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Vibration Characteristics of a Deployable Controllable-Geometry Truss Boom

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and Space Administration

Scientific and Technical
Information Branch

SUMMARY

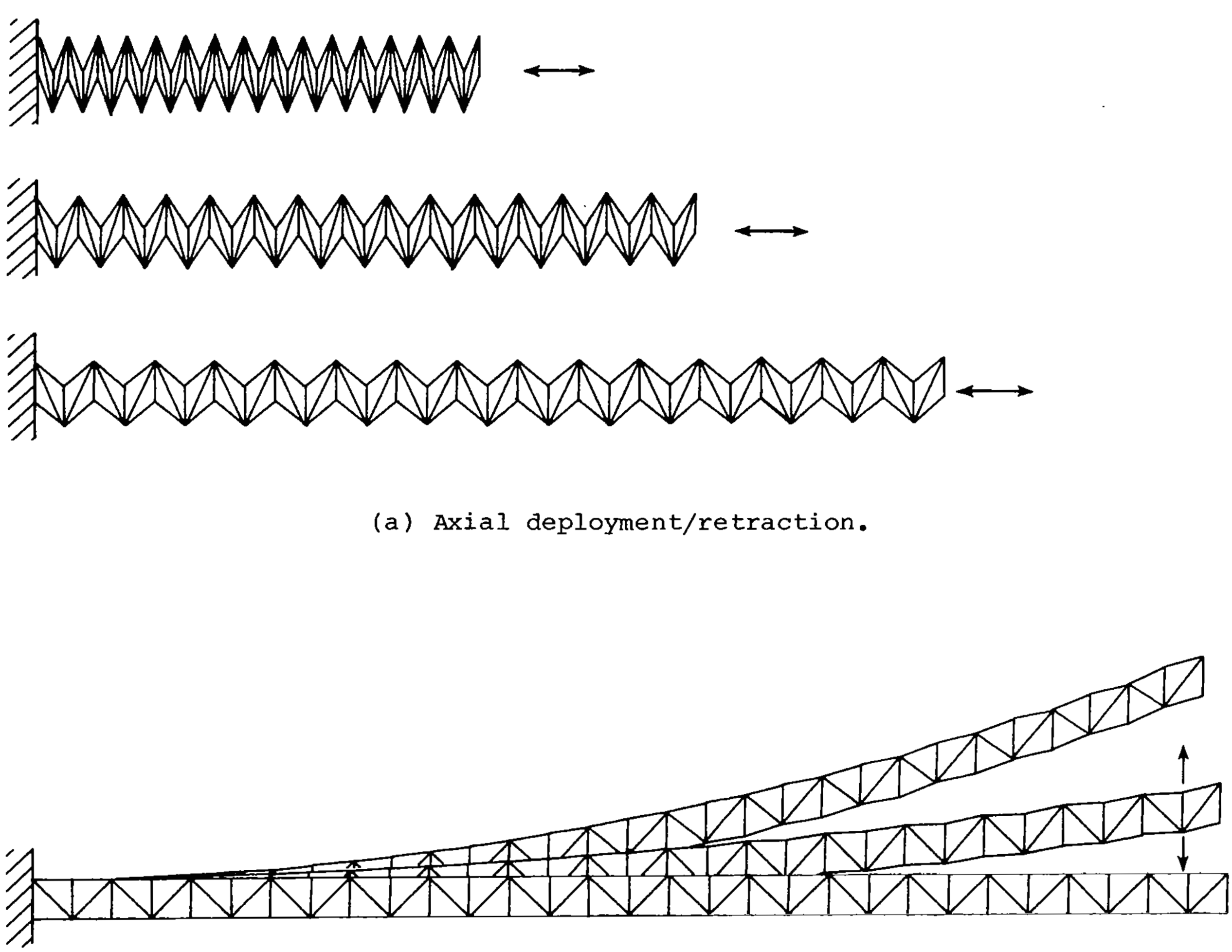
An analytical study was made to evaluate changes in the fundamental frequency of a two-dimensional cantilevered truss boom at various stages of deployment. The truss could be axially deployed or retracted and undergo a variety of controlled-geometry changes by shortening or lengthening the telescoping diagonal members in each bay. Both untapered and tapered versions of the truss boom were modeled and analyzed using the finite-element method. When fully deployed, a quadratically tapered truss, in which the members in the tip bay had an area one-tenth the area in the root bay, had a fundamental frequency which was significantly higher than that of the untapered base-line truss. Large reductions in fundamental frequency occurred for both the untapered and tapered trusses when they were uniformly retracted or maneuvered laterally from their fully deployed position. These frequency reductions can be minimized, however, if truss geometries are selected which maintain cantilever root stiffness during truss maneuvers.

INTRODUCTION

Currently, there is considerable interest in the possibility of placing large structures in space. These structures may initially be on the order of 20 to 30 m across and then expand to more than 100 m across as man's capability in space increases. (See ref. 1.) Typical missions which require these large space structures include science and applications platforms, remote-sensing and communications antennas, and permanent space stations or space-operations centers.

It is anticipated that some type of long truss boom or space crane will be an integral part of these large structures, especially a platform or space station. Space cranes can perform docking or berthing operations with visiting spacecraft, handle cargo loading and unloading, and move objects to different locations on a platform. The existing Shuttle remote manipulator system (RMS), described in reference 2, has the potential to perform these tasks but suffers a major drawback. The RMS, as currently designed, is inefficient from a packaging standpoint because its packaged length is equal to its deployed length. Thus, the maximum length of the RMS is constrained to be the length of the Space Shuttle orbiter bay.

A deployable truss concept has been designed which is an alternative to the RMS for a space crane or boom and which possesses the added feature that it packages efficiently. (See fig. 1.) This truss has an independently controlled actuator in each telescoping diagonal member. The truss can be packaged for stowing on the Shuttle by fully extending all the diagonal members. Once in orbit, the truss can function as a straight-line manipulator by simultaneous extension or retraction of all the diagonal members. (See fig. 1(a).) Since each actuator is independently controlled, the truss can also be maneuvered laterally (see fig. 1(b)) and, thus, is called a serpentine truss. Structural characteristics of a serpentine truss vary as the truss geometry changes. Before serpentine trusses can be considered for use in space, however, their structural characteristics and dynamic behavior must be analyzed and understood.



(a) Axial deployment/retraction.

(b) Serpentine operation.

Figure 1.- Representative operational modes of serpentine truss.

As a first step in understanding serpentine structures, an analytical investigation was conducted of the two-dimensional cantilevered truss boom shown in figure 1. The truss was analyzed by using an existing finite-element computer program, and the fundamental natural-vibration frequency and mode shape were determined at selected stages of deployment and serpentine operation. A study of the fundamental frequency provides a convenient and efficient way of characterizing the dynamic behavior of the truss. Because tapering can result in a more structurally efficient distribution of truss mass and stiffness, tapered truss models were also studied. The fundamental frequencies of untapered and tapered trusses at various stages of deployment and serpentine operation are compared with the fundamental frequency of the fully deployed untapered (base-line) truss.

