BENDING OF UNFURLABLE TUBULAR STRUCTURES IN SPACE

by

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1. INTRODUCTION

Recent developments in spacecraft technology have led to the requirement for lightweight, long tubular booms that can be launched in compact containers and unfurled in space. Typical applications are booms for gravity-gradient stabilization (1), for separation of delicate instruments from the main spacecraft, and booms for erection of very long antennas (2). The construction of these booms is such that the unsupported structure would collapse from its own weight in ground environments; consequently, the associated design problems are quite different from those encountered in conventional structural design.

The proper functioning of spacecraft utilizing such booms depends on the straightness of the unfurled boom in space. The major causes of boom bending are listed in Table 1. The items are divided into two groups, depending on whether bending is localized in a small portion of the boom, or whether bending is gradually distributed along the entire length of the boom. Items listed under "Localized Bending" may cause total failure of the boom, but they are preventable in all cases; items listed under "Gradual Bending" cannot be totally eliminated, but proper design can keep them within acceptable tolerances. The following discussion will explore in detail the various causes of boom bending.

2. LOCALIZED BOOM BENDING

2.1 Inertial and Coriolis Forces During Boom Deployment

Some residual rotation of the spacecraft is inevitably present when boom deployment is initiated. The radial deployment of the boom in this rotating frame of reference causes boom bending and shear due to: (a) inertial forces, and (b) Coriolis forces. The inertial forces result from the de-spin of the spacecraft caused by the increase in moment of inertia. Boom loading is in the direction of the initial rotation. Coriolis forces are those which, for example, are experienced by a person walking on a rotating turntable. In this instance, boom loading is in a direction opposite to loading caused by inertial forces. The combined effect of the inertial and Coriolis accelerations may

TABLE 1

MAJOR CAUSES OF BOOM BENDING

Type of Bending	Cause	Predictability	Remedy	Preventable	Relative Importance*	Reference Section
Localized Bending						
Elastic deformation during deployment	Inertial and Coriolis Forces during deployment.	Yes	Limiting deployment velocity and initial angular rate.	Yes	1	2.1
Elastic deformation during deployment	Rebound at the end of deployment.	Yes	Regulate deployment velocity. Provide energy dissipation mechanism.	Yes	1	2.2
Due to space environment	Localized cold welding of boom sections due to defects of material or coating.	Yes	Quality control in production. Limit amount of testing.	Yes	1	2.3
Gradual Bending						
Permanent deformation during deployment	Non-homogeneous material properties.	Yes	Quality control and sample testing.	No	2	3.1
Permanent deformation during deployment	Tolerances (dimensional, heat treatment, etc.	Yes	Quality control and sample testing.	No	2	3.1
Permanent deformation during deployment	Induced by deployment mechanism.	Yes	Quality control and sample testing.	No	2	3.1

*Relative worst-case system performance, if cause is not eliminated: 1. Total failure
2. Marginal
3. Acceptable

TABLE 1 (Continued)

Type of Bending	Cause	Predictability	Remedy	Preventable	Relative Importance*	Reference Section
Gradual Bending (Continued)						
Orbit dependent deformation	Uneven heating due to solar radiation.	Yes	Optimize thermal properties of boom. Minimize projected area.	No	3	3.2.1
Orbit dependent deformation	Heating due to earth albedo	Yes	Optimize thermal properties of boom. Minimize project area.	No	3	3.2.1
Orbit dependent deformation	Thermally-induced impulse	Yes	Optimize thermal properties of boom. Minimize projected area. Twilight orbit.	No	2	3.2.2
Orbit dependent deformation	Gravity gradient	Yes	Minimize weight and length	No	3	3.2.3
Orbit dependent deformation	Variation of gravity gradient due to orbit eccentricity (inhomogeneous earth).	Yes	Optimize orbit	No	3	3.2.3
Orbit dependent deformation	Solar pressure	Yes	Minimize projected area	No	3	3.2.4

*Relative worst-case system performance, if cause is not eliminated:
1. Total failure
2. Marginal
3. Acceptable

TABLE 1 (Continued)

