Scaled Dynamic Model of a Free Rotating Cable-Connected Space Station

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Introduction

THIS report discusses a model for simulating the unforced motion of a rotating flexible space station. As illustrated in Fig. 1, the space station consists of a manned module which is connected to a counterweight (an empty booster rocket) by a single cable. By rotating the entire structure about the combined system center of mass (c.m.), centrifugal forces arise which generate artificial gravity.

Modeling this type of system presents two major difficulties. 1) The model suspension system must eliminate the influence of gravity. 2) No constraints may be added that appreciably alter the natural motion of the system in space. One approach is to place the model into free flight by dropping or catapulting it; however, this method has several disadvantages. For example, measurements are difficult to take, aerodynamic effects may become significant as the translational velocity of the mass center is increased, and the initial conditions are difficult to control. For the present investigation an alternative approach was employed—a suspension system was designed to overcome the above difficulties.

The following section presents the results of a model test program. This is followed by a description of the model suspension system and a discussion of how it effectively eliminates the influences of gravity on the cable-connected structure.

Discussion

The model is illustrated in Fig. 2. For convenience in experimentation, the model dimensions were selected as 1/100th of those of the full-size vehicle. Other scaling factors are presented in Table 1. and the mass properties are summarized in Table 2.

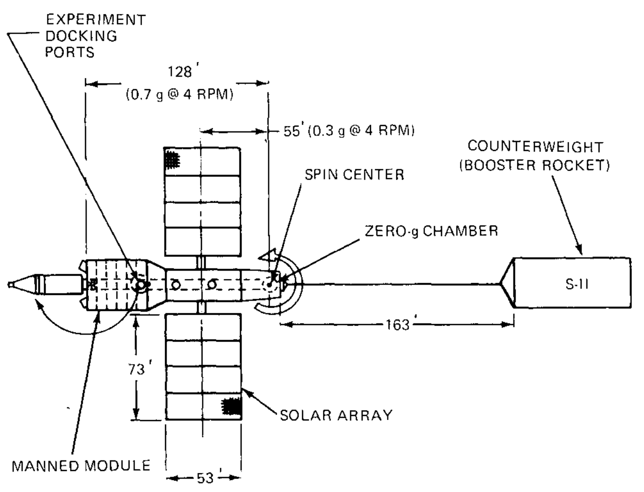

Fig. 1 Space station artificial-gravity experiment.

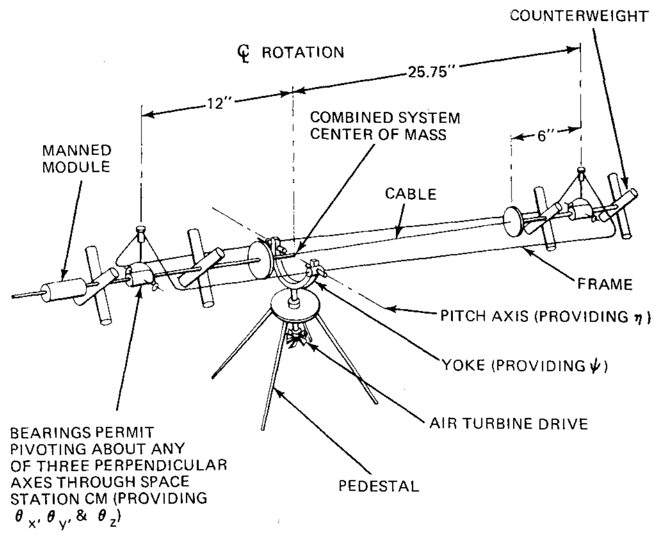

Fig. 2 Cable-connected space station model and suspension system.

Testing was performed at an angular velocity of 24 rpm, six times full-scale rotation. The model was manually disturbed in an attempt to excite the mode shapes predicted in Ref. 1 (and illustrated in Fig. 3). A motion picture was prepared to record these modal motions. Since the period of excitation was long enough to count oscillation cycles, a stop watch was the only instrument needed to measure the frequencies.

These measured frequencies were also compared with the frequencies computed by use of the formulas developed in Ref. 1. Close agreement between measured and computed frequencies was obtained (see Table 3). In fact, all frequencies agreed within 9%.