SYMBOLS

A_i cross-sectional area of each truss member in ith bay, m^2

E Young's modulus, Pa

e	increment in diagonal elongation, m
f	fundamental frequency, Hz
f_0	fundamental frequency of fully deployed base-line truss, Hz
I	area moment of inertia, m^4
i	ith bay number
L	truss length, m
l_i	diagonal member length in ith bay, m
m	total truss mass, kg
δ	tip deflection, m
η	initial diagonal elongation, m
θ_b	truss base angle, deg
θ_t	truss tip angle, deg
λ	taper ratio
μ	mass per unit length, kg/m

Subscripts:

A	section A (fully deployed section of truss)
0	fully deployed base-line truss
1,2,...,30	bay numbers

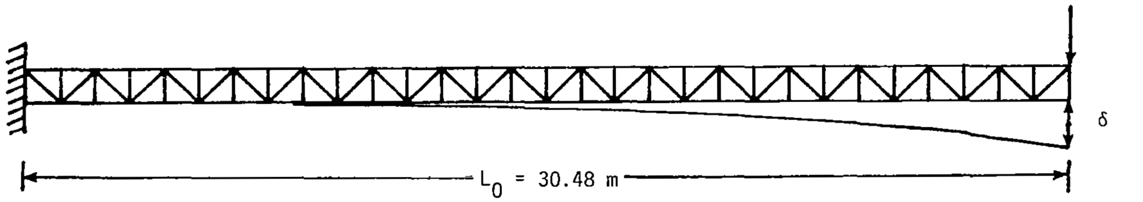
Abbreviations:

EAL	engineering analysis language
RMS	remote manipulator system

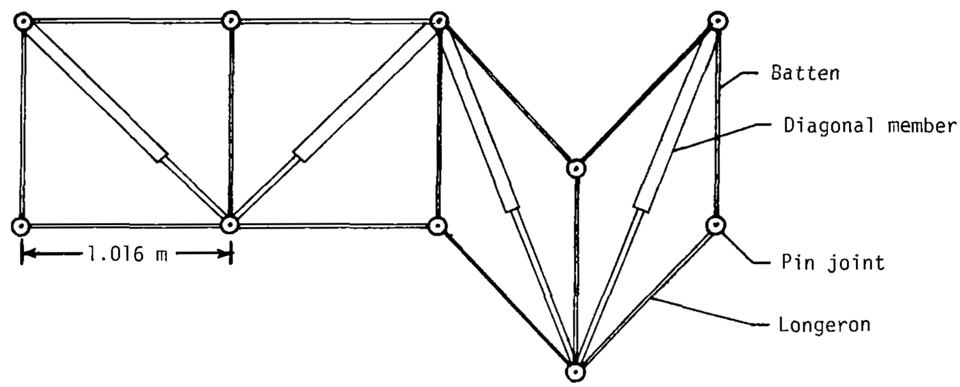
TRUSS DESCRIPTION

General Requirements and Sizing

Base-line model.- The two-dimensional deployable truss is assumed to have pin joints connecting all the members and an independently controlled actuator in each diagonal member. (See fig. 2.) A bay of the truss consists of two longerons, a diagonal, and a right-side batten. (See fig. 3.) The base-line truss is sized according to the following two requirements: First, the truss must have a fully deployed length, L_0 of 30.48 m; and second, the cantilevered truss must support a tip load of 2.77 to 3.46 N, such that the ratio of tip deflection to the fully deployed truss length δ/L_0 is approximately 0.01. (See fig. 2(a).)



(a) Fully deployed truss.



(b) Truss details.

Figure 2.- Model of two-dimensional deployable truss.

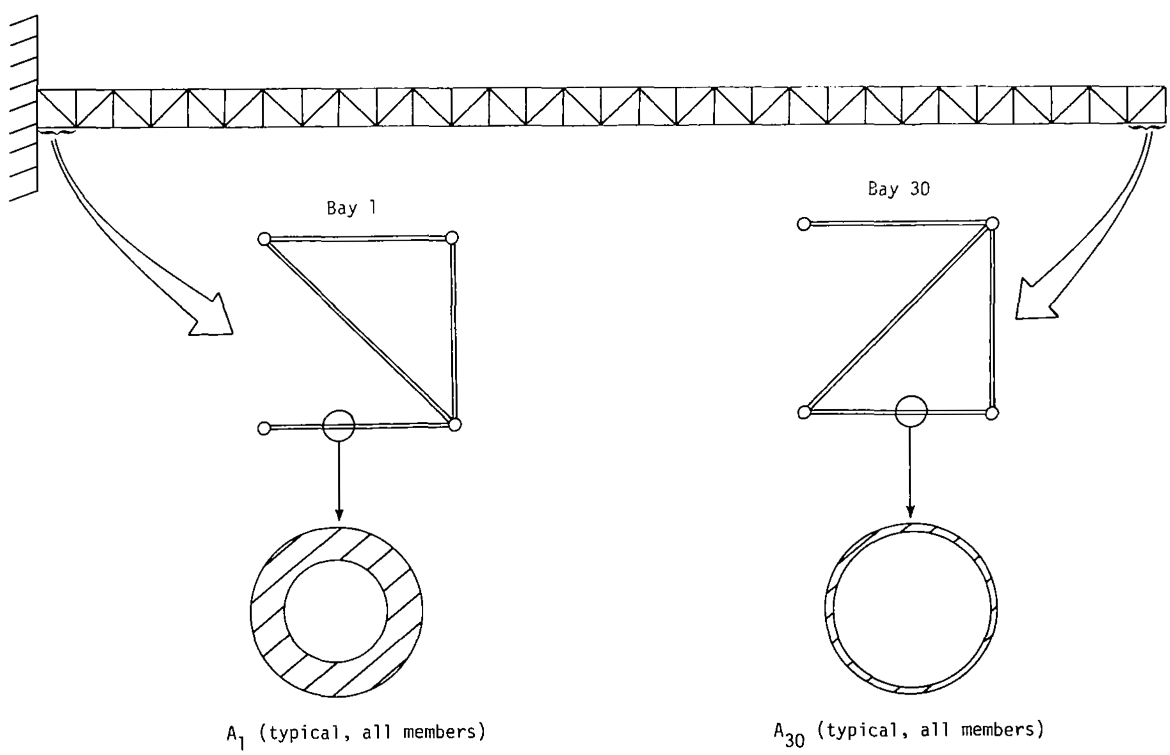


Figure 3.- Truss tapering scheme.

The resulting base-line truss can support a tip load of 3.2 N and maintain $\delta/L_0 = 0.01$. It has 30 identical bays, each with a length and depth of 1.016 m (see fig. 2(b)), and has a uniform distribution of mass, stiffness, and member cross-sectional areas along its length. Other features of the truss are summarized in table I.

TABLE I.- BASE-LINE TRUSS FEATURES

Number of bays	30
Bay length, m	1.016
Bay depth, m	1.016
Longeron area, μm^2	88.65
Batten area, μm^2	88.65
Diagonal area, μm^2	88.65
Modulus (aluminum), GPa	68.9

Tapered model.- The effect that tapering the truss has on its fundamental frequency is also examined. In general, tapering a cantilevered truss so that the cross-sectional area at the tip is less than that at the base increases the truss fundamental frequency because a more efficient distribution of truss mass and stiffness is achieved. The cross-sectional areas of the truss members (longerons, battens, and diagonals), rather than the overall truss geometry, are tapered so that the truss can be packaged according to the method shown in figure 1. The area-tapering method is as follows: The two longerons, the diagonal, and the right-side batten of bay 1 each have a cross-sectional area of A_1. At the tip bay of the truss (bay 30), the longerons, batten, and diagonal each have an area of A_{30}, where $0 \leq A_{30} \leq A_1$. The taper ratio λ of the truss is defined as

$$\lambda = A_{30}/A_1 \qquad (0 \leq \lambda \leq 1) \tag{1}$$

Two interpolation functions, based on the taper ratio, are used to determine the areas of the members in each bay. For the case of linear tapering, the areas are given by

$$A_i = A_1\left[1 - \frac{(1 - \lambda)(i - 1)}{29}\right] \tag{2}$$

where

A_i cross-sectional area of each truss member in ith bay, m^2

A_1 cross-sectional area of each truss member in first bay, m^2

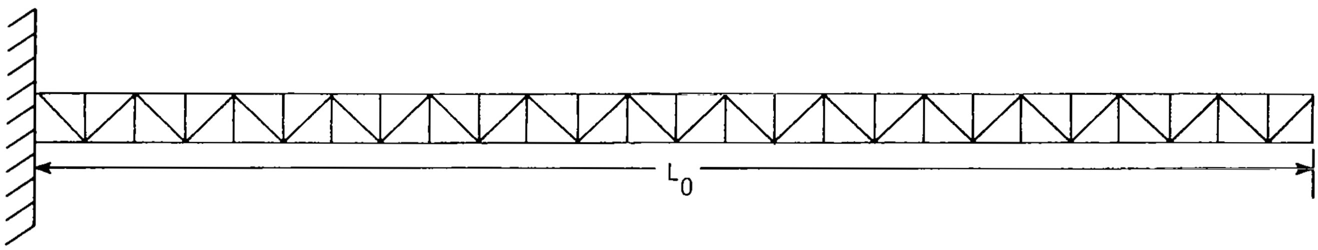
Similarly, for the case of quadratic tapering, the cross-sectional areas are given by

