Structural Flexibility of Motion Systems in the Space Environment

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Abstract—**The state-of-the-art, focus on interdisciplinary approaches and positions are summarized, and a kaleidoscope of future directions in the design, analysis and control of lightweight robotic and telerobotic motions systems for space application is provided. The emphasis is on providing a logical connection between the special demands of space applications and the design of the motion system. Flexibility is presented as a natural consequence of these demands. A number of technologies are relevant to extending feasible performance into regions of the design space previously avoided due to the resulting flexibility of the structures and drives. Control technology is considered foremost in the paper, but passive damping, structural materials, structural design, operational strategy and sensor technology are closely related. Numerous references are presented for the reader wishing to employ these technologies, but the details of those papers cannot be presented in a paper of this breadth.**

I. Introduction

Autonomous systems provide a logical way for human kind to explore hazardous environments of space, underwater, nuclear accidents, and other natural or man-made disasters. In space specifically, spectacular success with deep space probes has shown us a way to learn about environments we don't want to be in. In near space, in earth orbit, on the moon, and even on near planets, we observe a reluctance by the human race to delegate the task of exploration and operation to remote and autonomous systems. It is likely that this reluctance will be overcome in the near future, by the space programs of one country if not the other. This paper will provide an overview of current research applicable to motion systems for space application. Arm-like devices in particular that exist to move themselves and perhaps some payload will be considered. Other structures with some similar behavior such deployable antennae and booms will be mostly ignored.

II. Why Space Means Long and Lean

Space application has dictated a number of constraints and penalties on design that have become hallmarks of systems for space, more specifically for systems that have to be launched from Earth into space. To achieve escape velocity, economy strongly encourages light weight designs. Every kilogram of payload requires about 23 kilogram of fuel on a typical shuttle mission. At the same time the weightlessness of space gives license to designers to ignore the gravity loads that dominate the actuators and structures of any motion system in Earth's gravity. Weightlessness also means that mobility provided by wheels and legs on ground based systems is ineffective for space based systems. The tendency to float away means that even though repositioning of mass can be obtained with negligible exertion (if you can wait), exceptional care must be taken to avoid unintentional repositioning. Thus the Space Shuttle has a long arm to move things into and out of the cargo bay. Its weight is light, 450 kg (994 lbs), although it was designed to move a mass of 27 200 kg (60 000 lbs.) The space station Freedom has several proposed material handling systems, including long manipulator arms, (space cranes) on which are mounted smaller manipulator arms. Earth based systems might employ vehicles to cover these distances. The long arms are flexible, and the structures on which they are mounted are flexible. When they move, they will move slowly, at least by current wisdom, because the resultant dynamics are complex and difficult to predict. The third constraint of space based systems shows up here: conservatism. The very high cost and visibility of space missions means that any avoidable uncertainty will be avoided.

III. Philosophies of Arm Structure Design

With the need for long structures and light weight motion systems, one might assume that space system designers have mastered the problem of flexible motion control. This is certainly not true of systems currently deployed. While extensive effort has gone to predict the behavior of flexible motion systems to assure acceptable performance and safety, little technology has been applied to improving that behavior. Designers of Earth-bound robots have a philosophy that avoids confronting the flexible monster. I call this philosophy the machine tool philosophy: Make it heavy; heavy enough to pass as rigid. Designers of space based systems have their own strategy: Move it slowly; slowly enough to pass as static. This conservative strategy is usually preferred by the responsible program manager when it will suffice.

The conservative strategy is often preferred by those controlling and responsible for resources, resources that are spent to solve the problems that are encountered. A "problem" is usually the current limits on performance in the satisfaction of a task or application requirements due to the current combination of technologies. A "solution" is an equally temporary fix, that allows an additional increment of performance in some relevant dimension. Space problems now begin to require a flexible structure solution.

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IV. Robots in Space

In this paper an overview of flexible motion systems for space applications will be presented. Focus will be on motion systems that will have a robotic or teleoperated nature, so arms and cranes will be of more interest than deployable antennas and vehicle structures. The potential applications will be discussed briefly to set the stage for exploring the characteristic problems and possible solutions.

When is a system flexible anyway? It depends on the time scale of the task to be solved and on the length scale of the needed dynamic accuracy. For our purposes a system will be structurally flexible when deflections too large to complete a task persist too long to allow the task to be completed. Typically the deflections are dynamic: vibrations due to applied or inertial forces.

