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ATTITUDE STABILITY OF A CLASS OF PARTIALLY FLEXIBLE SPINNING SATELLITES

by Thomas W. Flatley

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Greenbelt, Md.

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ABSTRACT

A stability criterion is presented for spinning satellites, which consist of a rigid, symmetric, central body and four radial booms of arbitrary flexibility.

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INTRODUCTION

Spacecraft flexibility can invalidate the well known attitude stability criterion for spinning satellites. That is, rotation of a satellite about the maximum moment of inertia axis for the nominal spacecraft configuration may not be stable in the presence of energy dissipation. If structural flexibility permits configuration changes and strain energy storage when the spacecraft spins about an axis other than the nominal spin axis, a new criterion is needed.

The class of spacecraft considered here consists of a rigid, symmetric central body with four equally spaced uniform radial booms nominally in a plane through the center of mass and normal to the intended spin axis (Figure 1).

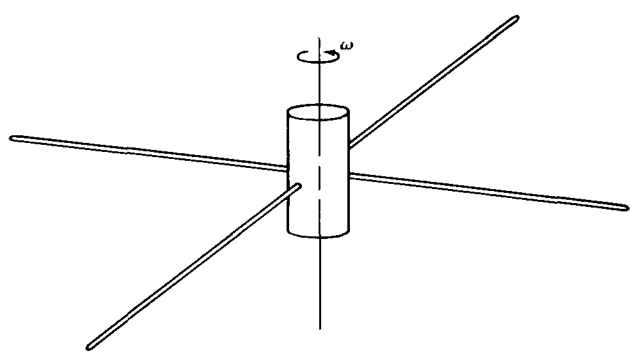

Figure 1—Satellite configuration.

STABILITY CRITERION

Approach

Consider a forced rotation of the system at a rate ω about a body fixed axis through the center of mass and at an angle α with respect to the nominal spin axis, with the booms in dynamic equilibrium. Associate with this rotation a moment of inertia $I(\alpha, \omega)$, a kinetic energy $1/2\ I\omega^2$, and a potential energy $V(\alpha, \omega)$.

Consider also a rotation about the nominal spin axis with an equivalent angular momentum. Associate with this rotation an angular velocity ω_0, a moment of inertia I_0, a kinetic energy $1/2\ I_0 \omega_0^2$, and no potential energy. If the kinetic energy of this rotation is less than the total energy associated with the forced rotation, then rotation about the nominal axis is stable in the presence of energy dissipation.

This stability criterion can be expressed as

$$\frac{1}{2} I_0 \omega_0^2 < \frac{1}{2} I\omega^2 + V ,$$

or,

$$\frac{2V}{\omega^2} > I\left(\frac{I}{I_0} - 1\right) ,$$

which becomes

$$\frac{2V}{\omega^2} > I - I_0 ,$$

for small α when $I \approx I_0$.

Analysis of Forced Rotation

Potential Energy

Locate $\boldsymbol{\omega}$ such that only one pair of booms is deflected. The potential energy of the system will be

$$V = 2\int_0^{\ell} \frac{M^2}{2EI}\, ds ,$$

where M = bending moment, EI = boom stiffness factor, and ℓ = boom length.

If we let

$$\frac{M}{EI} = \frac{1}{R} = \frac{d\theta}{ds} ,$$

the left hand side of the stability criterion becomes

$$LHS = \frac{2EI}{\omega^2}\int_0^{\ell}\left(\frac{d\theta}{ds}\right)^2 ds .$$

See Figure 2.