$$A_i = A_1\left[1 - \frac{(1 - \lambda)(i - 1)}{29}\right]^2 \tag{3}$$

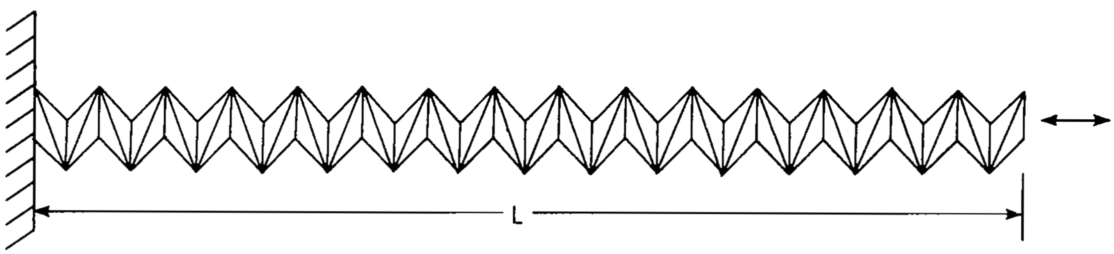
In this study, the tapered truss is sized so that the areas of the members in the first bay equal that of the base-line truss (i.e., $A_1 = 88.65\ \mu m^2$). An important point to make here is that the tapered truss will not necessarily meet the deflection criterion of $\delta/L_0 = 0.01$ for the 3.2-N applied tip loading.

Truss Operating Modes

Uniform axial operation.- One of the basic operating modes of this truss is axial deployment and retraction, and two deployment/retraction schemes are chosen for this study. The first scheme, shown in figure 4, is called uniform deployment and retraction. With this scheme all diagonals are actuated simultaneously. If the truss starts out fully deployed (see fig. 4(a)) and the diagonals are all lengthened an equal amount, the truss assumes a configuration similar to that shown in figure 4(b). The deployment ratio of the truss is defined as L/L_0, where L is the current length of the truss and L_0 is the length of the fully deployed truss.



(a) Fully deployed truss.



(b) Partially deployed/retracted truss.

Figure 4.- Uniform deployment/retraction scheme.

Selective axial operation.- The second scheme for axial deployment and retraction (see fig. 5) is called selective deployment and retraction. With this scheme, the truss is divided into two sections: section A, consisting of a selected number of fully deployed bays, and section B, where all the remaining bays are either uniformly retracted to some intermediate stage of deployment or all are fully retracted. The deployment ratio is once again defined as L/L_0. Another parameter which is important to the scheme for selective axial deployment and retraction is the ratio of the length of section A to the length of the fully deployed truss L_A/L_0. Examples of various ratios of L_A/L_0 for a given value of L/L_0 are illustrated in figure 6. For each configuration in figure 6, the total length L is 24.38 m and, thus,

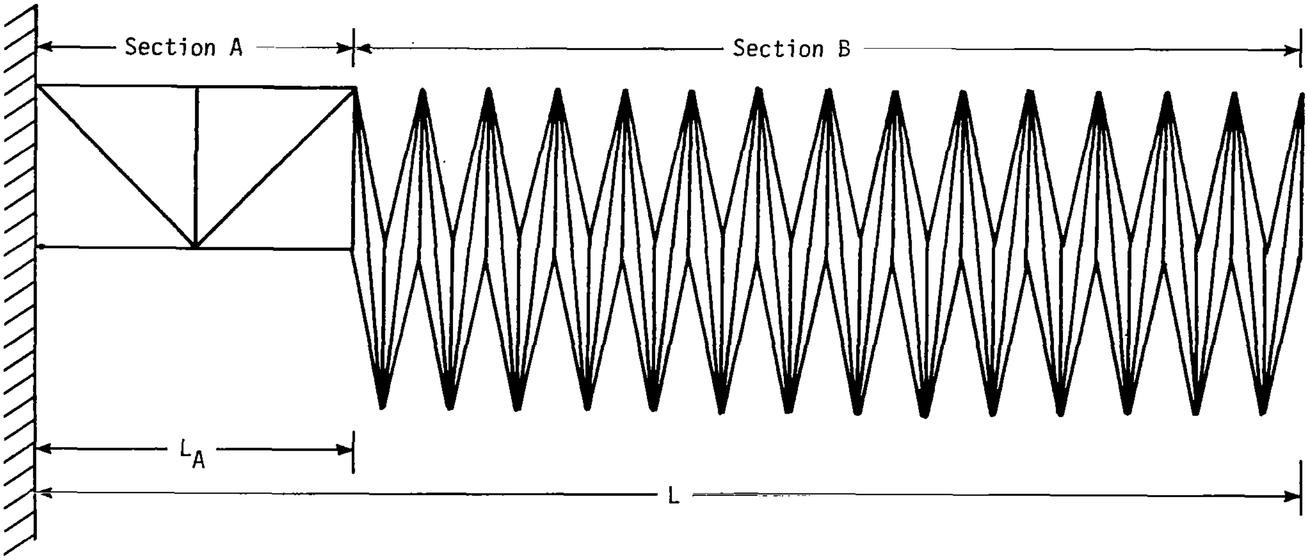
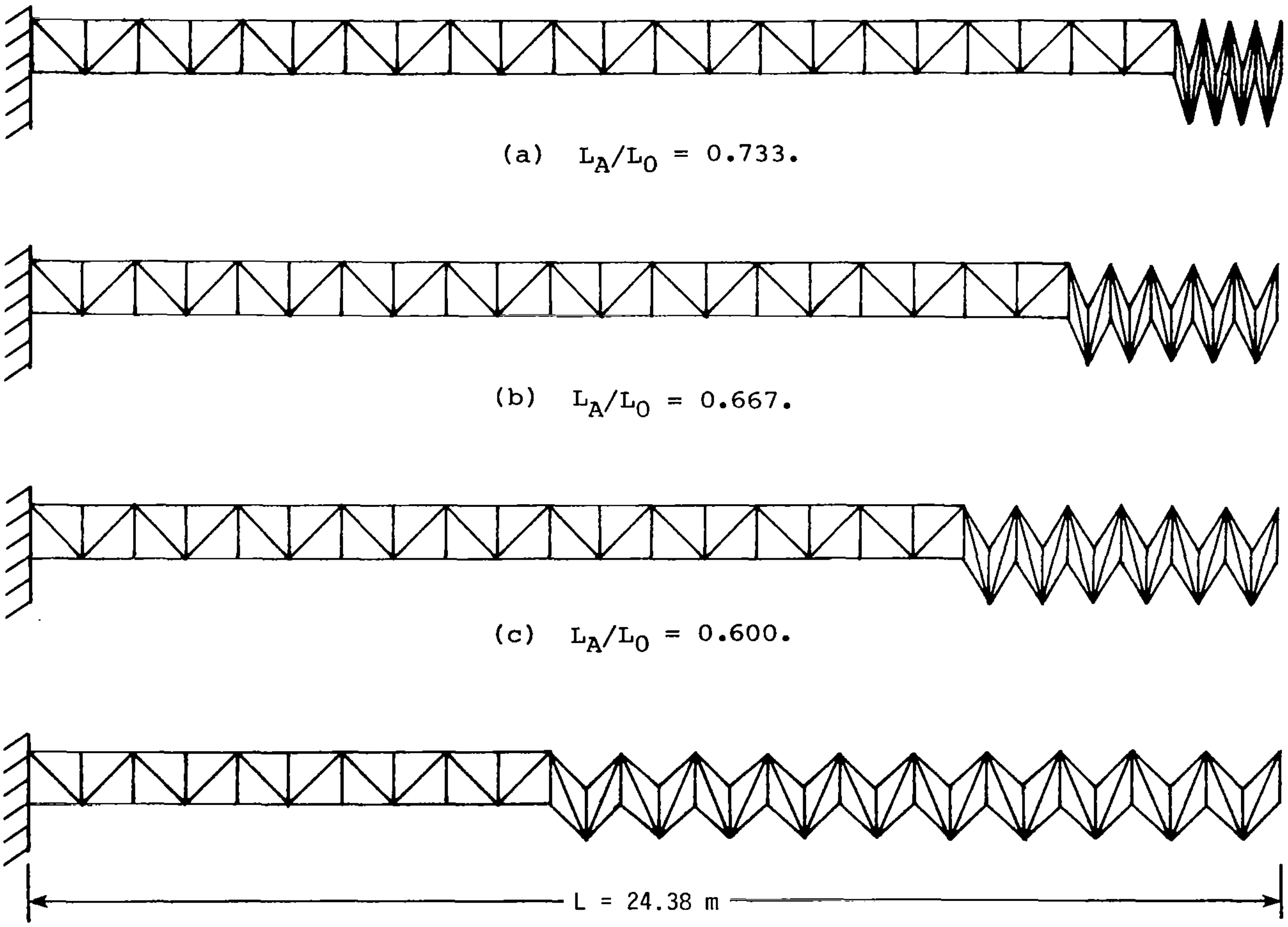


Figure 5.- Selective deployment/retraction scheme.



