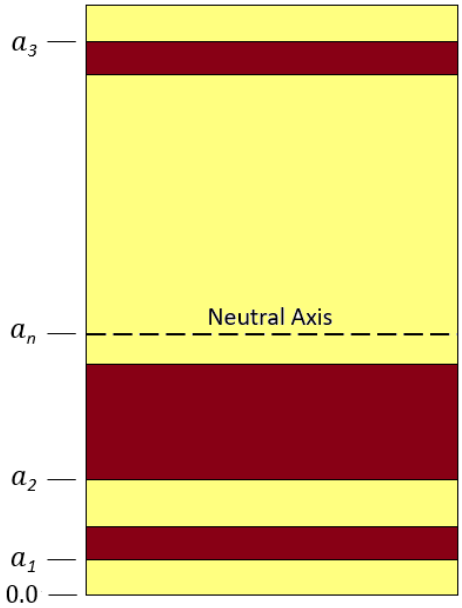

Figure 7: Copper Layer Surface Locations

Strain is highest at the smallest diameter of curvature of the Flex-Tape. The smallest diameter of Flex-Tape curvature was expected to be the rotor OD (See Fig. 5). However, a smaller diameter curvature was observed just beyond the interface between the rigid and flexible portion near the Flex-Tape rotor attachment (See Fig. 6). Strain is lowest at the largest diameter of curvature, which occurs at the housing ID.

True material strain was evaluated using Eq. 2 for various curvatures D_i using the rotor OD, the smaller diameter near the rigid-flexible interface, and the housing ID. Other parameters required include copper layer surface distance a_i and neutral axis distance a_n from the zero location (See Fig. 7). Note that for each copper layer, a_i was chosen to be the copper layer surface farthest from the neutral axis, which results in worst case strain. These strains were ultimately used to evaluate stresses.

$$\varepsilon_{True} = \frac{a_i}{\left(\frac{D_i}{2} + a_n\right)} \qquad (2)$$

10.2 Alternating Strain

Next, alternating strain is calculated in order to eventually determine the fatigue life cycles to material failure. In calculating alternating strain, it is important to understand that the inner strain for each respective copper thickness contains two disctinct strains: strain at the housing ID and strain at the rotor OD. Strain near the rigid to flex interface (Fig. 6) is fairly constant with cycles, so is not relevant. Delta strain leads to fatigue.

$$\Delta\varepsilon_{alternating} = \varepsilon_{ID} - \varepsilon_{OD} \tag{3}$$

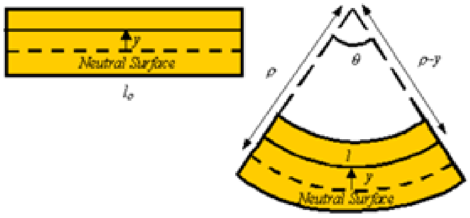

Figure 8. One-sided Strain Bending Behavior

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One-sided strain Eq. 4.1 is a proof equation based upon a bending cycle that does not include reversed flexing (See Fig. 8) [2]. *Results of Copper Foil Ductility Round Robin Study*, IPC-TR-484 [3] strain Eq. 4.2 includes a “2” multiplier in the numerator presumably based upon a bending cycle that includes fully reversed flexing.

The foil flexing test equipment of Fig. 9 was used for the IPC-TR-484 foil study. In order to achieve fully reversable cycles (R= -1) the mandrel needs to move in a vertical motion (+1:-1). The electrodeposited copper sample is bent twice during each loading scenerio. Though the Flex-Tape only sees a one-sided strain, it was deemed acceptable to include the “2” multiplier for our analysis.