The vision of robots in space is not new. Certainly, robots and teleoperated manipulators have been seriously considered by researchers and designers for at least 25 years. In space, just as in factories or nuclear installations, we desire to perform human tasks in environments inhospitable to human kind. We wish to separate the human in time and/or space from the task. What is the task? A representative sample would include deployment of equipment, construction of habitats and vehicles, retrieval of equipment and samples, repair and maintenance of equipment, operation of equipment for experiments, surveillance and manufacture, and unloading supplies from vehicles. These may be performed in weightlessness or in the gravity of a moon or planet.

The major space programs in the past have had a commitment to man in space for piloting vehicles and for Extra-Vehicular Activity (EVA), romantically known as space walking. This hazardous activity is a prominent target application for mechanical arms. The space shuttle's remote manipulator system (RMS) is the most dramatic example implemented to date. The space station will have longer arms and the success of the RMS in certain tasks encourages this evolution while recent failures of the RMS in satellite retrieval have boosted EVA.

Other systems have been considered for decades for removing astronauts from the hazards of space by greater degrees. Concepts that were contemporary with or even preceded the RMS have been periodically abandoned and resurrected. Most recently the flight telerobotic servicer (FTS) project was cancelled. This combination of vehicle and arm was to perform a variety of satellite and vehicle servicing tasks. The remote operator of such a device might be in orbit nearby. The human can be even further removed from the task and space hazards by leaving him or her on Earth. The time delay for communications to a remote system from Earth is certainly a complicating factor in this option. Feedback of force information to a remote master separated by a time delay can cause unstable behavior.

The time and length scale of systems for space operations are dramatically altered by human presence. The unwillingness of our race to be miniaturized has placed us increasingly at odds with the trend of "competing technologies" (i.e. microelectronics) when a clearly defined task is to be performed in space. The effect on space systems is an unyielding constraint on the length scale of our solutions to accommodate human dimension. Our motion systems must comply to this and other constraints. As a result, one can envision a lower bound on the needed reach of arms in space, and consequently job insurance for those researchers seeking to better design and control flexible structure systems.

V. The Job for Robots

New solutions to flexible structures problems will not be needed as long as the existing solutions succeed. But are new tasks envisioned for which the "go slow" strategy does not succeed? Either the time acceptable for completion must be smaller or the task content must be larger. A large increase in task content will extend the task completion time past acceptable limits. The proposed construction of a space station in earth orbit has a very large task content. Current teleoperation on earth takes perhaps eight times as long as direct manual manipulation. The net manipulation is orders of magnitude more time consuming than anything extravehicular that has been done before. Some work can be done with fixed automation, but much transportation and assembly remains to be done by motion systems that will have the space constraints leading to flexible structure designs. EVA offers a possible alternative to manipulators.

VI. Flexible Constraints

Let us return to the definition of "flexible." Flexibility refers to the deflection of a structure under applied or inertial (acceleration) forces. It is easy to argue that everything is flexible. The load applied to any structure results in finite deflection in finite time. Thus motion, inertia, restoring forces play their role in establishing mechanical vibrations in response to operational demands. The more realistic answer incorporates the requirements of the task to be performed. A system is flexible if the static and/or dynamic deflection is significant in the context of the task to be performed. Dynamic deflections involve units of distance and time. Flexibility constraints on design may be inactive (irrelevant) if strength, fatigue, buckling, or other constraints dominate the specification of the relevant structural parameters. For arm-like structures flexibility remains an active constraint, and may dominate all other constraints. If an arm is constrained by design to have a rigid behavior, the issue of flexibility has not gone away. The designer has chosen to fight other battles, probably because he or she knows better how to win them and thus achieve a satisfactory solution to the design challenge.

