TECHNOLOGIES APPLICABLE TO SPACE TETHERS

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Abstract

This paper presents an investigation of technologies which have been accumulated over the years, both on Earth and in space, dealing with tethers, ropes and cables. Many of these technologies can be applied, with modification, to both on-going and future space tether research and demonstration missions. The major areas of tether research and technology developments presented here include multi-megawatt power transmission, materials and structures, dynamics and control, environmental interactions, and in-space operations. These major topical areas are presented within the context of their associated research program or study.

Introduction

Most people realize that throughout the course of recorded history there have been many applications for using a linear tensile member, or tether, to connect two bodies on Earth. The applications for which a tether can be used in space, however, have just become popular within the past decade or so. The goal of this paper is to present a brief survey of various technologies that have accumulated both on Earth and in space which may be applied to space tether technology requirements. Baracat and Gartrell[1] have presented a summary of what these critical space technology needs are, based on the applications proposed for space tethers which are presented in the Tethers in Space Handbook.[2] This paper elaborates on these technologies, with special attention to those readily applicable with existing technology.

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Power Technology

An important technology program which is directly applicable to space tether power technology is the SP-100 - a nuclear space power system.[3] One of the most promising means of attaching the SP-100 to, say, a space station, is via the use of the so-called "coaxial transmission tube." The design of this complex tether involves many of the technologies associated with high voltage power transmission as can be seen from Table 1. Because the coaxial transmission tube operates at high voltage and in a complex plasma environment, conventional electrical design practice has been avoided. Instead of a heavily insulated cable, a pair of concentric tubes separated by a vacuum gap is employed so that the insulation material (vacuum gap) is divorced from the spacecraft plasma interaction. Marine cable technology has also developed many design philosophies for lower power transmission tethers, as well as for signal processing and communications using tethers.[9,10,11]

Table 1 Applicable Power Technology

- Complex electro-mechanical tether design ("coaxial transmission tube")
- Multi-megawatt power transmission via tether
- Electrical isolation from plasma
- Insulation technology using vacuum or pressurized gas
- Separator technology
- Power production using SP-100 technology
- Associated electrodynamic technology (signal processing and communication).

Materials and Structures Technology

Undoubtedly the largest benefit from existing technologies is in the area of materials and structures. The development of the 15-Meter Hoop/Column Antenna[4,5,6] has many simple, yet vitally important contributions to this technology area. Cables are used to structurally connect and stabilize hoop and column assemblies and to actively control the flexible RF reflective mesh surface. In the final assembly of the anticipated 100 meter antenna, 22.5 Km (14 miles) of tether lengths will be needed, with loads ranging from 0.27 N (.06 lb.) to 180 N (40 lb.). In the 15-meter test model, all cords were made of graphite, except for the upper hoop support cords which were of quartz to minimize the RF interference. A complex assembly of motors, pulleys and associated mechanisms are used to control the 96 control cords which actively shape the antenna reflector surface. Much practical experience was gained in the construction of the 15-meter model, and can certainly be applied to many existing and anticipated space tether applications.

Another fascinating technology program which can aid space tethers is that of on-orbit pultrusion.[7] Although this concept has not yet been completely developed for space tethers, it shows much promise, and if perfected, incredible versatility. For example, if a suitable supply of the raw thermoplastic material were on-board, a sophisticated shuttle or space station could produce tethers of any length as desired, with varying geometric properties (such as cross-sectional area) and varying physical properties (such as orientation of composite strength fibers) along its length. It could even add electromagnetic or optical conductors in various places along the tether length as needed. If a suitable thermoplastic were selected and formed into a flexible tether, another exciting possibility exists - replacing damaged sections of tether by cutting, then using a "plastic welder" to inductively melt the two sections of tether back together again. Of course, these ideas require more technology development, but the return on investment may be enormous.

Being a little more practical, research into existing naval rope technology[8] revealed much more fundamental knowledge such as the effect of knots on breakstrength. It was interesting to note that a knot is the worst termination possible due to the compressive loads generated by its convoluted path. A knot may reduce the rated breakstrength by as much as 50-60%. A large volume of literature was also found discussing proper reeling and unreeling procedures, splicing techniques, clipping and termination of rope ends, and advice on the routine care, inspection and repair of synthetic and wire ropes and cables.

Air and sea towing technology[9,10,11] has already contributed greatly to space tether technology, and will continue to do so because of the similarities of towing operations with space tether applications. One good example of this technology transfer is the use of High Impact Conductor (Hiwire)™ tether for the TSS-1 mission. This technology has been developed to accommodate high impact loads primarily through the use of two mechanisms - mechanical isolation between the conductor (copper) and strength member (Kevlar), and a high conductor helix angle. This results in an electromagnetic tether which can sustain impact loading without resultant loss of electrical continuity.[12] Another benefit of the high helix angle is that it allows for a large amount of thermal expansion in the conductor, without requiring a large length increase. Table 2 summarizes the materials and structures technology developments which could be applied to space tethers.

Table 2 Applicable Materials and Structures Technology

- Active control of reflector surfaces using multiple tethers
- Tether attachment to rigid structures
- Tether material selection for minimizing RF interference
- Strain relief technology

- Anti-snag shielding for multiple tether deployment

- Tether construction technology

- Bonding/Fastening technology:
  - bonding tethers to end-fittings
  - fastening truss to plates using tethers
  - "Y" bonding (2 tethers in, 1 out)

- Design of minimum cross-sectional area to withstand stress for complex electro-mechanical tethers

- Pultrusion manufacturing technology in zero-g:
  - construction of very long tethers
  - "plastic welder" using induction heating for attachment or repair of damaged tethers
  - tether construction with varying properties:
    * variable diameter
    * variable mechanical properties
    * variable inclusion of optical or electromagnetic cables as needed
    * variable lengths "to fit"

- Material selection and construction for selective physical properties (linear stress-strain, etc.)