Type of Bending	Cause	Predict-ability	Remedy	Prevent-able	Relative Importance*	Reference Section
Gradual Bending (Continued)						
Orbit dependent deformation	Micrometeorites	No	None. Damage probability small.	No	3	3.2.5
Orbit dependent deformation	Electromagnetic effects.	Yes	Equatorial orbit. Use nonmagnetic material.	Yes	3	3.2.6
Orbit dependent deformation	Active control	Yes	Minimize components producing buckling.	No	3	3.2.7
Orbit dependent deformation	Atmospheric drag.	Yes	Select higher orbit.	No	3	3.2.8
Environmentally induced.	Material degradation due to sublimation.	Yes	Proper selection of materials and coating.	No	3	3.3
Environmentally induced.	Radiation erosion.	No	None	No	3	3.3
Environmentally induced.	Solid particles erosion	No	None	No	3	3.3

*Relative worst-case system performance, if cause is not eliminated:
1. Total failure
2. Marginal
3. Acceptable

cause total failure (e.g., buckling) of the boom if the load exceeds the permissible bending moment or shear. During the retraction of the boom, both inertial and Coriolis forces act in the opposite directions.

Figure 1 shows the results of a study (3) of this problem. Figure 1-a shows the configuration of a two-body system separated by a boom that adequately describes the entire spectrum of systems from a dumbell having equal end-masses to an antenna having no end-masses in a fully deployed configuration. Figures 1-b and 1-c show the relations of parameters for a range that includes most systems of practical importance. Maximum loading occurs shortly after deployment is initiated, and total loading is kept within a safe range by limiting the deployment velocity and initial angular rate.

2.2 Rebound at the End of Deployment

The fully extended boom is a long, slender column that cannot support any appreciable amount of compression loading; therefore, the deployment mechanism must include some provision to minimize rebound. This is accomplished by using a regulator to program the extension velocity so that it is very small at the end of extension. Defective performance of the regulator may lead to total failure (buckling) of the boom.

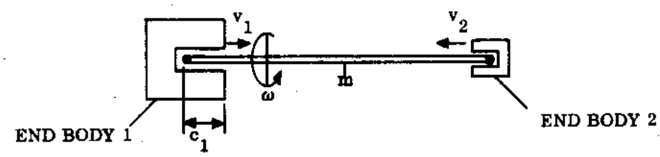
3. GRADUAL BOOM DEFORMATION

3.1 Deformation During Deployment

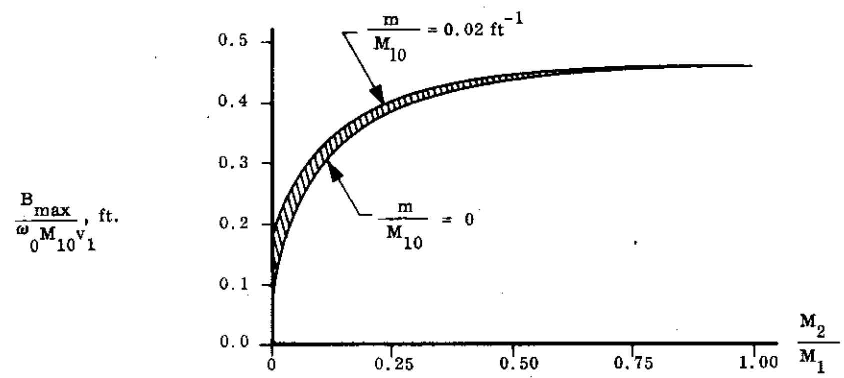
Permanent deformation that occurs during the extension of the boom is, at the present state-of-the-art, the most important limiting factor in boom performance. Deformation is due to: (a) manufacturing tolerances and (b) deployment mechanism. Manufacturing tolerances include non-homogeneous material properties, dimensional tolerances, uneven heat treatment, finishing, etc. Careful selection of materials and production control help minimize boom deformation. Permanent bending induced by the deployment mechanism can be minimized by increasing the length and smoothness of deployment-guiding elements. The total deformation effect from both sources can be reduced by compensatory bending of the boom in a direction opposite to that observed during ground-testing in a simulated 0-g environment. The ultimate direction of bending (or spiraling) of the boom in space is unpredictable and, therefore, cannot be corrected by a system compensation.