A word is in order about the relative importance of drive compliance and structural (link) compliance. Good *et al.* [1] found link compliance to be almost insignificant in a standard GE P50 robot, yet Book [2] showed that with an optimized drive the link compliance was quite significant. In fact existing arms are not designed with an optimal distribution of structural mass between links and drives. Reducing the link structural mass can improve the dynamic stiffness of the arm as evaluated by the arm's natural frequency with the actuators locked. The additional inertia does more damage

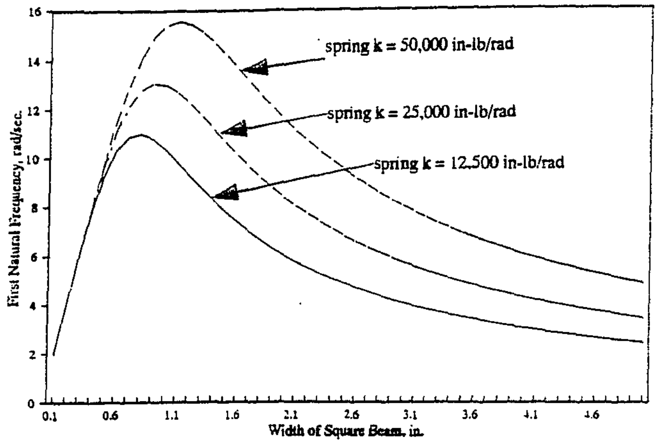

Fig. 1. Variation of fundamental frequency of a pinned-spring-beam system as the square beam is widened. (Beam length = 100 in., material: aluminum, springs: 12,500; 25,000; 50,000 in-lb/rad.)

than the reduced compliance in series with a fixed drive compliance. This is easily illustrated in Fig. 1 for a variable distributed beam hinged to a fixed rotational spring. Higher natural frequencies would be obtained by removing structural mass from the link, or better, by reallocating structural mass to the drive components. Other researchers have demonstrated this is relevant to the Space Shuttle RMS [3].

VII. What Should Be Controlled?

Two strategies for achieving improved behavior of flexible structures can be readily identified. A practical approach seeks to rapidly damp the vibrations of the flexible structure. When the vibrations cease, the tip should be at the desired position, assuming static deflection (if any) is accounted for by the final joint angles. The second strategy is more difficult but more desirable. The tip or other location on the arm is positioned explicitly as a function of time. Since the tip is dependent on joint variables as well as flexible variables that have no direct control inputs, the inverse dynamics and inverse kinematics problems are coupled.

VIII. The Flexible System Toolbox

All technologies are fair tools in the struggle to effectively employ flexible systems. The most direct technology is the material technology that defines the flexible behavior. A listing of the major technologies to consider include:

- Materials with improved stiffness and damping per unit weight
- Improved structure shapes
- Sensors and actuators distributed in the structure
- Passive damping treatments and devices
- Improved algorithms for command and feedback control
- Discrete actuators applying force in unconventional ways, such as inertial forces or forces transmitted through cables in tension
- Improved dynamic modeling that allows reliable design and control
- Sensors for detecting end-of-arm position, strain rate, and other system states conveniently and directly.

What are the pros and cons of these technologies?

IX. Material Technology

A stiffer, lighter material is the solution to all problems of flexibility. In spite of remarkable improvements in materials such as Kevlar, flexibility remains the active constraint in design. Thus we can do "better" if a flexible system is acceptable. Furthermore, the stiffest behavior is obtained with materials that are not homogeneous, such as fiber composites. They are difficult interface into the complete design, with drive components and the like. Almost as important as stiffness is the damping inherent in the material. While some energy is absorbed in all materials, the damping ratio can vary by a factor of 10. High damping makes control so much easier, since a constant damping ratio means high frequency vibrational modes damp out very quickly. As a result the inherent infinite dimensional problem becomes practically finite and perhaps even of modest order. Material damping is not characterized by a constant damping ratio or a constant damping coefficient. Structural damping is often approximated as inversely proportional to frequency for harmonic analysis. It is also represented as a complex shear or elastic modulus, with the imaginary part a small fraction (e.g. .01) of the static modulus [4].

Stiffer structures can be obtained with better structure shapes. Bending stiffness for a given length is characterized by the product of E, the elastic modulus of the material, and I, the area moment of inertia about the neutral axis passing through the area centroid. Placing material far from the neutral axis of bending to provide a large area moment of inertia is one example of a better structural shape. Practical limits are imposed by local shell buckling if this approach is followed blindly to a thin walled tube. A truss structure achieves a large moment of inertia without thin walls by collecting the structural material into the truss elements without substantially reducing the moment of inertia.