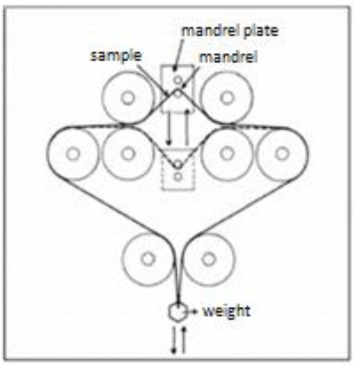

Figure 9. Foil Flexing Test Equipment
From IPC-TR-484 Study

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The equation from IPC-TR-484 [3] differed from the proof equation in that the numerator used t_M specimen core thickness rather than t gauge (measured) thickness. Specimen core thickness is smaller due to subtracting the plating/tooth adhesion thickness. We used t in place of t_M in both numerator and denominator since IPC-TR-484 justified $t_M = t$ when both sides of the foil are smooth. Also, 2ρ is defined as the mandrel diameter in Eq. 4.3 from IPC-TR-4484, but ρ is defined as the distance to the neutral axis in the proof (See Fig. 8).

$$\Delta\varepsilon_{one-sided} = \frac{-y}{\rho} = \frac{\left(\frac{t}{2}\right)}{\rho + \left(\frac{t}{2}\right)} = \frac{(t)}{2 * \left(\rho + \frac{t}{2}\right)} = \frac{t}{2\rho + t} \tag{4.1}$$

$$\Delta\varepsilon_{fully\ reversing} = \frac{2t}{2\rho + t} \tag{4.2}$$

where,

$\Delta\varepsilon$ = delta strain
y = distance above the neutral surface
r = radius to the neutral surface
t = gauge thickness

10.3 Alternating Strain Fatigue

Fatigue life cycles to failure is calculated from Eq. 4.3, which is IPC-TR-484 Eq. 1. The right side of the equation came from empirical data.

$$\Delta\varepsilon_{alternating} = \frac{2t}{2\rho + t} = N_f^{-0.6} + D_f^{0.75} + 0.9 * \frac{S_u}{E_i} * \frac{e^{D_i}}{0.36}^{0.1785 * log\frac{10^5}{N_f}} \tag{4.3}$$

where,

$\Delta\varepsilon$ = delta strain
t = gauge thickness
$2r$ = mandrel diameter (rotor OD, housing ID)
N_f = fatigue life cycles to failure
D_f = fatigue ductility
S_u = ultimate fatigue strength
E_i = modulus of elasticity

Important Note per IPC-TR-484:
… “Tensile strength and modulus of elasticity become paramount importance for applications in which foil is used in a continuous flexing mode with the expectation of large numbers in high cycles before failure. These tensile properties are of equal importance for predicting high cycle fatigue life of foils in such applications using Eq. 4.3 [in this document]. For fatigue life over $N_f > 10^4$ cycles to failure, the ductility of the foil becomes less important, and the fatigue life is a function of the tensile strength/modulus of elasticity ratio, S_u / E_i.

10.4 Endurance Knockdown Factors

Although this step is not necessary to successfully perform the analysis, the Marin equation was used to provide a more realistic outlook on material endurance. The endurance knockdown factors that were utilized in the fatigue analysis are shown in Tab. 2 [4].

$$S_e = K_a * K_b * K_d * K_e * K_f * S_e' \qquad (5)$$

Table 2. Endurance Knockdown Factors

No.	Variable	Value	Description
1	K_a	**ka 0.02 mm = 0.917** **ka 0.07 mm = 0.9** **ka core = 0.957**	Surface condition modification factor
2	K_b	**0.734**	Size modification factor
3	K_c	**1**	Load modification factor
4	K_d	**0.895**	Temperature modification factor
5	K_e	**0.826**	Reliability factor
6	K_f	**0.95**	Misc. effects modification factor
7	S_e'	**Se 0.02 mm = 1.89** **Se 0.07 mm = 2.02** **Se core = 2**	Rotary beam test specimen endurance limit

10.5 Results: Safety Factors

In order for the Flex-Tape to achieve a mission 2x life of 6,768 cycles or testing of 10,000 cycles, the relation below was used to calculate the respective safety factor:

$$\varepsilon_{Allowable\ Fatigue} > \varepsilon_{True\ Strain} \qquad (6)$$

$$\varphi = \frac{\varepsilon_{Allowable\ Fatigue}}{\varepsilon_{True\ Strain}} - 1 \qquad (7)$$

The results of the analysis from a safety factor perspective can be seen in Tab. 3. All of the copper traces can successfully survive fatigue of the required mission life and test cycles.