3.2 Orbit-Dependent Deformation

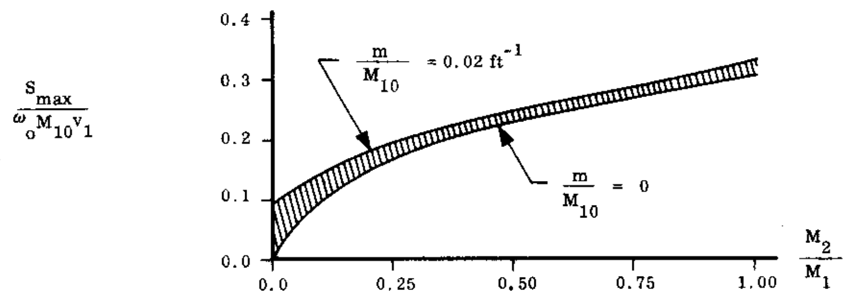
Boom bending due to orbit-dependent causes is generally small for short booms, but becomes significant for very long booms. For example, tip deflection for a 1000-foot-long boom (4) due to the combined effect of uneven heating, solar pressure, and gravity gradient effect is 400 feet. In contrast, the tip deflection of a similar 100-foot boom is less than 2 feet. However, as system performance requirements are becoming more stringent, considerable effort is being undertaken to reduce the tip deflection -- even for shorter



a. TWO BODY SYSTEM SEPARATED BY BOOM



b. BENDING MOMENT



c. SHEAR

NOMENCLATURE:

B	bending moment
I	moment of inertia
M	initial mass of end body
S	shear
c	length of boom in end body
m	mass of boom per unit length
v	velocity of ejection from end body
ω	angular velocity

SUBSCRIPTS:

0	initial
1	refers to end body 1
2	refers to end body 2

RANGE OF PARAMETERS:

$1.0 \leq M_{10} \leq 100$ slug

$0 \leq m \leq 0.020$ slug/ft

$1.0 \leq v_1 \leq 10.0$ ft/sec

$v_2 = 0$

$c_1 = c_2 = 1.5$ ft

$$\frac{I_{10}}{M_{10}} = \frac{I_{20}}{M_{20}} = 1\ ft^2$$

Figure 1 Maximum Bending Moment and Shear for Representative Range of Parameters of Two Body System Separated by Boom booms. In the following sections, we will discuss the various orbit-dependent causes in more detail.

3.2.1 Uneven Heating Due to Solar Radiation and Earth Albedo

When the boom is exposed to solar radiation, the side facing the sun heats up more than the far side, causing it to bend away from the sun. Steady-state temperature distribution and bending takes place when the heat received is equal to the amount re-radiated into space. The distribution is determined by the thermal properties of the internal and external surfaces of the boom, the conductivity of the material, and the geometry of the configuration.