(a) $L_A/L_0 = 0.733$.

(b) $L_A/L_0 = 0.667$.

(c) $L_A/L_0 = 0.600$.

(d) $L_A/L_0 = 0.333$.

Figure 6.- Examples of selective retraction with $L/L_0 = 0.8$.

$L/L_0 = 0.8$ for all the trusses. However, even though the ratio L_A/L_0 is different for each case, it is always within the limits $0 \leq L_A/L_0 \leq L/L_0$. When $L_A/L_0 = 0$, the truss reverts to the uniform deployment/retraction scheme; and when $L_A/L_0 = L/L_0$, all the bays in section B are fully retracted and locked and act as a tip mass.

Straight, lateral serpentine operation.- A large variety of truss geometries are possible during serpentine operation. In the straight, lateral serpentine operation shown in figure 7, the angle between the tip and the base of the truss θ_t remains constant along the length of the truss. This geometry is generated from the fully deployed truss by lengthening every other diagonal an equal amount. The limit on this type of maneuvering (achieved when every other bay is fully retracted) is $-45° \leq \theta_t \leq 45°$.

Curved, lateral serpentine operation.- One type of curved, lateral serpentine operation possible with this truss is shown in figure 8. Here, the diagonals in every other bay of the fully deployed truss are given progressively increasing elongations. The diagonal in bay 2 is given an initial elongation η; thus, the length of the bay-2 diagonal ι_2 is the sum of the lengths of the bay-1 diagonal plus the increment (i.e., $\iota_2 = \iota_1 + \eta$). In bay 4, the diagonal receives the same elongation η plus an additional increment e (i.e., $\iota_4 = \iota_1 + \eta + e$). Bay 6 receives the same elongation as bay 4 plus an additional increment e (i.e., $\iota_6 = \iota_1 + \eta + 2e$). Bay 8 gets an elongation $\eta + 3e$ (i.e., $\iota_8 = \iota_1 + \eta + 3e$), and so on, out to the tip of the truss. Full extension of the diagonal in bay 30 serves to limit the values of η and e. Thus, for the 30 bay trusses chosen for this study, η and e must satisfy

$$\eta + 14e \leq \iota_1(\sqrt{2} - 1) \tag{4}$$

The two angles used to describe this geometry are shown in figure 8. The first is the base angle θ_b, defined by using the origin and the second bay of the truss, and the second is the tip angle θ_t, defined by using the origin and bay 30. In the limit, as e goes to 0, θ_t goes to θ_b and the geometry of the truss reverts to the straight, lateral serpentine operation shown in figure 7. In all cases, the maximum angle θ_t will always be less than 45° and is achieved for a given η when e is chosen so that the diagonal in bay 30 is fully extended.

ANALYSIS

Since stiffness considerations are critical in the design of large spacecraft, the evaluation of their frequencies and mode shapes is extremely important. This task is difficult for a serpentine structure because the frequencies and mode shapes vary as the geometry of the truss changes. The aim here is to characterize the frequency behavior of the truss by studying a limited number of representative geometries. No attempt is made to examine every conceivable truss geometry.

For a cantilever beam with uniform cross section and uniform mass distribution, the fundamental frequency is given by (ref. 3)

$$f = 0.560\sqrt{\frac{EI}{\mu L^4}} \tag{5a}$$

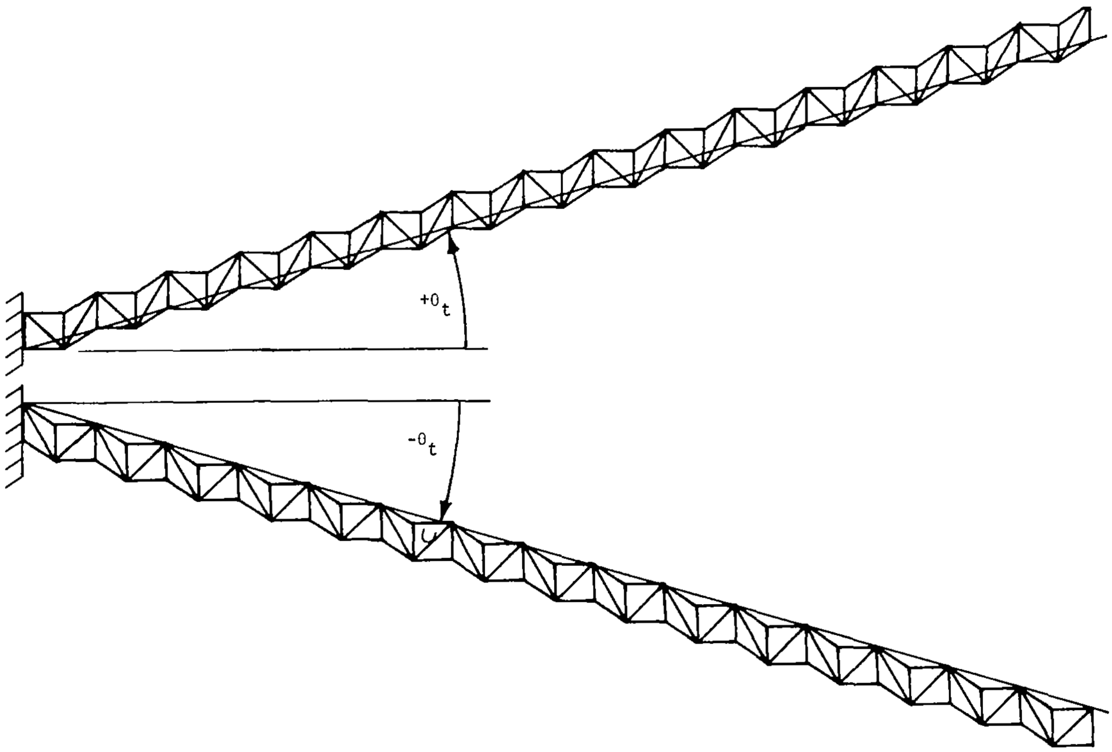


Figure 7.- Straight, lateral serpentine operation.