The model suspension system

Systems such as the cable-connected configuration shown in Fig. 4 generally require twelve degrees of freedom for a complete three-dimensional representation (three translational displacements and three angular displacements for each body). However, only eight degrees of freedom are required to obtain the free motion of the idealized space station. To understand this point, consider all of the twelve generalized coordinates shown in Fig. 4. These coordinates are the three displacements of the combined-system center of mass (X, Y, and Z), the position angles of line $C_1 C_2$ (ψ and η), the three rotation angles (roll, pitch, and yaw) for the manned module (θ_x, θ_y, θ_z) and the counterweight (ϕ_x, ϕ_y, ϕ_z), and the cable extension δ. Three of these coordinates, X, Y, and Z, do not require simulation because the model illustrates the motion of the free system and all remaining coordinates are independent of the trivial motion of the center of mass (which, in general, simply translates at constant velocity). In modeling the system, this information has been conveniently used to make the combined-system center of mass a stationary point, thus providing an Earth-fixed support point. Also, the cable is axially stiff, and variations in the extension are neglected; consequently, $\delta = 0$. Only the eight remaining

Table 1 Model scale factors

Parameter	Scale factor Model: prototype
Length	1:100
Weight density	18:1
Angular velocities and frequencies	6:1

Received June 19, 1970; revision received August 6, 1970. This work was performed under the joint sponsorship of the Grumman Aerospace Corporation Advanced Development Program, Project AD 06-03, and the Space Advanced Systems Program. The effort was initiated by E. Baird.

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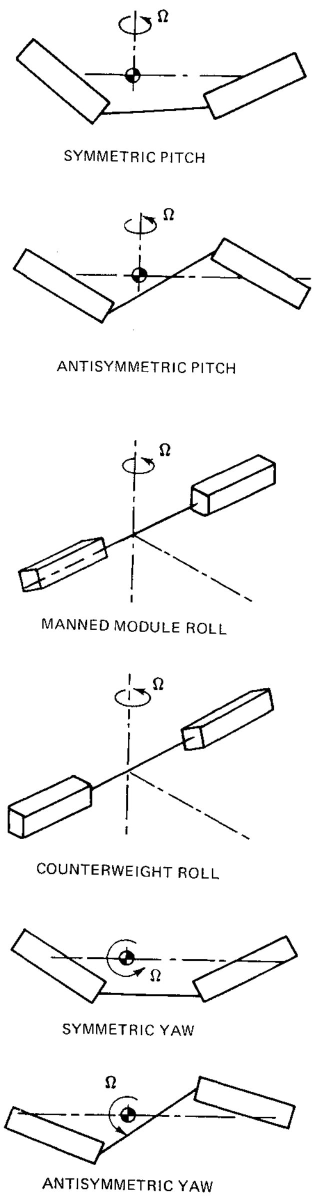

Fig. 3 Primary shapes of flexible-body modes.

coordinates $\psi, \eta, \theta_x, \theta_y, \theta_z, \varphi_x, \varphi_y$, and φ_z are needed to describe the motion.

The model suspension system is designed to nullify the influence of gravity. Moreover, it must do this without imposing any artificial restraint on the model. Its key features are as follows. 1) Each rigid body, as well as the combined system, is supported at its center of mass, thus nullifying the influences of the resultant gravity force and gravity torque. 2) The suspension system is designed to permit all of the above eight degrees of freedom; thus it offers no resistance to the natural motion of the free space station (except for small effects such as bearing friction and frame inertia).

The suspension system is shown in Fig. 2. It contains a yoke which pivots about the vertical axis of the pedestal, thus achieving the degree of freedom ψ; η is achieved by pivoting

Table 2 Mass properties of model

	Weight, lb	Moments of inertia about principal axes through component c.m., lb-in.[2]		
		I_x	I_y	I_z
Manned module	3.30	10.36	67.03	71.23
Counterweight	1.52	4.72	20.28	20.28