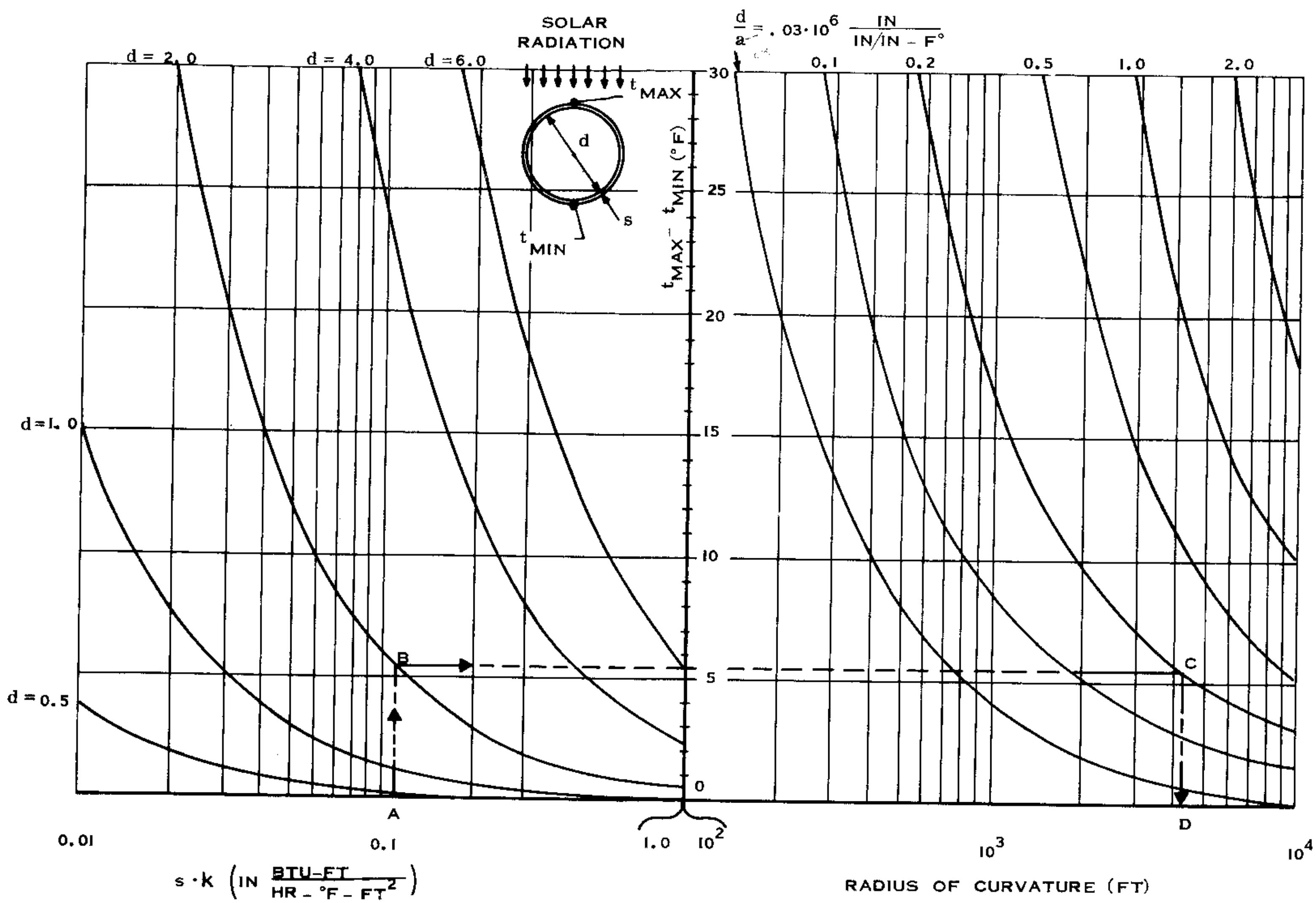
Figure 2 shows the results of a study made on pointing-error problems for passively stabilized spacecraft (5). The radius of curvature is calculated by following the path A, B, C, D of the sample calculation of a 2-inch diameter, berrylium copper boom 0.002-inch thick, having a highly-polished, silver-coated external surface covered by a coating to regulate emissivity. The resulting maximum temperature differential is 5.5^{o}F, and the corresponding radius of curvature is 4,200 feet. If the boom were made of stainless steel, the corresponding figures would be 27^{o}F and 600 feet. For angles of incidence other than 90 degrees, the difference between the temperature at any point on the periphery of the boom and the average temperature diminishes proportionately with the 1/4-power of the cosine of the angle of incidence of the solar radiation. An increase in the angle of incidence also reduces the average temperature, but this in itself does not influence boom bending since it does not induce differential elongation. Bending radius is independent of the modulus of elasticity and thickness of the material of the boom; curvature can be minimized by making the boom diameter small and by selecting boom materials having a small coefficient of expansion and good thermal conductivity.

Earth albedo radiation has the same effect as solar radiation, except to a much lesser degree. This effect can be neglected for practical calculations for all except for very low orbits.