X. Flexible Arm Control Algorithms

Of the technologies available for producing higher performance flexible structure systems, control algorithms are perhaps most attractive. Better control algorithms hold out the lure of something for nothing. Improved use of information with better computer control on ever more powerful computers replaces a lot of structural material with a little bit of silicon on a chip to achieve the same functional end. The necessary measurements for determining the state of the controllable system can usually be made, thus pole placement for the linearized flexible arm can achieve arbitrary pole placement [5]. In a practical sense, however, such a linear feedback control with observer can be undesirably sensitive to small changes in parameters or payload. When implemented on a digital computer the consequences are even more dramatic. When sampled for digital control, lightly damped high frequency modes "wrap around" near the unit circle to "alias" as low frequencies and interfere with the dominant modes in discrete time control implementations [6]. The value of structural damping bears mentioning again. Damping causes the under sampled structural frequencies to spiral in to the origin of the z plane, avoiding the interference with dominant modes that forces instability. Robustness to parameter uncertainties is essential with variable configurations, payloads, and other parameter variations one expects from a robot with long life.

Many of the advanced modern control algorithms have been applied to flexible arm control, but no results known by this author conclusively crown any algorithm as superior in all cases. Our experience and observations to date show the following:

- Linear state feedback is effective at controlling multi-link flexible structure dynamics [7], but it may be too sensitive to variations of the dynamics during operation.
- Strain rate or some equivalent is important to feed back to damp vibrations [8].
- Decoupled control of some arms is effective at controlling joint and corresponding flexible link motion [8].
- Adaptive algorithms that ignore flexibility do not eliminate or greatly improve the vibration problem [9].
- Simple adaptive gain scheduling is very effective in extending the local advantages of decoupled strain rate feedback to the overall work space. (unpublished results)
- Multiple time scale composite controls, e.g., based on the singular perturbation method, are effective simplifications for dealing with the complex problem [10]–[12]. Expect to be locked into a lower range of performance, however, in order to achieve the separation of time scales between the rigid and flexible subsystems.
- Robust control techniques based on bounded uncertainty estimates can be extended to flexible link arms. While stability proofs are reassuring they are not very helpful in obtaining a system of high performance [13].

A large number of control algorithms have been applied to the flexible arm problem for both space and terrestrial application. One recent and extensive survey is provided by Magee and Book [14].

XI. Dynamics of The Problem

Flexible arms are not all the same in some important aspects of the structure of the dynamic model. The difference between flexible drive and flexible link robots is now well recognized. The flexible link distributes compliance spatially, and leads to non-collocated sensors and actuators. Long arms are the most difficult to make stiff, but they also tend to be slow. The tip speed may be high but they are slow to change angle configuration. Consequently, the nonlinear terms of centrifugal and Coriolis acceleration tend to be small. In our experimental arm with two links, each 3 m. (10 ft) long, the nonlinear effects are primarily due to changes in the inertia matrix [15]. We cannot move it fast enough to have significant Coriolis and centrifugal terms, even though the tip will move at about 8 m/s. The inertia variation with joint angle is large, but the inertia variation with flexible variables tend to be small. In some cases at least, the flexibility can be represented as a linear flexible system coupled to the nonlinear rigid system.

When angular rotation speeds are much higher, the popular technique of discretizing the spatial variable of this distributed parameter system by assuming that a finite number mode shapes form a basis set for describing the shape has been shown to give pessimistic results [16]. This premature linearization of the effects of flexibility ignores the centrifugal stiffening (which tends to raise the system's natural frequency) and beam foreshortening (since the straight line distance to the tip is actually less than the beam length). Between these extremes the structure of the equations as commonly derived in journal papers is valid, but only if the arm is truly serial. Actuation links that support part of the structure's load are valuable design enhancements but they must be considered in deriving the dynamic behavior. A parallel mechanism can cause simplification in the model if care is taken in its design [17]. On the other hand some concessions in simplicity, weight, or manufacture may be necessary to make this happen.

Other imperfections in the construction of a mechanical device can have pronounced effects on the behavior. The clearance in joints is the most notable. Friction is not an imperfection in construction, but an unavoidable law of nature. Dry, or Coulomb friction is the most common but seldom represented in the dynamic equations, since linear or viscous friction is much easier to model. Some progress is being made in identifying and compensating for Coulomb friction [18].

An approximation seldom recognized is ignoring the gyroscopic effect of a high speed motor and speed reducer mounted on a moving link. For a flexible link carrying such a motor the gyroscopic torques could produce substantial out of plane excitations.