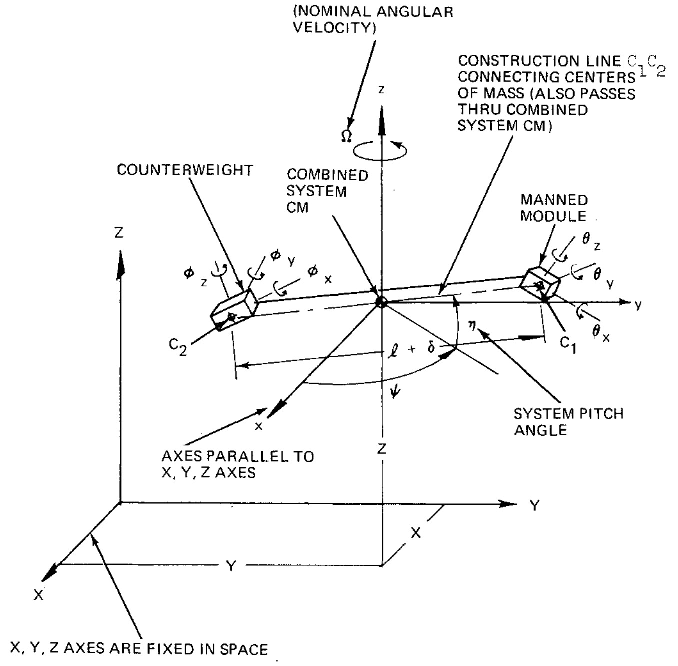

Fig. 4 Space station with coordinates.

the frame about the pitch axis of the yoke. As indicated in Fig. 4, the construction line connecting the centers of mass of the manned module and counterweight also contains the combined-system center of mass, which is a fixed point in space. The frame carries out the function of this construction line, and it is for this reason that one point on the frame, the center of mass of the combined system, can be held fixed in space. Each mass is suspended from the frame by a small swivel fitting which permits rotation in yaw (θ_z and ϕ_z), a small hanger/eyelet assembly which permits pitch (θ_y and ϕ_y), and a bearing which permits roll (θ_x and ϕ_x) freedom. A photograph of the assembly is shown in Fig. 5.

The driving torque for rotation of the model is supplied by an air jet impinging on a turbine wheel attached to the yoke shaft. After initial spin-up, the jet is turned off; however, an occasional pulse is applied to compensate for friction. This type of freewheeling drive permits variations in the rotational speed which exists due to the oscillatory motion of the model.

Spurious effects

Because of the mechanism required to eliminate the influence of gravity, certain spurious effects occur; for example, those caused by the mass of the supporting structure and support-bearing friction. Although no extensive design-analysis effort was conducted, an attempt was made to keep these effects small. For example, the suspension system is relatively light so that its inertia does not significantly influence the model dynamics. Suspension frame moments of inertia about the ψ and η axes were less than 10% of the

Table 3 Correlation of measured and computed model vibration frequencies

Mode	Frequencies, cps	
	Measured	Computed
Counterweight roll	0	0
Manned module roll	0.24	0.22
Rigid-body rotation (in tilted plane)	0.39	0.40
Symmetric pitch	1.30	1.27
Antisymmetric pitch	1.82	1.77
Symmetric yaw	1.16	1.18
Antisymmetric yaw	1.78	1.72

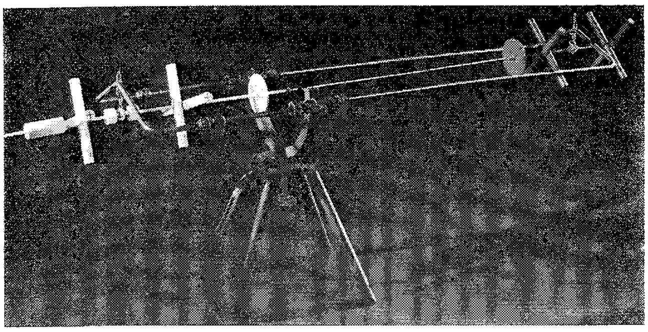

Fig. 5 Photograph of test assembly.

corresponding values for the combined system. Finally, certain pendulum modes of vibration of the model are possible since the short hanger/eyelet which suspends each mass from the frame permits small horizontal displacements. The fundamental frequencies due to these pendulum modes were detuned by adjusting the length of the hanger/eyelet assembly such that all pendulum frequencies were well above the natural frequencies under investigation.

Reference

[1] Austin, F., "Equations of Motion for a Rotating Cable-Connected Space Station," Structural Mechanics Memo STMECH 69.54, June 1969, Grumman Aerospace Corp., Bethpage, N. Y.