3.2.2 Thermally-Induced Impulse

An abrupt change in the temperature distribution at the periphery of the boom occurs each time the satellite moves from the earth's shadow into sunlight, causing a rapid heating of the boom. The effect of the sudden extension of parts of the boom is equivalent to an impulse excitation, resulting in free oscillation of the boom-satellite system. (These oscillations were detected from telemetry data received from the satellite 1963 22A (1)). If the system has no special provisions for damping out these oscillations, this motion is damped only by internal losses of the material. If the boom is made of berrylium copper having a low hysterysis coefficient, the oscillations will last several hours.

Thermally-induced impulses can be eliminated by selecting an orbit that is entirely in sunlight. If this is not possible, the amplitude of the oscillations can be reduced by suitably plating and coating the boom surface to minimize the absorption of solar energy and provide increased hysteresis damping.



NOMENCLATURE:

a	absorptivity	k	conductivity
e	emissivity	s	boom thickness
d	boom diameter	t	temperature

$a = 0.05; \quad e = 0.15$

Figure 2 Radius of Curvature of Booms Exposed To Perpendicular Solar Radiation

3.2.3 Gravity-Gradient Effect

The "gravity-gradient effect" is a misnomer for the combined effects of the gravitational and centrifugal gradients on spacecraft. It was demonstrated (1) that this effect can be utilized for passively stabilizing satellites to point at all times toward the center of the earth, just as the moon always presents its same side towards the earth. The effects also produce boom bending that is particularly pronounced for very long booms.

Each particle of the orbiting satellite is attracted towards the center of the earth by a force that is inversely proportional to the square of the distance and proportional to the radius of the instantaneous orbital path. Figure 3-a shows, schematically, the relationship of the forces with altitude for various boom elements. In the following discussion it is assumed that: (a) the entire spacecraft is in the orbital plane, (b) the spacecraft is symmetrical, (c) earth is a homogeneous sphere, (d) the orbit is circular, and (e) centrifugal forces due to spacecraft rotation about its own center of gravity are negligible. The dashed lines in Figure 3-b show boom bending due to the gravity-gradient effect. The elementary force acting on an elementary particle (6) is $\Delta F = 3\omega^2 x (\Delta m) \cos\theta$. By taking the components of the forces perpendicular to the boom and multiplying by the corresponding distances from the center of gravity of the system and integrating, we obtain the bending moment:

$$M = 0.5\, A\omega^2 l^3 \sin 2\theta$$

where:

A = boom cross-sectional area, feet square
M = bending moment, foot-pounds
l = boom length, feet
ω = orbital rate, radians per second
θ = included half-angle, radians
ρ = boom density, slugs