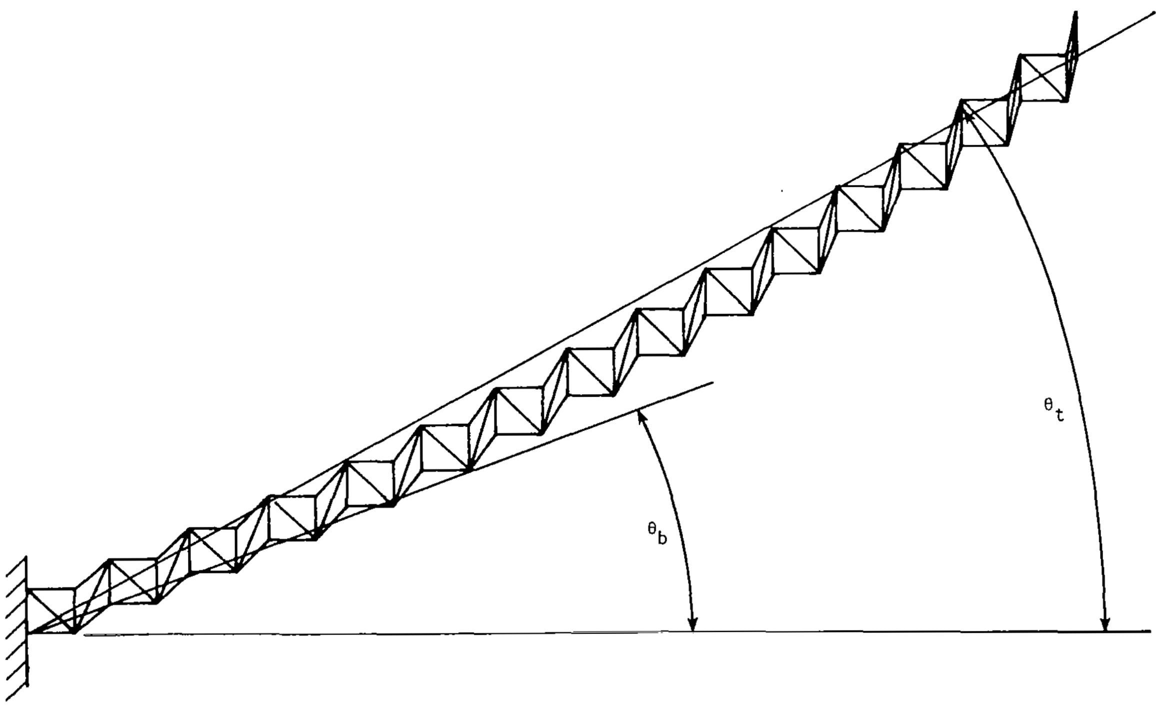


Figure 8.- Curved, lateral serpentine operation.

where

E	Young's modulus, Pa
I	moment of inertia of beam cross section, m^4
L	beam length, m
μ	mass per unit length of beam, kg/m

The mode shape associated with the frequency given in equation (5a) is first cantilever bending. Rewriting equation (5a) for the fundamental frequency of the fully deployed base-line truss gives

$$f_0 = 0.560\sqrt{\frac{EI_0}{\mu_0 L_0^4}} \tag{5b}$$

where the subscript 0 indicates the base-line beam. Dividing equation (5b) by equation (5a) and rearranging terms gives

$$\frac{I}{I_0} = \left(\frac{f}{f_0}\right)^2\left(\frac{L}{L_0}\right)^3 \tag{6}$$

Thus, the ratio of the first bending frequencies squared gives an indication of the relative bending stiffnesses of two truss configurations.

The two-dimensional truss, shown in figure 2 with features summarized in table I, was modeled with the finite-element-program EAL (engineering analysis language) from reference 4 by using rod elements. The finite-element model had 62 nodes, 120 degrees of freedom, and a diagonal mass matrix. The truss was modeled at various stages of uniform deployment/retraction, selective deployment/retraction, and serpentine operation. The EAL eigensolver was used to determine the fundamental frequency and mode shape resulting from each geometry.

The following four limitations are placed on the analysis because of differences between a real truss structure and the finite-element model.

(1) The finite-element model did not include any mass for the joints or actuators.

(2) In the finite-element model, the rod elements have no thickness and, thus, can rotate about the joint center without member interference. In a physical truss structure, this is not possible because the finite width of the members will cause interference and, thus, will influence joint design and reduce packaging efficiency.

(3) In the tapering schemes used, the wall thickness of the members is allowed to become arbitrarily small as the taper ratio decreases. In a physical structure, minimum gage constraints on the wall thickness of structural members must be maintained.

(4) The diagonal members are assumed to have a uniform cross section rather than a stepped cross section typical of a telescoping member.

These limitations do not invalidate any of the results obtained but represent, however, refinements which might be made in the structural model.

RESULTS AND DISCUSSION

Fully Deployed Truss

The fundamental frequency f of the fully deployed base-line truss was calculated by EAL to be 1.015 Hz. The associated mode shape, shown in figure 9, is

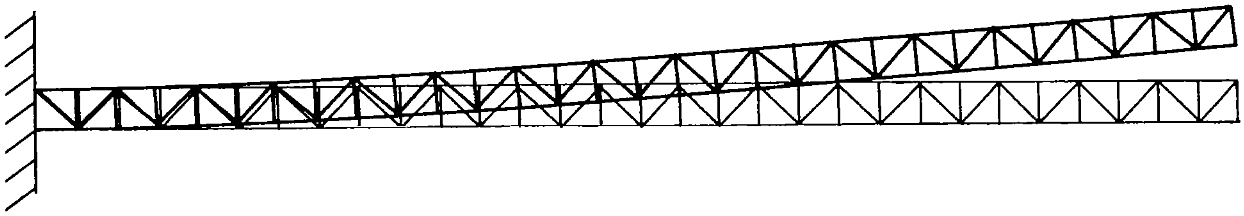


Figure 9.- First-mode shape for fully deployed truss.

first cantilever bending. Substituting the values $E = 68.9$ GPa, $I_0 = 45.8\ \mu m^4$, $\mu_0 = 1.09$ kg/m, and $L_0 = 30.48$ m into equation (5b) gives $f_0 = 1.03$ Hz. Thus, equation (5b) predicts a fundamental frequency for the truss which is approximately 1 percent greater than the frequency calculated by using EAL. Since equation (5b) assumes infinite shear stiffness, it predicts a frequency that is too high. The finite-element representation, however, includes truss deformation due to shear, thus achieving a more accurate representation of the truss stiffness. The fundamental frequency obtained from the finite-element analysis is used for all subsequent comparisons in this report.

Figure 10 summarizes the effect that tapering has on the frequency and mass of the fully deployed truss. The quantities plotted on the ordinate are the ratio of frequencies squared $(f/f_0)^2$ and the ratio of the tapered-truss mass to the base-line-truss mass. The truss is always fully deployed, and the taper ratio (A_{30}/A_1) is plotted on the abscissa. All results were obtained by using EAL finite-element analysis.

The results show that the tapering scheme used in the present study causes the frequency ratio to increase and the mass ratio to decrease. The frequency increase is due in part to a reduction of truss mass and in part to a more efficient stiffness distribution. As was noted before, the tapered truss was not required to meet the base-line-truss δ/L_0 constraint. At a taper ratio of 0.1, the fundamental frequency for the quadratically tapered truss is 3.6 times the fundamental frequency for the base-line truss. Similarly, for linear tapering, the fundamental frequency is 3.1 times as large. The mass of the truss is reduced by approximately 50 percent at a taper ratio of 0.1 for both tapering schemes.