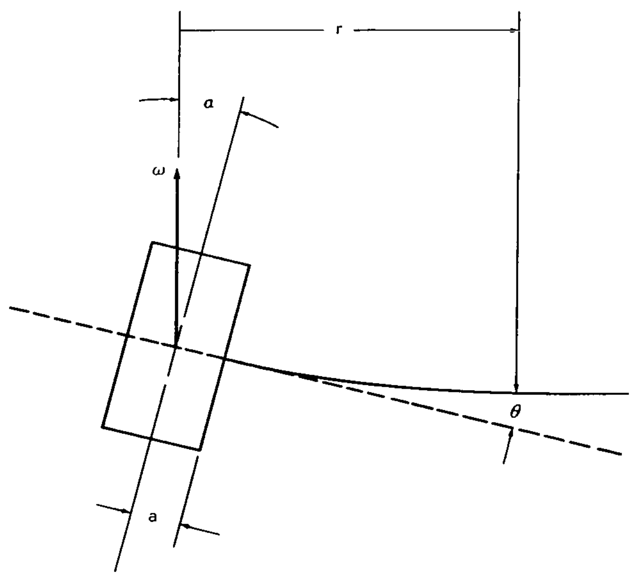

Figure 2—Deflected boom geometry.

Moment of Inertia

The moment of inertia about the axis of forced rotation will be

$$I = I_R \cos^2\alpha + I_P \sin^2\alpha$$

$$+ \frac{2}{3}\rho\left[(a+\ell)^3 - a^3\right] + 2\int_0^{\ell}\rho r^2\, ds ,$$

where I_R and I_P are central body moments of inertia, a is the radius at which the boom is attached, and ρ is the boom's lineal mass density.

Now,

$$I_0 = I_R + \frac{2}{3}\rho\left[(a+\ell)^3 - a^3\right] + 2\int_0^{\ell} \rho(a+s)^2\,ds\ ,$$

so

$$I - I_0 = \left(I_P - I_R\right)\sin^2\alpha + 2\rho\int_0^{\ell}\left[r^2 - (a+s)^2\right]ds\ .$$

Now $dr/ds = \cos(\alpha - \theta)$, and $r(0) = a\cos\alpha$. Thus for small α,

$$r \approx a\left(1 - \frac{\alpha^2}{2}\right) + \int_0^s \left[1 - \frac{(\alpha-\theta)^2}{2}\right]ds\ ,$$

which becomes

$$r \approx (a+s) - \frac{\alpha^2}{2}\left[a + \int_0^s \left(\frac{\theta}{\alpha} - 1\right)^2 ds\right].$$

Then

$$r^2 \approx (a+s)^2 - \alpha^2(a+s)\left[a + \int_0^s \left(\frac{\theta}{\alpha} - 1\right)^2 ds\right],$$

and

$$2\rho\int_0^{\ell}\left[r^2 - (a+s)^2\right]ds \approx -\rho\alpha^2\left\{a(a+s)^2\Big|_0^{\ell} + \int_0^{\ell}\left[2(a+s)\int_0^s\left(\frac{\theta}{\alpha} - 1\right)^2 ds\right]ds\right\}.$$

Thus, for small α, the right hand side of the stability criterion becomes

$$\text{RHS} = \alpha^2\left\{I_P - I_R - \rho a\ell(2a+\ell) - \rho\int_0^{\ell}\left[(2a+2s)\int_0^s\left(\frac{\theta}{\alpha} - 1\right)^2 ds\right]ds\right\}.$$

Introducing the dimensionless quantities

$$\phi = \frac{\theta}{\alpha} - 1 , \qquad u = \frac{s}{\ell} ,$$

and

$$\epsilon = \frac{2a}{\ell} ,$$

the stability criterion becomes

$$\frac{2EI}{\omega^2 \ell} \int_0^1 \left(\frac{d\phi}{du}\right)^2 du > I_P - I_R - \rho\ell^3 \left\{\frac{\epsilon}{2} (\epsilon + 1) - \int_0^1 \left[(\epsilon + 2u) \int_0^u \phi^2 \, du\right] du\right\} ,$$

and a stability boundary can be written

$$\Delta I = \rho\ell^3 \left\{\frac{1}{k} \int_0^1 \left(\frac{d\phi}{du}\right)^2 du + \frac{\epsilon}{2} (\epsilon + 1) + \int_0^1 \left[(\epsilon + 2u) \int_0^u \phi^2 \, du\right] du\right\} ,$$