To summarize on the dynamics of flexible systems: Standard equations need not apply. Robotic structures have long mistakenly been assumed rigid. Assuming any other generic form including flexibility could be just as wrong in a specific case. Multibody dynamics is a complex subject and more work combining experiments and analysis needs to be done to understand the structure of dynamic models that applies to useful designs. Theoretical control developments based on assumed equation structure are appearing today that are useful. One cannot be sure which theory is useful to which design. Experiments are proof of existence of at least one instance of a dynamic structure. Experience has shown that generalizing from the wrong experimental results can be just as wrong as generalizing from the wrong analytical model.

XII. Noncollocation and Nonminimum Phase

When a distributed parameter system is forced at one point and its response is measured at another point, the system is said to be non-collocated. Since the system is theoretically of infinite dimension, a transfer function would contain an infinite number of terms with various time constants or periods and amplitudes. It can be shown for elastic systems that non-minimum phase dynamics will result if the finite dimensional model retains terms of sufficiently high frequency [19]. Non-minimum phase produces various symptoms: reverse action, zeros in the right half plane, delay due to wave propagation and phase in the frequency response that is not "minimum" for the order of the system. Many theoretical results are complicated by or even totally voided by a system of non-minimum phase.

Inverse plant controls are viewed in the linear case as the inverse of a transfer function. Zeros of the transfer function become poles of the inverse plant, and a transfer function with right half plane poles are representative of instability. The alternative to instability, as predicted by transform theory, is acausality. That is, a system response that occurs before the input. This comes from using a different region of convergence in the inverse transform calculation. While a real time system must be causal, acausal systems can be used to calculate a torque history that will result in a trajectory prescribed before the motion begins. The input is the desired trajectory, and response of the inverse dynamics is the torque to be applied. This acausal inverse dynamics can be implemented if the trajectory is known in advance [20], [21], [22], [23]. While in theory the input to the non-collocated system must be applied infinitely far in advance, in practice anticipation of one or two time constants is needed.

It should be emphasized that inverse dynamics as a total solution to open loop control is not practical in most cases. The variability of the parameters demands corrections be provided by feedback controls. It is also imperative that the computational demands be kept in check. For a single link linearization and time domain solution procedures have made on- line trajectory calculations feasible [22]. For multiple links the techniques have demanded super computer effort in the past [23]. It appears likely that improved calculation schemes will evolve for multiple links as well, though perhaps involving simplifications and assumptions not applicable in all cases.

Inverse dynamic calculations can give desired values for all the system states that are consistent with the specified tip conditions. These trajectories are needed if certain tracking feedback controls are to be applied [24]. Other feedback controls show almost equivalent performance using only a subset of the states [20]. These flexible states also provide a convenient way to unite position and force control, since force will always result in deflection of a flexible arm. Hence state trajectories for a tip force history are predictable from a static model of arm bending.

XIII. Shaping The Commands

While inverse dynamic equations allow the advance prescription of the entire tip trajectory, the demands on calculation time are substantial. Prescribing the complete trajectory may not be desirable, or even possible. Teleoperated arm motion is an example where this is true. One might still hope to modify the input specification of joint angles to result in tip motion without exciting the dominant modes of vibration. One thinks of smoothing or shaping the inputs to be better suited to the vibratory nature of the system. Notch filters can be applied, but while the frequency domain specification looks promising, the transient response of these filters is not very good.

Singer [25] proposed an alternative for linear systems they referred to as input shaping. In the simplest form of input shaping an impulse input would be shaped into two impulses, with the second delayed by 1/2 period of the vibration frequency to be avoided. Singer showed that by further shaping, i.e. generating more pulses, the undesirable sensitivity to errors in the frequency could be reduced. Singer's work also showed that multiple modes of vibration could be handled as well.

For some flexible motion systems the natural frequencies change dramatically. An example is an articulated arm or any multi-link arm with variable inertia outboard of flexibility. The variable frequency was treated by Magee [26] with an extension of input shaping he called command shaping. Magee first measuring the frequency and damping ratio throughout the system's work space. A variable delay between successive pulses in the shaped response was based on these measurements with care to avoid transient effects.