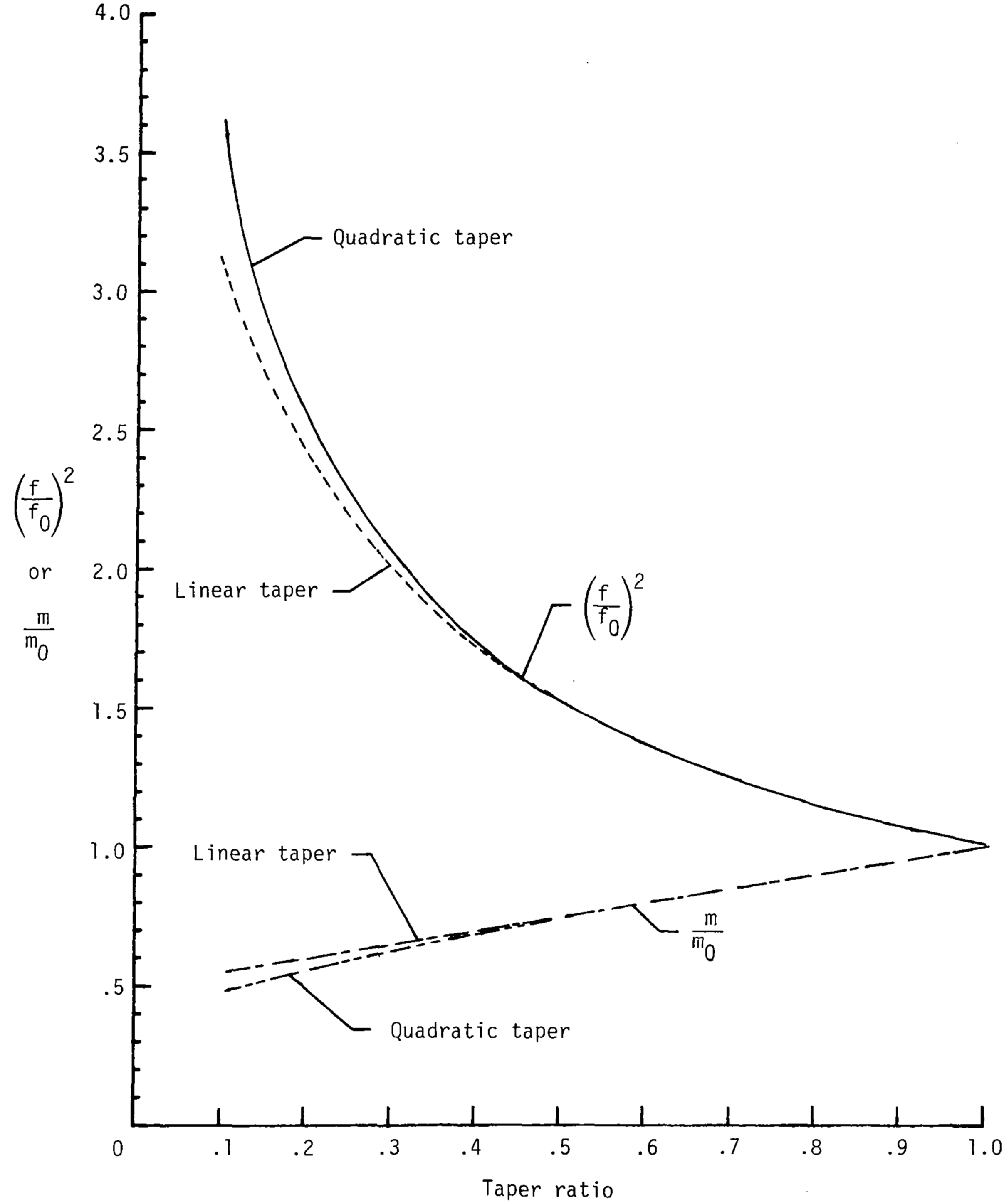


Figure 10.- Effect of taper on fully deployed truss frequency and mass.

Uniform Axial Deployment/Retraction Operation

Figure 11 shows the variation of the fundamental frequency with deployment ratio L/L_0 during uniform axial deployment/retraction operation. The two cases shown are

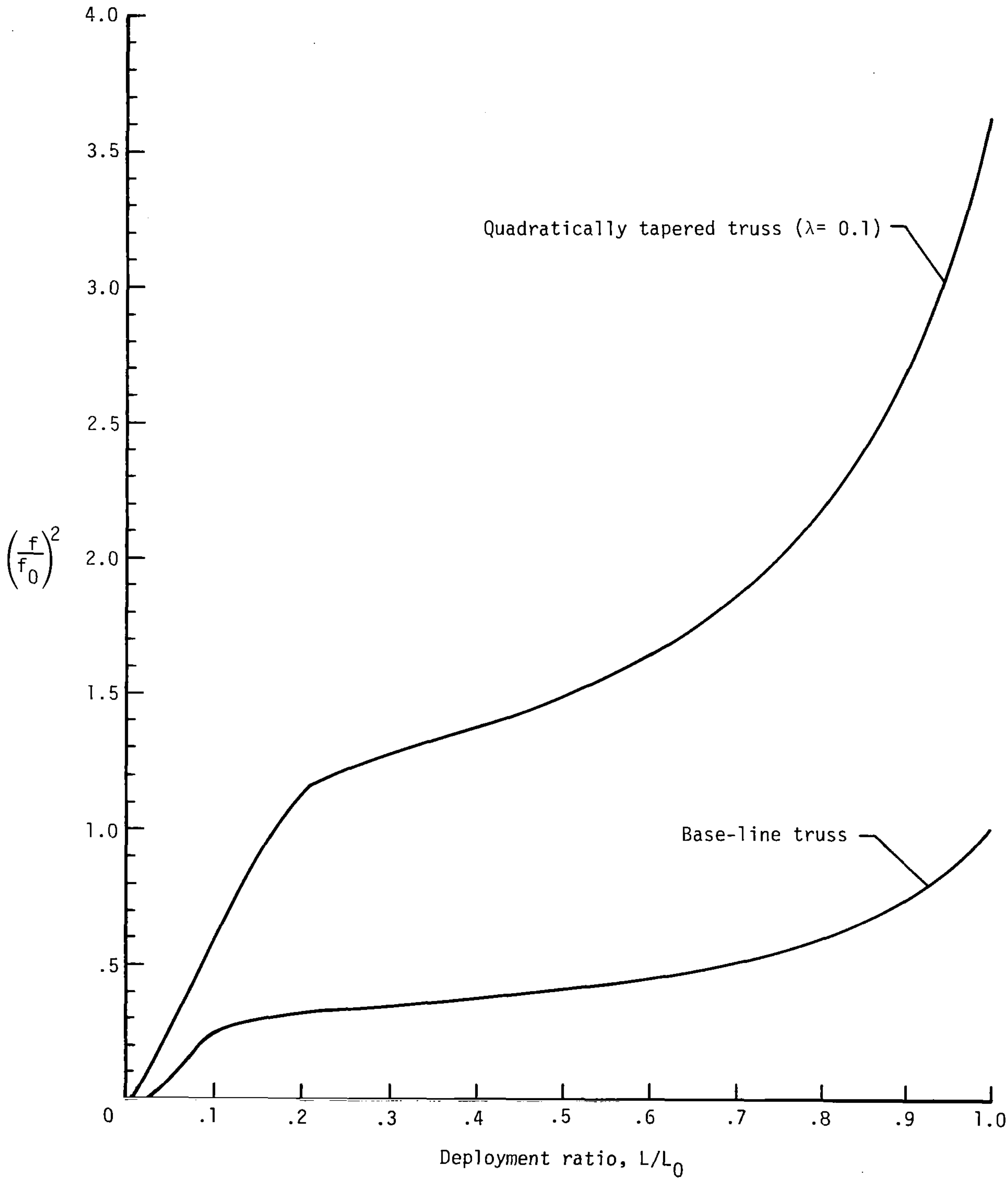


Figure 11.- Variation of fundamental frequency during uniform deployment/retraction of truss.

the base-line truss and the quadratically tapered truss with a taper ratio of 0.1. Because of a decrease in the truss bending stiffness, the frequency ratios of both trusses decrease as the truss is retracted.

The fundamental mode shape changes during uniform retraction, and its behavior can be summarized as follows: For both trusses, the mode shape of the fully deployed truss is first cantilever bending. As the truss begins to retract, the first mode starts picking up an axial component so that the mode shape is primarily bending with some axial coupling. As the truss is retracted farther, the mode transition is completed, the mode shape shows a pure axial vibration of the truss, and first cantilever bending becomes a higher (second, third, etc.) vibration mode. For the base-line truss, the transition from a combination of bending and axial vibration to a pure axial mode shape occurs near a deployment ratio of 0.15. For the quadratically tapered truss with a taper ratio equal to 0.1, the transition occurs at a deployment ratio of approximately 0.25.

By using the frequency information from figure 11 and equation (6), the variation of the truss bending stiffness I/I_0 during deployment can be determined. This result is summarized for the base-line truss in figure 12. It should be noted that the assumption that the mode shape is first bending is implicit in equations (5); thus, the curve in figure 12 extends only between deployment ratios of 0.3 and 1.0. A similar curve cannot be derived for the tapered truss because equation (6) is valid only for trusses with a uniform mass and stiffness distribution. The important result illustrated in figure 7 is the dramatic decrease in bending stiffness that occurs as the truss is uniformly retracted.