Table 3. Safety Factor Final Results

No.	Description	Cycle	Safety Factor
1	0.02 mm (0.5 oz) Top copper trace	6768	57%
2	0.02 mm (0.5 oz) Top copper trace	10000	47%
3	0.07 mm (2 oz) copper trace	6768	591%
4	0.07 mm (2 oz) copper trace	10000	507%
5	0.02 mm (0.5 oz) bottom copper trace	6768	84%

Copper trace stress was empirically obtained from DuPont test data for each copper weight. Figure 10 and Fig. 11 illustrate the respective copper stresses. It was important for the analysis to provide an illustration of true stress relative to true strain at a respective material fatigue cycle. Utilizing empirical data for stress evaluation provides a higher degree of confidence in the analysis.

Figures below courtesy of DuPont.

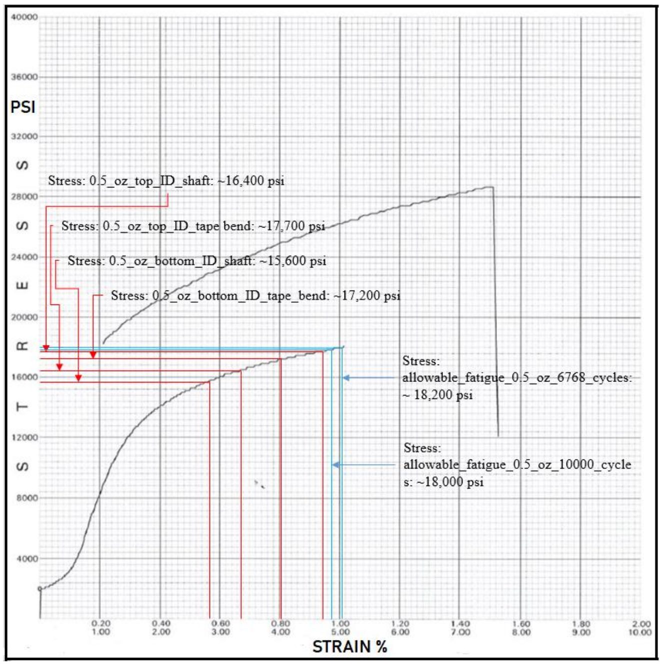

Figure 10. 0.02 mm (0.5 oz) Copper Stress vs. Strain

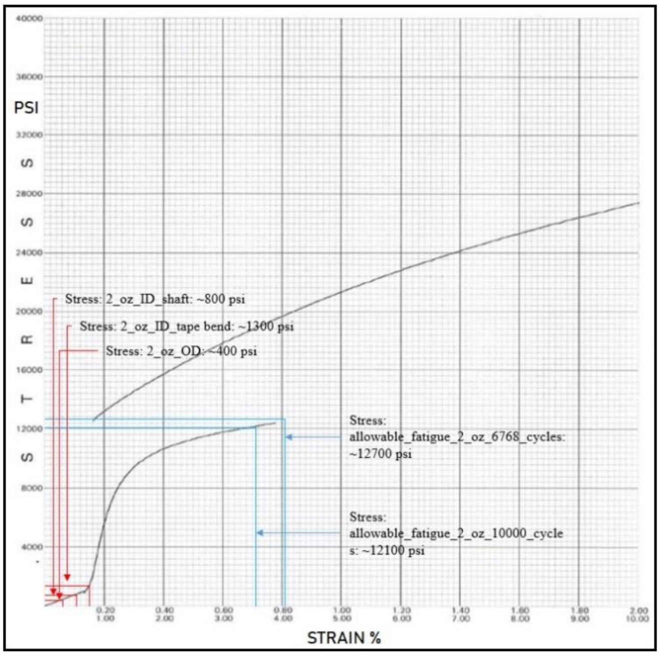

Figure 11. 0.07 mm (2 oz) Copper Stress vs. Strain

11 ENGINEERING MODEL FLEX-CAPSULE

An engineering model (EM) Flex-Capsule was printed from plastic (See Fig. 12). This unit was not a final design and did not include actuator interface details. The rotor included an interface to a ground support equipment motor for test purposes.