where

$$k = \frac{\rho\omega^2 \ell^4}{2EI} .$$

Series Representation

Now, let

$$\phi \approx \sum_{n=1}^{N} \phi_n u^{n-1} .$$

It follows that

$$\phi^2 = \sum_{n=1}^{N} \sum_{j=1}^{n} \phi_j \phi_{n+1-j} u^{n-1} ,$$

$$\int_0^u \phi^2 \, du = \sum_{n=1}^{N} \frac{u^n}{n} \sum_{j=1}^{n} \phi_j \phi_{n+1-j} ,$$

$$\int_0^1 \left[(\epsilon + 2u) \int_0^u \phi^2 \, du \right] du = \sum_{n=1}^{N} \frac{1}{n} \left[\frac{\epsilon}{n+1} + \frac{2}{n+2} \right] \sum_{j=1}^{n} \phi_j \, \phi_{n+1-j} \; ,$$

$$\frac{d\phi}{du} = \sum_{n=1}^{N} (n-1) \, \phi_n \, u^{n-2} = \sum_{n=1}^{N-1} n \, \phi_{n+1} \, u^{n-1} \; ,$$

$$\left(\frac{d\phi}{du} \right)^2 = \sum_{n=1}^{N-1} \sum_{j=1}^{n} j(n+1-j) \, \phi_{j+1} \, \phi_{n+2-j} \, u^{n-1} \; ,$$

$$\int_0^1 \left(\frac{d\phi}{du} \right)^2 du = \sum_{n=1}^{N-1} \frac{1}{n} \sum_{j=1}^{n} j(n+1-j) \, \phi_{j+1} \, \phi_{n+2-j} \; .$$

The stability boundary thus becomes

$$\Delta I = \rho \ell^3 \left\{ \frac{1}{k} \sum_{n=1}^{N-1} \frac{1}{n} \sum_{j=1}^{n} j(n+1-j) \, \phi_{j+1} \, \phi_{n+2-j} + \frac{\epsilon}{2} (1 + \epsilon) + \sum_{n=1}^{N} \frac{1}{n} \left[\frac{\epsilon}{n+1} + \frac{2}{n+2} \right] \sum_{j=1}^{n} \phi_j \, \phi_{n+1-j} \right\} .$$

ROD ANALYSIS

Equilibrium Beam Equations

The equations of equilibrium for a thin rod and the constitutive relationship for an elastic rod are

$$\frac{d\mathbf{F}}{ds} + \mathbf{p} = \mathbf{0} \; ,$$

$$\frac{d\mathbf{M}}{ds} + \mathbf{u} \times \mathbf{F} + \mathbf{m} = \mathbf{0} \; ,$$

and

$$M = EI \, \frac{1}{R} \; .^*$$

See Figure 3.

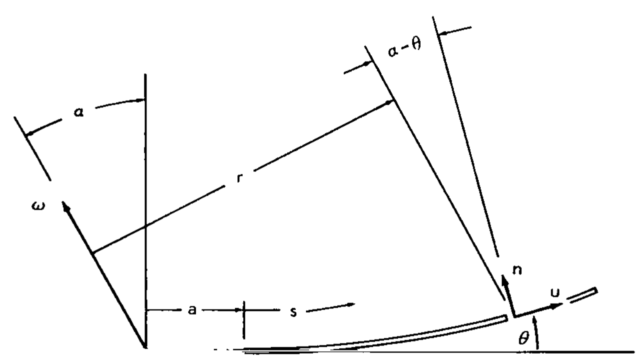

Figure 3—Planar bending of elastic rod.

*Hildebrand, Francis B., "Advanced Calculus for Applications," Prentice-Hall, Inc., Englewood Cliffs, N. J., 1964.

For the planar problem at hand,

$\mathbf{F} = T\mathbf{u} + Q\mathbf{n}$, where T = tension, Q = shear;

$\mathbf{p}$ = centrifugal loading $= \rho\omega^2 \mathbf{r}$;

$\mathbf{M} = M\mathbf{b}$, where M = bending moment, $\mathbf{b} = \mathbf{u} \times \mathbf{n}$;

$\mathbf{m}$ = applied couples $= \mathbf{0}$;

$\frac{1}{R} = \frac{d\theta}{ds}$, where θ = slope of rod;

$\frac{d\mathbf{u}}{ds} = \frac{d\theta}{ds}\mathbf{n}$; and $\frac{d\mathbf{n}}{ds} = -\frac{d\theta}{ds}\mathbf{u}$.