- High-Impact technology

- Extreme temperature variations

- Towing technology:
  - high impact due to "air pockets"
  - electromagnetic cable technology

- Design and selection of tethers for:
  - cyclic loading
  - fatigue
  - high coefficients of friction
  - strength

- Testing

- Quality control

- Use of scaling law theory in order to properly test scale models of tethers.

- Construction and assembly:
  - splicing techniques
  - terminations
  - clips
  - swaging
  - knots

- Care and storage:
  - coiling and uncoiling
  - drum winding
  - inspection and repair

Dynamics and Control Technology

Cutchins, et al[13] have developed a very detailed dynamic model to examine the damping characteristics of wire rope, using a finite-element model which describes the cable as groups of separate curved rods in the shape of helices (which is a very realistic model of the strands in a tether). These curved rods are free to move relative to each other (as they do in a tether), but under the influence of variable coulomb friction forces. In this computer program, various core materials can be modelled.

Nonlinear dynamics of guyed wires attached to long slender booms has also been examined.[14] Although not as glamorous as some of the more exotic space tether applications, guy wires used to support very long, thin structural members will be a very real and important application for space tethers. Much practical experience such as pre-tensioning support cables can be learned from the literature.

Innovative technology abounds in the form of deployment and retrieval mechanisms for cables, especially those in the marine sector. Many of these mechanisms would probably have to be altered for use with space tethers, but the basic design constraints should remain unchanged. For example, special precautions must be taken when winding electro-mechanical or optical-mechanical cables onto drums or through sheaves. All mechanisms should be properly grooved to support a round configuration and prevent flattening, and very low tensile loads should be applied, such as by using a tension capstan ahead of the drum.[8,9,10,11,15] A detailed analysis of mechanisms which are used in marine and air towing operations was not performed for this study due to the large number of such mechanisms. It is recommended that such a study should be performed in the future.

Table 3 Applicable Dynamics and Control Technology

- Dynamic modelling of tether using finite-element technique
- Damping in wire ropes
- Internal energy dissipation due to internal friction
- Wire rope vibration isolator technology
- Dynamic modelling of various internal core materials
- Deployment/retrieval dynamics and technology
- use of tethers as guy wires to support long slender booms
- Effect of cable slackening as a nonlinear effect
- Effect of applied impulsive loading on guy cables and booms
- Mechanisms:
  - cable pulleys
  - drums
  - sheaves

Environmental Interactions Technology

Crucial to the success of any tether application is the minimization of orbital debris collision hazard.[1] The number of trackable objects in near-earth orbit has been increasing at an alarming rate of 13% per year, therefore, this problem will only worsen for tether applications in the mid-term to far-term. An interesting concept which deals with collision hazard is presently being studied and is called the "micrometeoroid bumper."[3] This bumper would essentially be a thin wall of material exterior to the main structural wall of the tether, and separated by an appropriate gap. This bumper would serve to break up and disperse the micrometeoroid into smaller pieces which would then impact the structural wall over a wider area, minimizing catastrophic failure. It may be possible to incorporate this technology inexpensively for future critical tether applications, possibly by providing an exterior sleeve of thin mylar or other suitable material.

Another area of technology very suitable to space tethers is that of guy wires for supporting antennas.[9,10,11] Because of their critical structural purpose and constant exposure to UV radiation, water and wind, this particular application may well teach us technology that could be applied to space tethers. The 15-Meter Hoop/Column Antenna Program[4,5,6] can greatly contribute to the area of environmental interaction technology. All tether and associated mechanisms to be used on this antenna were carefully examined for their reliability and operation in the space environment. It was especially critical to this particular program that material properties did not degrade as the active control of the antenna surface was the primary purpose of the tethers.

Table 4 Applicable Environmental Interactions Technology

- Micrometeoroid protection technology:
  - "micrometeoroid bumper"
  - redundancy of critical members
  - dual wall technology
  - collision hazard estimation
- UV and other radiation protection
- Thermal protection
- Vacuum protection

In-Space Operations Technology

Although many technologies applicable to tethers already exist, in most cases they can not be directly applied in space without further development. There has been progress in robotics and teleoperations in many disciplines, and these should find analogies to space tether applications. Many of the automated functions being researched for Space Station fall into this category. One of the major technologies, with perhaps the greatest impact to space tethers, will be that of in-space inspection and repair. Since future applications call for increasing lengths of tethers and associated cross-sectional areas[1,2] we can surmise that these same tethers will be more susceptible to failure from micrometeoroid impact. Automated inspection and repair techniques which are currently used for terrestrial pipes and cables could contribute to the present endeavors with space tethers.

Table 5 Applicable In-Space Operations Technology

- Tether construction in space using pultrusion technology
- Tether inspection and repair
- Robotics and teleoperations
- Deployment/retrieval technology

Conclusion

Many of the proposed applications for space tethers rely on critical technology advancements and developments. It has been shown that many previous or on-going technology developments can aid in satisfying some of these critical areas. Much of the existing technology relies on data gathered from cable and rope technology on Earth and must be adapted for in-space use. Directly applicable space technology programs, such as the 15-Meter Hoop/Column Antenna were discussed. With the proper research and application of existing ideas, it is hoped that the space tether community will benefit from the multitude of previous and on-going technology programs dealing with ropes, cables, and tethers.

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