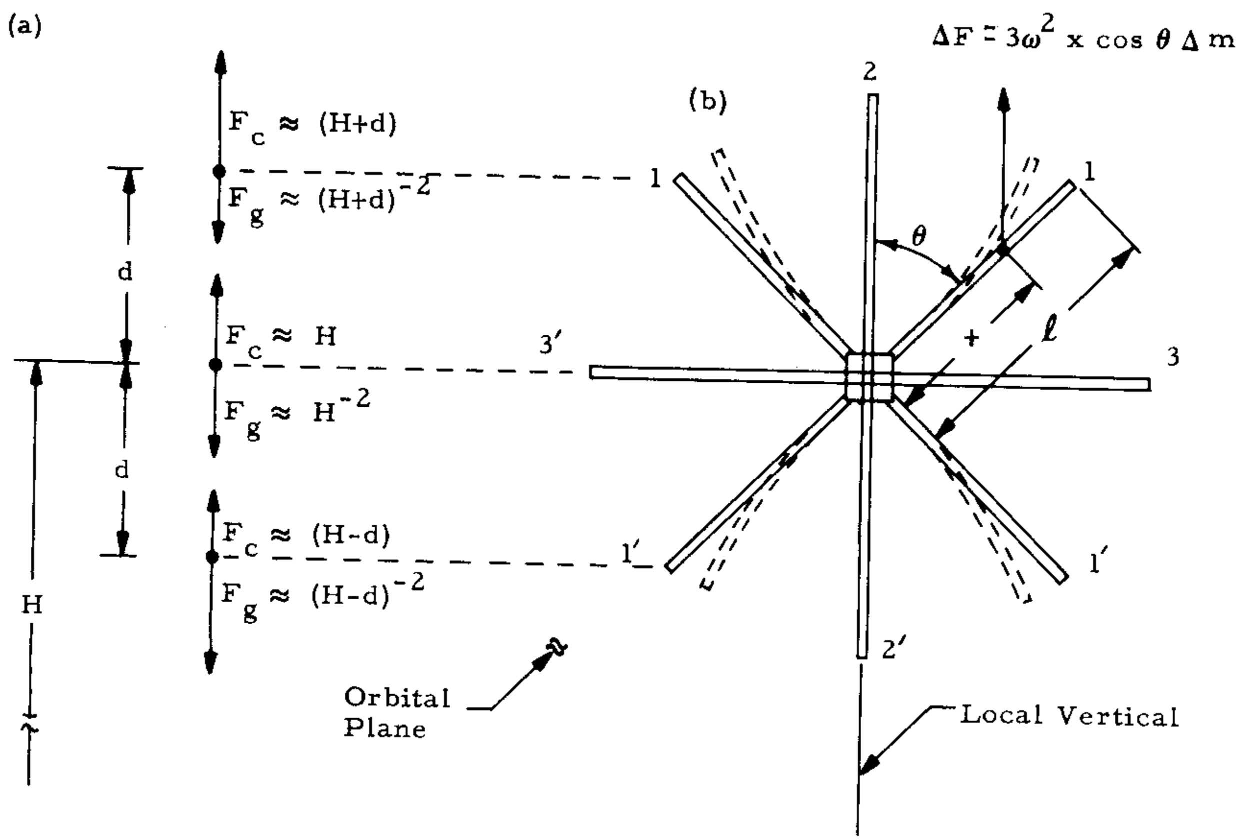
This equation indicates that the bending moment is maximum for θ = 45 degrees (booms 1 and 1') and is equal to zero for θ = 0 (booms 2 and 2') and θ = 90 degrees (booms 3 and 3'). This gravity gradient effect is an important design consideration for systems that contain long booms since bending is proportional to the cube of boom length.

Maximum tensile stress is obtained by considering the sum of the axial components of the forces per unit area:

$$\sigma_{max} = 3\omega^2 \rho\, l \cos^2\theta$$

Stress is linearly proportional to the length and density of the boom material and the square of orbital rate. It is maximum for θ = 0 (booms 2 and 2') and equal to zero for θ = 90 degrees (boom 3 and 3').

Variations of the gravity-gradient forces due to orbit eccentricity and the non-homogeneous earth induce additional bending moments which become significant only for very eccentric orbits.



a) Relation of gravitational and centrifugal forces per unit mass with altitude for various boom elements.

b) General configuration of symmetrical satellite with three long booms.

Figure 3 Boom Bending Due to Gradient of Gravitational and Centrifugal Forces

3.2.4 Solar Pressure

Solar pressure on the boom is produced by the momentum of the photon stream from solar radiation. Its magnitude depends on the angle of incidence and the reflectivity of the surface. For perpendicular incidence in earth orbit, it is equal to $N \times 4.53 \times 10^{-5}$ dynes per square centimeter, where $1 \leq N \leq 2$; the low limit applies to an ideal absorber and the high limit to an ideal reflector of photons. The sun also emits other particles, such as protons and electrons; however, the produced pressures are insignificant in comparison because they have low linear momenta.

The maximum bending moment and the corresponding tip deflection, for any set of booms, such as shown in Figure 3-b, exposed to perpendicular solar radiation, is given by:

$$M_{max} = 0.5 \, Sdl^2$$

$$f = Sdl^4/8EI$$

where:

M_{max} = maximum bending moment, in-lbs

f = tip deflection, in.
$S = N \times 6.56 \times 10^{-10}$, lbs per in^2
d = boom diameter, in.
l = boom length, in.
E = modulus of elasticity, lbs per in^2
I = inertia, in^4

These equations were developed on the basis of small-angle approximation and are sufficiently accurate only for short booms having a uniform cross-section. For large deflections, we must consider additional terms in the equations and take into account the variation of angle of incidence. The calculations are best performed numerically, since there is no closed-form solution.