Now, the magnitude of $\mathbf{r}$ is given by

$$r = a\cos\alpha + \int_0^s \cos(\alpha - \theta)\, ds ,$$

and a unit vector parallel to $\mathbf{r}$ is

$$\hat{r} = \mathbf{u}\cos(\alpha - \theta) + \mathbf{n}\sin(\alpha - \theta) .$$

Thus keeping only first order terms in the small angles α and θ we have the approximation

$$\mathbf{r} \approx (a + s)\left[\mathbf{u} + (\alpha - \theta)\mathbf{n}\right] .$$

The equilibrium beam equations thus reduce to:

$$\frac{dT}{ds} - Q\frac{d\theta}{ds} + \rho\omega^2(a + s) = 0 ,$$

$$\frac{dQ}{ds} + T\frac{d\theta}{ds} + \rho\omega^2(a + s)(\alpha - \theta) = 0 ,$$

$$\frac{dM}{ds} + Q = 0 ,$$

$$\frac{M}{EI} = \frac{d\theta}{ds} .$$

The corresponding boundary conditions are

$$\theta(0) = M(\ell) = T(\ell) = Q(\ell) = 0 .$$

If we ignore the product of the small terms Q and $d\theta/ds$, integrate the first equation, and combine, we have

$$EI \frac{d^3\theta}{ds^3} = \frac{\rho\omega^2}{2}\left[(a+\ell)^2-(a+s)^2\right]\frac{d\theta}{ds} + \rho\omega^2(a+s)(\alpha-\theta) ,$$

$$\frac{d^3\theta}{ds^3} = \frac{\rho\omega^2}{2EI}\left\{2\alpha(a+s) + \left(2a\ell+\ell^2\right)\frac{d\theta}{ds} - 2a\left(s\frac{d\theta}{ds}+\theta\right) - \left(s^2\frac{d\theta}{ds}+2s\theta\right)\right\} ,$$

$$\theta(0) = \frac{d\theta}{ds}(\ell) = \frac{d^2\theta}{ds^2}(\ell) = 0 .$$

This equation integrates once,

$$\frac{d^2\theta}{ds^2} = \frac{\rho\omega^2}{2EI}\left\{\alpha(a+s)^2 + \ell(2a+\ell)\theta - 2as\theta - s^2\theta + c\right\} .$$

Since

$$\frac{d^2\theta}{ds^2}(\ell) = 0 ,$$

then

$$c = -\alpha(a+\ell)^2 .$$

Now, making the substitutions

$$\phi = \frac{\theta}{\alpha} - 1 , \qquad u = \frac{s}{\ell} , \qquad \epsilon = 2\frac{a}{\ell} ,$$

we have

$$\alpha\frac{d^2\phi}{du^2} = \frac{\rho\omega^2\ell^4}{2EI}\,\alpha\left\{\left(\frac{\epsilon}{2}+u\right)^2 + (\epsilon+1)(\phi+1) - \epsilon u(\phi+1) - u^2(\phi+1) - \left(\frac{\epsilon}{2}+1\right)^2\right\} ,$$

$$\frac{d^2\phi}{du^2} = k\left\{\epsilon+1-\epsilon u-u^2\right\}\phi ,$$

$$= k\left\{\epsilon(1-u)+(1+u)(1-u)\right\}\phi ,$$

$$= k(1+\epsilon+u)(1-u)\phi .$$

The boundary conditions for this equation are

$$\phi(0) = -1, \qquad \frac{d\phi}{du}(1) = 0 .$$

Power Series Solution

We now seek a power series solution of the form

$$\phi = \sum_{n=1}^{N} \phi_n u^{n-1} ,$$

where N is large enough for convergence.