While Singer placed the input shaping outside the feedback loop, we chose to place the input shaping inside the loop, with the shaping filter acting on the error signal produced by the joint controllers [26]. In this way, the commanded and actual values of the joints can be directly compared. This does raise concern about stability, since the modified command shaping law introduces time delays into the feedback loop. A step response does show additional overshoot with modified command shaping. Zuo and Wang [27] has analyzed the destabilizing effect of this delay.

XIV. Where Do You Place Control Inputs?

Actuator placement has an important effect on the flexible dynamics as well as the rigid dynamics. Collocation of the actuator with the point to be positioned (call it the tip) allows sensing and actuation of the tip motion to be collocated. Collocation allows a minimum phase response. Short of thrusters applied at the tip of the arm, how can collocation be achieved? In an ideal sense it cannot be achieved. In a practical sense a transmission of torque to the tip that avoids the slow propagation dynamics of the beam in bending will achieve the desired goal. A cable in tension has been shown to do this to a good level of approximation [28]. Redundant fast degrees of freedom with essentially rigid links placed near the end of a flexible link can also produce a minimum phase system [29]. In some applications a new strategy of operation can be employed. By bracing the large flexible arm on a passive support a comparable effect is achieved [30], [31]. The braced arm then requires additional degrees of freedom to carry out a general motion. In all the above solutions additional actuators are used to compensate for the flexible degrees of freedom that hinder the completion of the task.

In some cases actuators are effective if distributed along the length of the link. Piezoelectric films and ceramics are capable of being used either as sensors or actuators [32]. As actuators their induced motion is small, but it is appropriately applied to produce active damping forces on the arm.

XV. What Do You Sense and How?

For rigid arms tip position and velocity is algebraicly related to the joint position and velocity, and if the arm is nonredundant the inverse of the relation exists. To sense the flexible variables completely is hopeless, but we can be satisfied to sense a suitable finite number. What to sense is as much a matter of sensor technology and task characteristics as of control and dynamics. If one wants the end point to be precisely positioned the good sensing of the end point position introduces the least uncertainty [33]. To achieve good endpoint sensing in an absolute reference frame is technically challenging, to say the least. If one can engineer the work space suitably, it is more feasible to sense tip position relative to the goal. While this resolves the goal's position there remain uncertainties in the state of the system for control purposes. Sensing relative to a goal can be performed rapidly and accurately with cameras tracking landmarks in at least two degrees of freedom [34]. Tracking throughout the work space might not be as important as tracking near the final goal position.

Strain gages remain as one of the most available and relevant sensors for flexible states. By sensing at n positions one can algebraically reconstruct n assumed modal amplitudes. The tip deflection can also be calculated from this information and hence the deflected tip position. While good strain measurements are possible, stiffer systems may result in a low signal-to-noise ratio. High frequency noise may need filtering. This noise is most problematical when obtaining the strain rate. Clean signals for the derivative are crucial for accurate strain rate approximations from differencing strain samples. Observers and estimators may be preferred for their filtering properties, although more they are more complicated to implement and require knowledge of the system dynamics. New devices to directly sense strain rate are in the testing phase, but are oriented to extension rather than bending.

XVI. Damping Enhancement

Damping is an energy dissipation process. It is the most reliable and traditional means of eliminating vibration. The dissipation of energy requires motion and corresponding force of appropriate sign. Arm vibration will damp out in a few cycles if the joints will allow motion and provide frictional or damping actuator torque. Too much friction impedes motion to the extent that energy is slowly removed from the vibrational modes. In effect there is a poor impedance match between the two components. Coulomb or dry friction torque proportional to the normal force between rubbing surfaces will lock the joint, stopping all joint motion when the vibrational torque is below the break away torque. This is responsible for very lightly damped, low amplitude oscillations in many arms, both flexible and "rigid." To provide damping properties distributed throughout the structure it is possible to provide surface treatments to the link. One such treatment is the "constrained layer damping treatment" [6]. During bending the outer surface of a beam undergoes elongation that provides the relative motion for energy dissipation. A viscoelastic material sandwiched between a thin but stiff constraining layer completes the damping treatment. By segmenting the constraining layer along the direction of stretch the best impedance match can be achieve allowing motion while providing a resisting force. While this treatment can be applied to metal links, incorporating the damping into the design of a composite link is an appealing concept [35]. It is not clear how these materials will perform in prolonged service in a space environment of vacuum and temperature extremes.

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