The EM was used for developing the assembly process, verifying angular rotation, and also for performing a preliminary life test that did not include environmental conditions. We did have concerns about friction and wear between the Flex-Tapes, but we decided to first test it without lubrication. Not surprisingly, debris was generated. The life requirement cycles were met and operational torque was measured before and after the preliminary test.

With a desire to prevent debris migration throughout the mechanism and to reduce wear, we chose to lubricate the Flex-Tapes. We initially applied a low outgassing grease, but eventually opted for using a low outgassing oil. A minimal amount of Brayco 815z oil was applied as a film onto the Flex-Tapes. This alleviated our friction, wear, and debris production concerns.

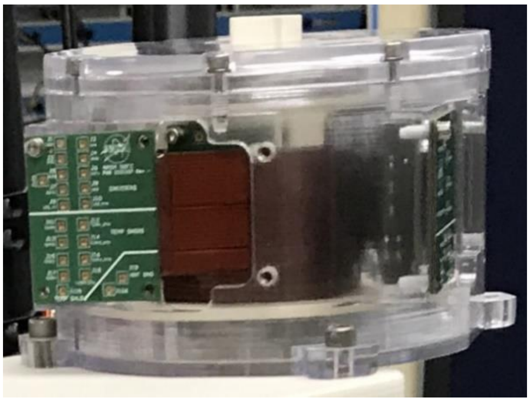

Figure 12. Engineering Model Flex-Capsule

12 LIFE TEST UNIT FLEX-CAPSULE

The life test unit was assembled from the same lot of parts as the flight parts. A full life test including environmental was performed and passed. Pre- and post-life test torque measurements made were nominal. Disassembly followed by inspection did not reveal any anomalies (See Fig. 13).

13 FLIGHT MODEL FLEX-CAPSULES

Both assembly and test campaign were uneventful. Though all flight hardware developments require a significant level of work to go through the development and qualification process, in this case, as far as issues arising resulting in the need to solve problems, redesign, and modify assembly processes, this development was as straightforward as they come. We had few issues arise throughout the effort.

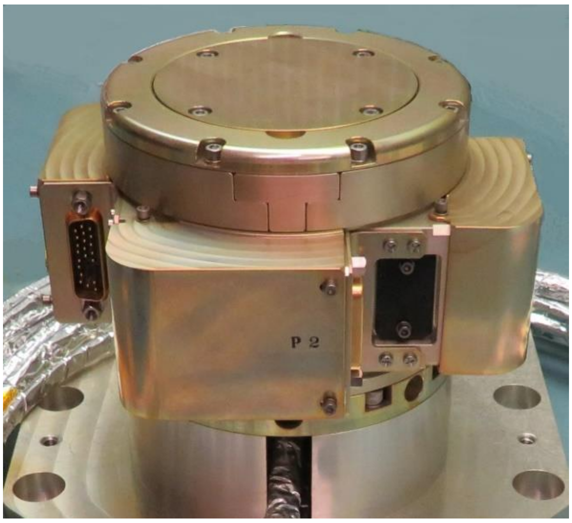

Figure 13. Life Test Unit Flex-Capsule on Vibe Mount

14 EMI TESTING

During the common mode conducted emissions EMI testing that was performed at the gimbal level, there was an exceedance of our 50db/μA spec. However, it was determined to be the result of external gimbal harnessing that used a Neptape shield that was damaged. Retesting with conventional braided shield eliminated the outage. Thus, the EMI exceedance had nothing to do with the Flex-Capsule.