Selective Axial Deployment/Retraction Operation

The fundamental frequencies and mode shapes associated with selective axial deployment/retraction operation of the base-line truss are summarized for a particular deployment ratio in figure 13. Note that the truss geometry is the same as that in figure 6 and that the deployment ratio for all the geometries shown in figure 13 remains constant at 0.8. The ratio L_A/L_0, however, varies from 0.733 to 0.267. For $L_A/L_0 = 0.733$, the frequency ratio $(f/f_0)^2$ is 1.275 (fig. 13(a)) and the mode shape is first cantilever bending of the overall truss. As L_A/L_0 decreases, the frequency ratio increases (fig. 13(b)), reaching a maximum of $(f/f_0)^2 = 1.359$ at $L_A/L_0 = 0.600$ (fig. 13(c)). The mode shape for these values of L_A/L_0 remains first cantilever bending of the overall truss. The frequency ratio then begins decreasing with decreasing L_A/L_0 (figs. 13(d), 13(e), and 13(f)) and passes through 1.006 at $L_A/L_0 = 0.267$ (fig. 13(g)). As L_A/L_0 is decreased from 0.467, the mode shape changes from one of first cantilever bending of the overall truss to a mode shape where the amount of bending in the fully deployed section A decreases while the amount of bending in the partially deployed section B increases. At $L_A/L_0 = 0.267$, the mode shape shows most of the bending occurring in section B with very little occurring in section A. (See fig. 13(g).)

Figure 14 shows the variation of frequency ratio as a function of L_A/L_0 for the selective deployment/retraction scheme. In this figure, the points given in figure 13 for $L/L_0 = 0.8$ are represented by the circular symbols. Similarly, results for $L/L_0 = 0.7$, 0.6, 0.5, and 0.267 were also calculated and are presented in figure 14. The curves shown were faired through the data points to provide continuity and to suggest results for points not calculated. The curves for each deployment ratio intersect the ordinate at the appropriate uniform deployment/retraction values.

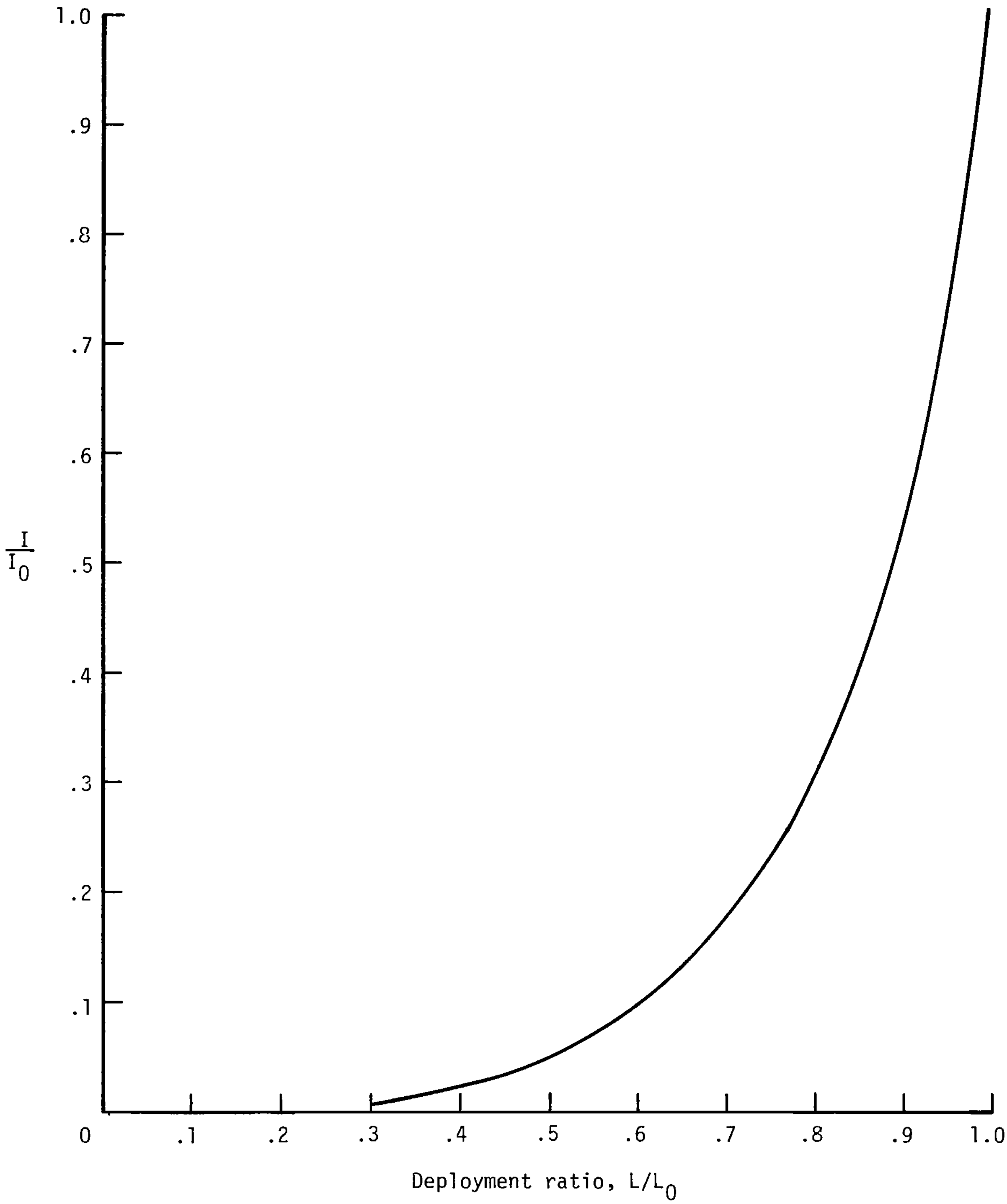
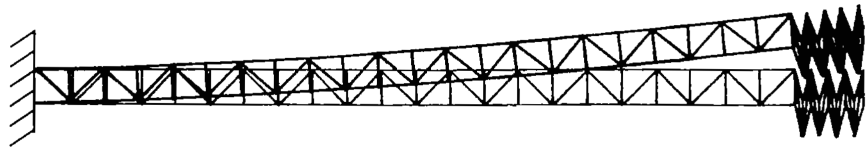


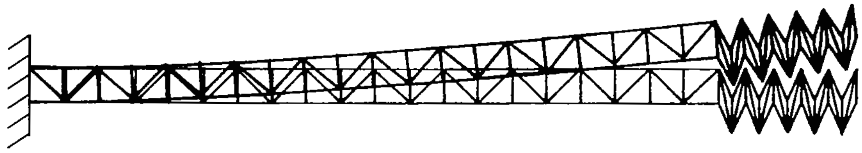
Figure 12.- Bending stiffness during uniform deployment/retraction base-line truss.