Deployment Dynamics of Rotating Cable-Connected Space Stations

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Nomenclature

$\mathbf{a}$ = acceleration of mass element
dm = mass of cable element
$d(t)$ = variable distance from center of mass to mass m_1
$\mathbf{F}_g$ = gravity gradient force
$\mathbf{F}_T$ = net tension force on cable element
G_e = gravitational constant
$\mathbf{i}$ = unit vector directed along rotating x axis
$\mathbf{j}$ = unit vector directed along rotating y axis
$\mathbf{k}$ = unit vector directed perpendicular to the xy plane
$l(t)$ = deployed length of the cable
L = total length of cable
m_1 = constant end mass which contains the undeployed cable
m_2 = constant end mass
$\mathbf{r}$ = position vector from Earth center to cable element
$\mathbf{R}_o$ = position vector from Earth center to system center of mass
t = time
T = cable tension
xyz = axis system rotating in orbital plane
x = coordinate directed along a line from m_1 to system mass center
y = coordinate directed perpendicular to x axis
ζ = distance from mass center to m_2, $(l - d)$
θ = angle from local horizontal to rotating x axis
$\dot{\theta}$ = angular velocity
$\ddot{\theta}$ = angular acceleration
$\boldsymbol{\varrho}$ = position vector from mass center to cable element
σ = dm/dx
Ω = orbital frequency

Introduction

THE need to provide artificial gravity to crew members in a weightless environment is a vague physiological problem which has not yet been answered. There is some evidence that prolonged periods of weightlessness may cause irreparable damage to the human body and until it is shown that extended orbital stay times are harmless, no one is likely to insist that the artificial gravity capability be omitted. Accordingly, space stations of the future will provide an artificial gravity environment for the crew members. One means of providing artificial gravity is to rotate the space station while in orbit. The simplest design of such a system consists of a cable or a set of cables connecting two end masses, perhaps an Apollo spacecraft and experimental module with an S-IV rocket stage,[1] and may include a reel in, reel out capability. The basic feasibility of a rotating tethered system was investigated during the Gemini XI mission.[2]

Investigations of the deployment (reel in, reel out) of rotating cable-connected space stations[3] and the somewhat similar problem of the retrieval of a tethered inert mass[4] have been accomplished. These works, however, disregard the mass of the cable. Accordingly, no information is available concerning the waveform of the cable during deployment. Evidently, the inertia forces of the cable transmit a force input to each end mass, but the nature of the force is unknown until the waveform of the cable is known. As a result, the transverse motion of the cable during deployment could cause undesirable effects on the end masses. Moreover, knowing the waveform allows the tension to be calculated, and thus provides important cable design information. Accordingly, the deployment problem should be studied by considering the mass of the cable.

As a first step, this note derives the equations of motion for the cable during the deployment of a rotating cable-connected space station in Earth orbit.

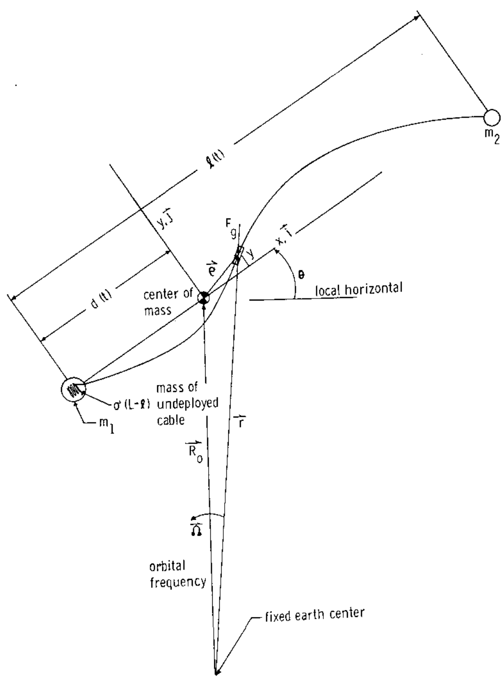

Fig. 1 Idealized model of space station system during deployment.

Received June 29, 1970; revision received August 7, 1970. This work was accomplished while the author was an ASEE-NASA Summer Faculty Fellow at Langley Research Center, Hampton, Va., in 1969. The author is indebted to A. P. Boresi, Professor of Theoretical and Applied Mechanics at the University of Illinois, for his helpful comments.

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