15 EASE OF DEVELOPMENT

There was no desire to go through great pains to develop the Flex-Capsule to be as small as it could possibly be. A relatively small Flex-Capsule diameter can be achieved when there is only one conductive layer in a Flex-Tape. Multiple layers result in requiring a larger bend radius to keep stresses down. When there is only one conductive layer, thus allowing a small bend radius of the flexible PCB, the process to attach conductors to the flexible PCB require a labor-intensive process to directly solder the harnessing to the flexible PCB.

With shielding layers, the larger minimum bend radius left enough space for the Flex-Tape rigid boards to conveniently interface with the harnessing that passes though the actuator hollow tube. Four Flex-Tape boards form a square cross-section when viewing the rotor along its axis, forming an adequate space for the harnessing to feed into the hollow shaft.

During assembly, the design came together very harmoniously. Integrating harnessing for the most part was straightforward though Flex-Tape inner harness connections were moderately more challenging due to space constraints. With the OD of the Flex-Capsule housing matching that of the actuator, the angular rotation turned out to be what was needed plus a small margin.

16 POINTS TO CONSIDER

It should be apparent that the Flex-Tapes need to be thin. Ours happened to be 0.35 mm (0.0138 in). As flexible PCB thickness grows due to a desire to add conductors, minimum radius needed for preventing excessive stress grows rapidly. Just adding one more layer of copper from 3 to 4 increases the total thickness and increases stresses significantly. Either wide thin Flex-Tapes or multiple thinner Flex-Tapes are best implemented. A recommended case study paper is entitled, *Analysis of a Dynamic Flexed Flat Cable Harness* [5].

For the Flex-Capsule, we had shielding layers for both power and signal Flex-Tapes. With Flex-Tape against Flex-Tape, there are then two shielding layers separating power traces from signal traces. Perhaps it is not necessary to have that many shielding layers such that signal Flex-Tape can have three signal layers without shielding layers. We never investigated reducing the number of shielding layers, but if there is adequate shielding from the other Flex-Tape layers in contact, this could be a way to increase the number of signal conductors. Certainly, there would need to be room for harnessing to pass through the hollow tube diameter to handle additional harness conductors. We also did not consider using shielding films, which would be more robust, since the shields see the highest stress.

At the OD of the Flex-Capsule, we chose to interface with high density D-Sub connectors using stranded hookup wires to connect from each Flex-Tape rigid board to each D-Sub connector. This is a standard process we commonly use for our electronics boxes. We certainly could have used Micro-D connectors, each with a pigtail. The PCB vendor also can install a Micro-D directly to the flex. In that case, the flex would continue past the rigid board, eliminating stranded hookup wires. We chose not to go that route since we would be adding another process to the PCB vendor that we would prefer to maintain control over, and the active length of the flexible portion of the PCB within the Flex-Capsule ID would have been reduced with that process.

17 CONCLUSION

Flexible PCB has been around for decades though we never used it before to replace a gimbal Cable Wrap. We sized the Flex-Capsule to match the diameter of the Honeybee P35 actuator housing and saved an estimated 5 kg mass due to smaller and lighter actuators and Flex-Capsules, those smaller devices also resulting in a smaller and lighter gimbal bracket. An estimated 2 kg mass was saved by implementing Flex-Capsules over Cable Wraps, 1 kg per Flex-Capsule (See Fig. 14).

No doubt, we are very pleased that we chose to develop the Flex-Capsule rather than going through a traditional round wire Cable Wrap development. In addition to achieving a more compact design with reduced mass, we also realized the elimination of labor intensive manufacturing processes, simplifed assembly, and have experienced a development with minimal issues.

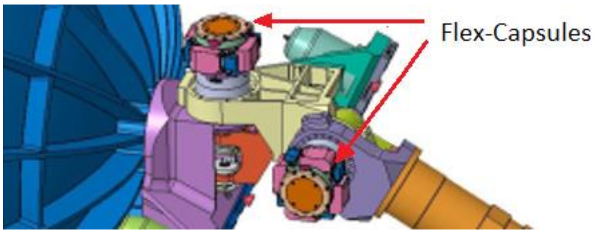

Figure 14. Roman Space Telescope High Gain Antenna Flex-Capsules on Gimbal Actuators

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