3.2.5 Micrometeorites

Depending on the properties of the impinging micrometeorites (composition, shape, linear momentum, angle of incidence, etc.), and the properties of the boom (material, thickness, etc.), these particles will have one of the following effects:

a. Coalesce with the boom and deliver the entire momentum.

b. Splash some material backwards (cratering effect) delivering more than the corresponding momentum discussed in case a.

c. Prenetrate through the boom and deliver only part of its momentum to the boom.

The effect of the impact is in all cases similar to the thermally induced impact discussed in Section 2.2.2, except that the force acts only upon a very small area instead of being distributed over the entire length of the boom. A grazing impact may cause torsional loading of the boom. The probability of a direct hit of the extremity of the boom (where the moment arm is large) is small as confirmed by the impact data from the Explorer-16 satellite.

3.2.6 Electromagnetic Effects

Hysteresis currents are generated in a boom made of conductive material when it moves in the earth's magnetic field. The energy for generating the currents is derived from the kinetic energy of the system; consequently, the vehicle is decelerated. The associated inertial forces depend on the magnetic field which is cyclic in position and time and is influenced by sources other than the earth (e.g., sun spots). The resulting bending moment is minimized by selecting an equatorial orbit that is nearly a path of constant field strength or by using nonconductive materials.

If the material of the boom is magnetic, it tends to align itself with the earth's magnetic field. The generated torques also produce inertial forces and bending moments.

3.2.7 Active Control

Following are the two principal categories of active spacecraft actuation methods:

a. Propulsion, such as gas jets, vapor pressure, ion engines, activation of coils for alignment with magnetic field, etc.

b. Internal moving parts, such as reaction wheels, rate gyros, etc.

Boom-bending moments are induced by the inertial forces resulting from the methods used for active control. They depend on many parameters and no general relations can be developed, but they can be held within safe limits by good dynamic systems design.

3.2.8 Atmospheric Drag

Atmospheric drag is the largest source of boom bending at orbital heights below 400 miles. A dynamic pressure of about 6×10^5 dyne per cm^2 (D - 8.7 lbs per in^2) is typical. The equations for maximum bending moment and tip deflection given in Section 2.2.4 are applicable by substituting the value D for S. The same restrictions on validity of the equations are applicable.

3.3 Environmentally Induced Bending

Of the principal characteristics of space environment, radiation, hard vacuum, meteorites of various sizes, and temperature extremes cause material and surface degradation and, indirectly, boom bending. Zero gravity, on the other hand, enables us to erect long, lightweight booms that would collapse under their own weight on the earth.

Hard vacuum in space (10^{-10} torr at an altitude of 500 miles, 10^{-12} torr at 1,000 miles) greatly accelerates sublimation of boom surfaces, i.e., boom material particles leave the surface. The impact of small, solid particles and radiation from various sources (solar flares, radiation due to protons and electrons trapped in Van Allen belt, cosmic and auroral radiation) also cause boom surface degradation. Consequently, thermal absorptivity and emissivity change, resulting in increased boom bending due to uneven heating of the boom periphery, thermally-induced impact, and solar pressure, as discussed in Sections 3.2.1, 3.2.2, and 3.2.4.

4. CONCLUSIONS

Boom bending can be either localized or gradually distributed over the entire length of the boom. Localized bending occurs during boom deployment and is due to inertial and Corialis forces, rebound at the end of deployment, and localized cold welding. The deformation may in the worst case lead to total failure of the boom, but is in all cases predictable and preventible. Three classes of gradual boom bending are discussed: (a) initial distortion, (b) orbit dependent distortion, and (c) slowly induced distortion due to space exposure. Gradual bending cannot be entirely eliminated, and the object of the design is to keep it within tolerable limits. Results of calculations and diagrams are presented for various cases of practical importance.