To satisfy the boundary conditions,

$$\phi_1 = -1 ,$$

and

$$\sum_{n=1}^{N} (n-1)\phi_n = \sum_{n=1}^{N-1} n\phi_{n+1} = 0 .$$

Now

$$\frac{d^2\phi}{du^2} = \sum_{n=1}^{N} (n-1)(n-2)\phi_n u^{n-3} ,$$

$$= 2\phi_3 + 6\phi_4 + \sum_{n=5}^{N} (n-1)(n-2)\phi_n u^{n-3} ,$$

$$= 2\phi_3 + 6\phi_4 u + \sum_{n=1}^{N-4} (n+3)(n+2)\phi_{n+4} u^{n+1} ;$$

and

$$k(\epsilon+1)\phi = \sum_{n=1}^{N} k(\epsilon+1)\phi_n u^{n-1} ,$$

$$= -k(\epsilon+1) + k(\epsilon+1)\phi_2 u + \sum_{n=1}^{N-2} k(\epsilon+1)\phi_{n+2} u^{n+1} ,$$

$$-k\epsilon u\phi = -\sum_{n=1}^{N} k\epsilon\phi_n u^n = k\epsilon u - \sum_{n=1}^{N-1} k\epsilon\phi_{n+1} u^{n+1} ,$$

$$-ku^2\phi = -\sum_{n=1}^{N} k\phi_n u^{n+1} .$$

Term by term comparison of the resulting equation yields

$$\phi_3 = -\frac{k}{2}(1+\epsilon) ;$$

$$\phi_4 = \frac{k}{6}\left[\epsilon + (1+\epsilon)\phi_2\right] ;$$

$$(n+3)(n+2)\phi_{n+4} = k(1+\epsilon)\phi_{n+2} - k\epsilon\phi_{n+1} - k\phi_n ,$$

$$\phi_{n+4} = \frac{k}{(n+3)(n+2)}\left[(1+\epsilon)\phi_{n+2} - \epsilon\phi_{n+1} - \phi_n\right] ,$$

$$n = 1, 2, \cdots, N-4 ;$$

and

$$\phi_n = \frac{k}{(n-1)(n-2)}\left[(1+\epsilon)\phi_{n-2} - \epsilon\phi_{n-3} - \phi_{n-4}\right] ,$$

$$n = 5, 6, \cdots, N .$$

Now each of these terms will be the sum of a constant and a linear term in ϕ_2, i.e. $\phi_i = a_i + b_i\phi_2$. Thus it is convenient to express each as a complex quantity (a_i, b_i). Then, when multiplying terms by constants and forming linear combinations of terms, the constant and ϕ_2 dependent portions of the result are automatically obtained.

With this convention,

$$\phi_1 = (-1, 0) ,$$

$$\phi_2 = (0, 1) ,$$

$$\phi_3 = \left(-(1+\epsilon)k/2, 0\right) ,$$

$$\phi_4 = \left(\epsilon k/6, (1+\epsilon)k/6\right) .$$

ϕ_2 is then determined from the boundary condition as follows:

$$\sum_{n=1}^{N-1} n\phi_{n+1} = (A, B) \Rightarrow A + B\phi_2 = 0 ,$$

$$\phi_2 = -\frac{A}{B} = -\, \mathrm{real}\left(\sum_{n=1}^{N-1} n\phi_{n+1}\right) \Bigg/ \mathrm{imag}\left(\sum_{n=1}^{N-1} n\phi_{n+1}\right) .$$

Values for all other terms are then calculated according to

$$\phi_i = \mathrm{real}(\phi_i) + \phi_2 \left[\mathrm{imag}(\phi_i)\right] .$$

The previously mentioned "stability boundary" can be written as a function of k, ϵ, and N:

$$\frac{\Delta I}{\rho \ell^3} = \frac{\epsilon}{2}(1+\epsilon) + \frac{1}{k}\sum_{n=1}^{N-1} \frac{1}{n} \sum_{j=1}^{n} j(n+1-j)\,\phi_{j+1}\,\phi_{n+2-j}$$

$$+ \sum_{n=1}^{N} \frac{1}{n}\left[\frac{\epsilon}{n+1} + \frac{2}{n+2}\right] \sum_{j=1}^{n} \phi_j\,\phi_{n+1-j} .$$

Limiting Cases

In the extreme cases of infinite beam stiffness, where no deflection is possible, and vanishing beam stiffness, where the beam behaves as though hinged, no potential energy is associated with the forced rotation. The stability boundary is then

$$\frac{\Delta I}{\rho \ell^3} = \frac{\epsilon}{2}(1+\epsilon) + \int_0^1 \left[(\epsilon + 2u) \int_0^u \phi^2\, du\right] du .$$

In the rigid rod case ($k = 0$),

$$\theta \equiv 0 , \qquad \phi \equiv -1 ,$$

so

$$\frac{\Delta I}{\rho \ell^3} = \frac{\epsilon}{2}(1+\epsilon) + \int_0^1 (\epsilon + 2u)\, u\, du ,$$

$$= \frac{2}{3} + \epsilon + \frac{\epsilon^2}{2} .$$

Thus for stability

$$\Delta I = I_P - I_R < \rho \ell^3 \left[\frac{2}{3} + \epsilon + \frac{\epsilon^2}{2}\right] .$$

Because the roll and pitch moments of inertia of the undistorted satellite are

$$C = I_R + \frac{4}{3}\rho\left[3a^2\ell + 3a\ell^2 + \ell^3\right] ,$$

$$A = I_P + \frac{2}{3}\rho\left[3a^2\ell + 3a\ell^2 + \ell^3\right] ,$$

respectively, and because $\epsilon = 2(a/\ell)$, then

$$C = I_R + 2\rho\ell^3 \left[\frac{\epsilon^2}{2} + \epsilon + 1\right] ,$$

$$A = I_P + \rho\ell^3 \left[\frac{\epsilon^2}{2} + \epsilon + 1\right] ,$$

$$I_P - I_R < C - I_R - A + I_P ,$$

$$C > A ,$$

so that the stability criterion reduces to the familiar "rigid body" criterion.

In the hinged rod case $(k = \infty)$,

$$\theta \equiv \alpha , \qquad \phi \equiv 0$$

so

$$\frac{\Delta I}{\rho\ell^3} = \frac{\epsilon}{2}(1 + \epsilon) .$$

Consider the possibility of a forced rotation, with hinged booms, being stable. Then, the torque on the central body caused by the centrifugal forces on the hinged booms (Figure 4) must be just enough to maintain a constant angular velocity in body coordinates, i.e.

$$\omega_x \equiv 0 ,$$

$$\omega_y \equiv \omega \sin\alpha ,$$

$$\omega_z \equiv \omega \cos\alpha .$$

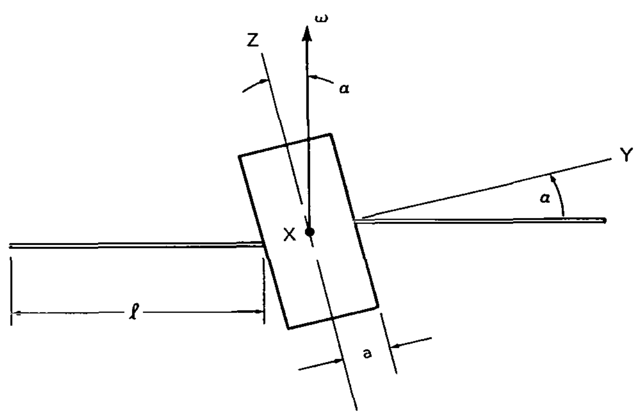

Figure 4—Steady spin with hinged rods.

The torque on the central body is

$$T = T_x = -2(a \sin \alpha) \int_0^{\ell} \rho(a \cos \alpha + s)\, \omega^2\, ds \ ,$$

$$= -2a\rho\omega^2 \sin \alpha \left[a\ell \cos \alpha + \frac{\ell^2}{2} \right] .$$

The Euler equations reduce to one,

$$\left(I_R - I_P\right) \omega_y \omega_z = -a\ell^2 \rho\omega^2 \sin \alpha \left[2\frac{a}{\ell} + 1 \right] ,$$

$$\Delta I \cos \alpha = \rho a \ell^2 \left[1 + 2\frac{a}{\ell} \right] .$$

For small α,

$$\Delta I = \rho\ell^3 \frac{a}{\ell} \left[1 + 2\frac{a}{\ell} \right] ,$$

$$\frac{\Delta I}{\rho\ell^3} = \frac{\epsilon}{2}(1 + \epsilon) ,$$

which is identical to the stability boundary above.