A great deal of experimental and theoretical work is presently being conducted on the subject discussed in this paper. Means for minimizing some problems are contrary to the means for minimizing others, but fortunately, not all problems are encountered on all missions. Therefore, the task of the design engineer is to determine the dominant factor and to optimize the system accordingly. The never-ending desire to further improve system performance will impose more stringent requirements and will stimulate much more work in this field in the near future.

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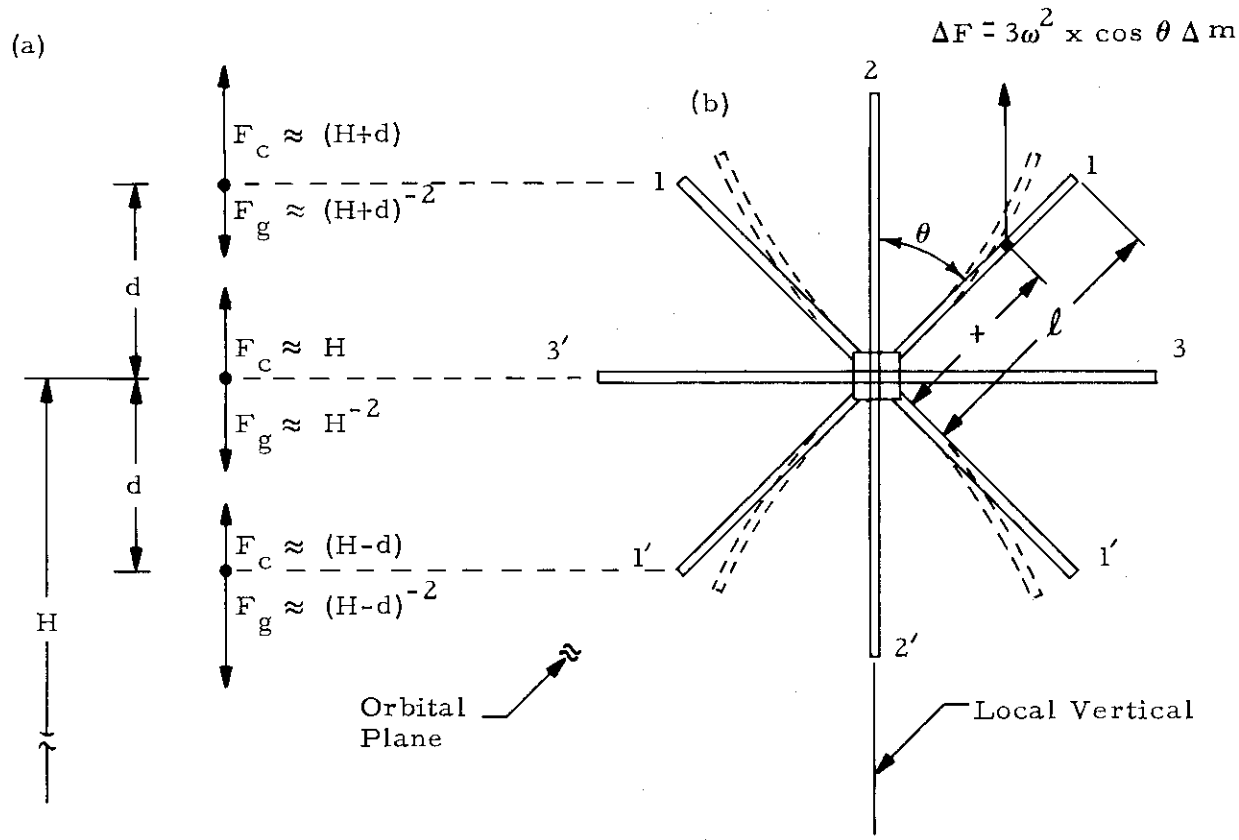

a) Relation of gravitational and centrifugal forces per unit mass with altitude for various boom elements.

b) General configuration of symmetrical satellite with three long booms.

Figure 3 Boom Bending Due to Gradient of Gravitational and Centrifugal Forces