RESULTS

The "stability boundary" dealt with above represents a maximum value of $\Delta I/\rho\ell^3$ for which the attitude motion of the spacecraft will be stable. If one plots this quantity as a function of the parameter k for some value of ϵ, the region above the curve represents unstable combinations of variables and the region below stable configurations. Consideration of the limiting cases just described produces the values of $\Delta I/\rho\ell^3$ asymptotically approached by the ends of the curve. For the general case $0 < k < \infty$, points were calculated by the digital computation method described in this report.

Figure 5 and Table 1 show the results obtained for intermediate values of k and several values of ϵ. The dashed lines indicate asymptotic values for $k = 0$ and $k = \infty$.

Parameter definitions pertinent to use of the figure are:

ΔI = maximum tolerable moment of inertia difference for the central body,

ρ = lineal mass density of booms,

ℓ = length of each boom,

ϵ = 2 a/ℓ, where a = radius at which boom is attached;

and

$$k = \frac{\rho \omega^2 \ell^4}{2EI},$$

where ω = spin rate, and EI = boom stiffness factor.

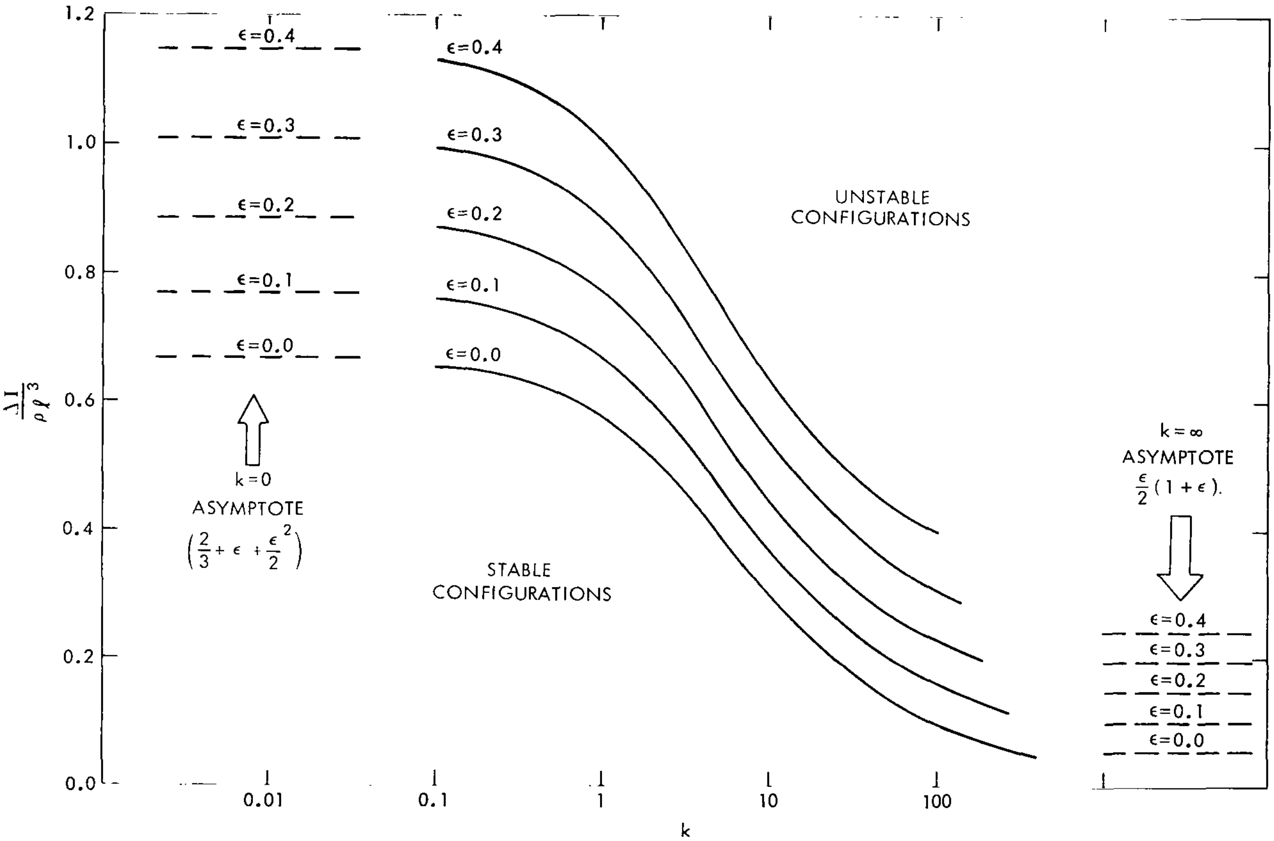

Figure 5—Resultant stability criteria.

Table 1

Results $(\Delta I/\rho\ell^3)$ in Tabular Form.

k \ ϵ	0.0	0.1	0.2	0.3	0.4
0	.6667	.7717	.8867	1.0117	1.1467
0.1	.6564	.7599	.8734	.9967	1.1300
1	.5787	.6722	.7751	.8875	1.0092
10	.3023	.3719	.4508	.5393	.6374
100	.0997	.1594	.2289	.3083	.3974
∞	.0000	.0550	.1200	.1950	.2800

From the monotonic nature of the curves, it is apparent that an increase in spin rate has a destabilizing effect, while an increase in boom stiffness (EI) is stabilizing. The effect of length and density changes are not so obvious, but, in the limiting cases of very small and very large k, it can be shown that increasing either one has a stabilizing effect. This is probably also true in general.

In addition to the obvious use of these nondimensionalized results to check for attitude stability (given some arbitrary set of design parameters), one could use them to generate design charts of various types for specific applications. For instance, one could display the stabilizing ability of a given type of boom (i.e., ρ and EI specified), attached at a known radius a, by plotting ΔI versus boom length for various spin rates. An envelope for such curves can be determined from the "limiting case" stability boundaries above, i.e.

$$\Delta I_{max} = \rho\ell^3\left(\frac{2}{3} + \epsilon + \frac{\epsilon^2}{2}\right),$$

$$= \rho\left(\frac{2}{3}\ell^3 + 2a\ell^2 + 2a^2\ell\right),$$

$$\Delta I_{min} = \rho\ell^3 \frac{\epsilon}{2}(1 + \epsilon),$$

$$= \rho\left(a\ell^2 + 2a^2\ell\right).$$

Curves for various spin rates could be constructed by interpolation between data points generated as follows:

1. Select arbitrary points $(1, \Delta I)$ within the envelope.
2. Compute corresponding ϵ and $\Delta I/\rho\ell^3$ for each.

3. From Figure 5, determine values of k for each point.
4. Calculate corresponding ω's from the equation

$$\omega^2 = \frac{2EIk}{\rho \ell^4} .$$

Figure 6 shows a qualitative example of such a chart. The upper and lower boundaries of the shaded region correspond to the cases $\omega = 0$ and $\omega = \infty$, respectively. For a given ΔI and spin rate, the minimum boom length required for attitude stability can then be found from the plot as shown.

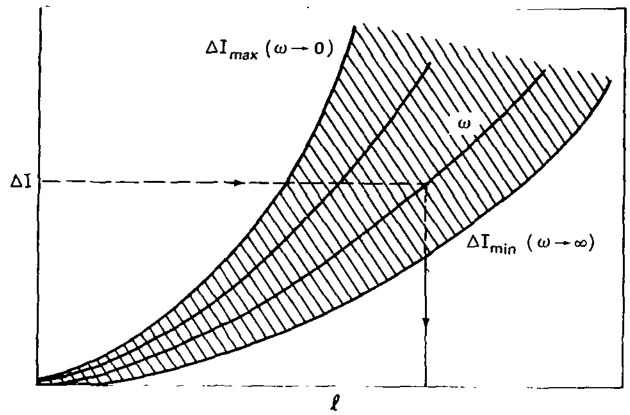

Figure 6—Typical qualitative design chart.

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