$\left(\frac{f}{f_0}\right)^2 = 1.275$



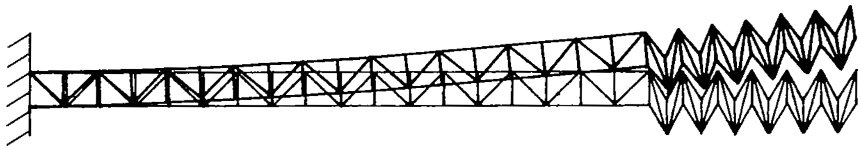
(a) $L_A/L_0 = 0.733.$

$\left(\frac{f}{f_0}\right)^2 = 1.328$



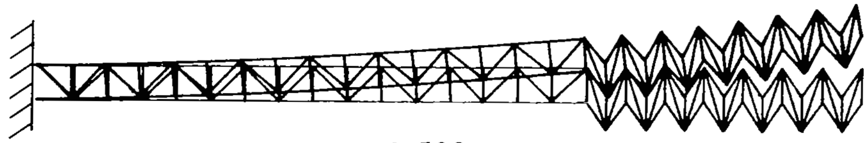
(b) $L_A/L_0 = 0.667.$

$\left(\frac{f}{f_0}\right)^2 = 1.359$



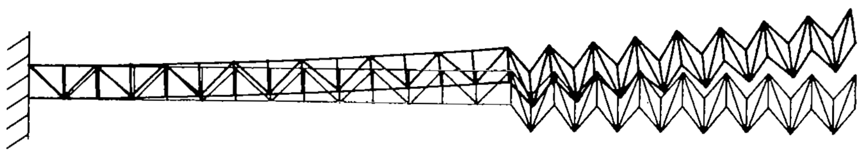
(c) $L_A/L_0 = 0.600.$

$\left(\frac{f}{f_0}\right)^2 = 1.354$



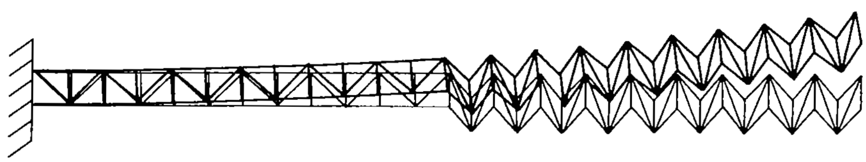
(d) $L_A/L_0 = 0.533.$

$\left(\frac{f}{f_0}\right)^2 = 1.313$



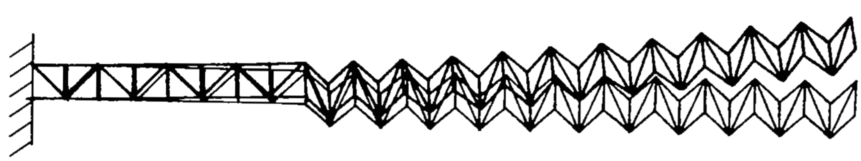
(e) $L_A/L_0 = 0.467.$

$\left(\frac{f}{f_0}\right)^2 = 1.231$



(f) $L_A/L_0 = 0.400.$

$\left(\frac{f}{f_0}\right)^2 = 1.006$



(g) $L_A/L_0 = 0.267.$

Figure 13.- Frequency ratios and mode shapes for selective deployment/retraction of base-line truss with $L/L_0 = 0.8$.

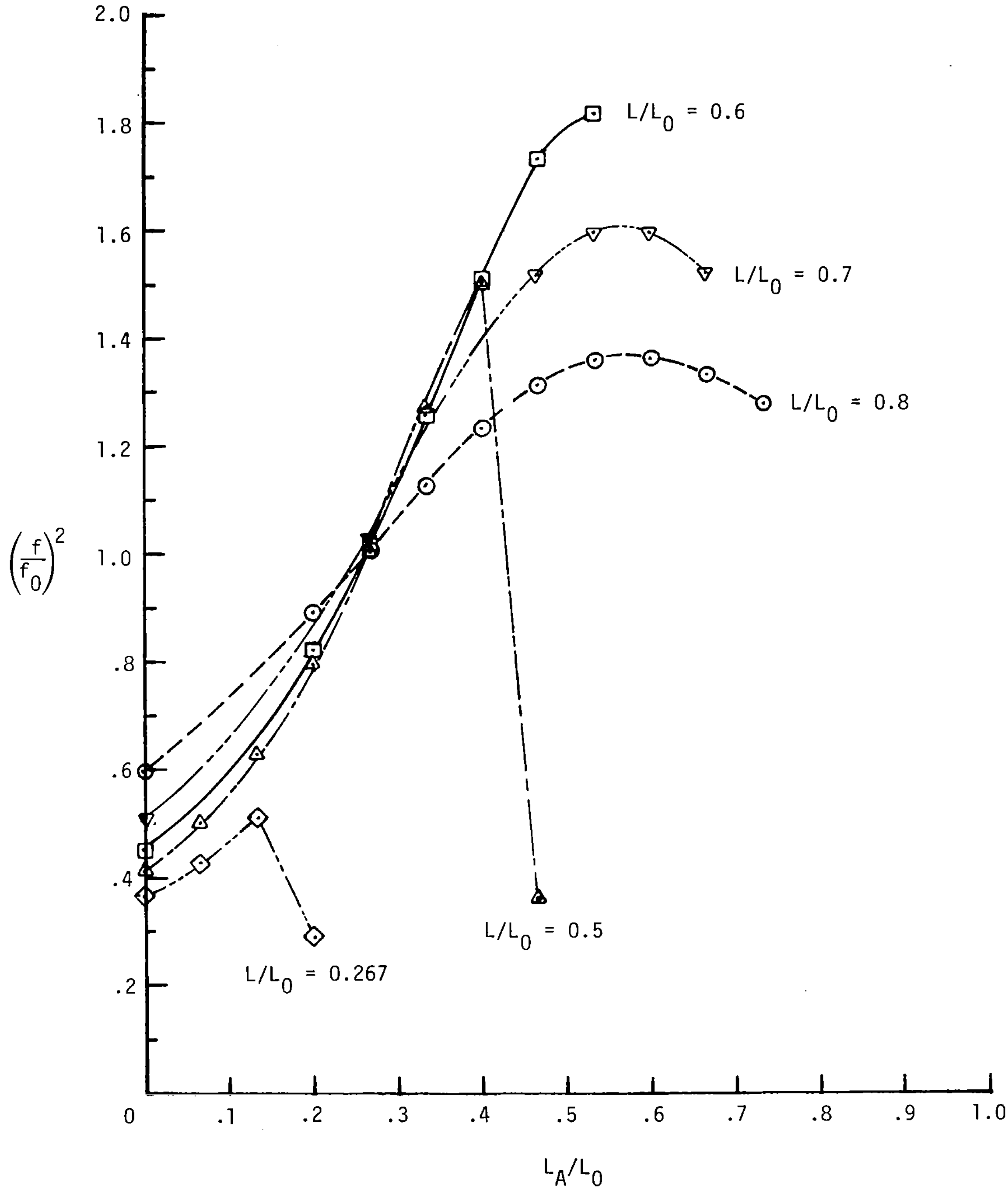


Figure 14.- Frequency ratios for selective deployment/retraction of base-line truss.

The frequency ratio starts at the uniform deployment/retraction value when $L_A/L_0 = 0$ (see fig. 11) and, in general, rises with increasing L_A/L_0, reaches a peak, and then begins decreasing. Note that for deployment ratios equal to 0.8 and 0.7, the peaks of the curves appear to occur at $L_A/L_0 = 0.600$. Also, for the deployment ratios of 0.5, 0.6, 0.7, and 0.8, the frequency ratio appears to pass through 1.0 at $L_A/L_0 \approx 0.267$. (See table II.) The reasons the frequencies peak and pass through unity at these two particular values of L_A/L_0 are not known.

TABLE II.- FREQUENCY RATIO FOR $L_A/L_0 = 0.267$
AT FOUR DEPLOYMENT RATIOS

Deployment ratio, L/L_0	Frequency ratio, $(f/f_0)^2$
0.8	1.007
.7	1.014
.6	1.018
.5	1.010

Variations from the general frequency trends occur at $L_A/L_0 = 0.467$ for $L/L_0 = 0.5$, and at $L_A/L_0 = 0.20$ for $L/L_0 = 0.267$. For these two cases, the retracted section B of the truss vibrates axially. It should be recalled from the discussion of figure 11 that during uniform retraction (which is taking place in section B), the truss mode is pure axial vibration for $L/L_0 < 0.15$. Thus, the fundamental frequency and mode shape for these two particular cases reflect a stiff truss (section A) with a spring (section B) vibrating axially at the tip. All the other configurations reflect fundamental frequencies associated with mode shapes which are primarily first cantilever bending.

In figure 15, the frequency variation with L_A/L_0 for the selective deployment/retraction scheme is shown for a quadratically tapered truss with a taper ratio equal to 0.1. For the two values of deployment ratio shown (L/L_0 = 0.6 and 0.8), the general behavior of the frequency ratio with L_A/L_0 is similar to that for the base-line truss. The maximum frequency ratio for $L/L_0 = 0.8$ occurs at $L_A/L_0 = 0.600$. A sharp decrease in frequency occurs for $L/L_0 = 0.6$ at $L_A/L_0 = 0.533$. This, again, is due to a change in the first mode of the tapered truss to a pure axial vibration of the retracted section B.

Figures 14 and 15 show that during the selective deployment/retraction scheme, a wide range of frequencies are possible for the truss, but for each deployment ratio, $(f/f_0)^2$ reaches a maximum at some particular value of L_A/L_0. Figure 16 shows the variation of these maximum frequency ratios as a function of the truss deployment ratio. For both the base-line and tapered trusses, the frequency ratio increases from the respective fully deployed values with decreasing deployment ratio, reaches a maximum at $L/L_0 = 0.6$, and then decreases with decreasing deployment ratio. Figure 16 shows that for $0.2 < L/L_0 \leq 1.0$, the selective deployment/retraction scheme, because it results in higher frequency ratios, is superior to the uniform scheme.

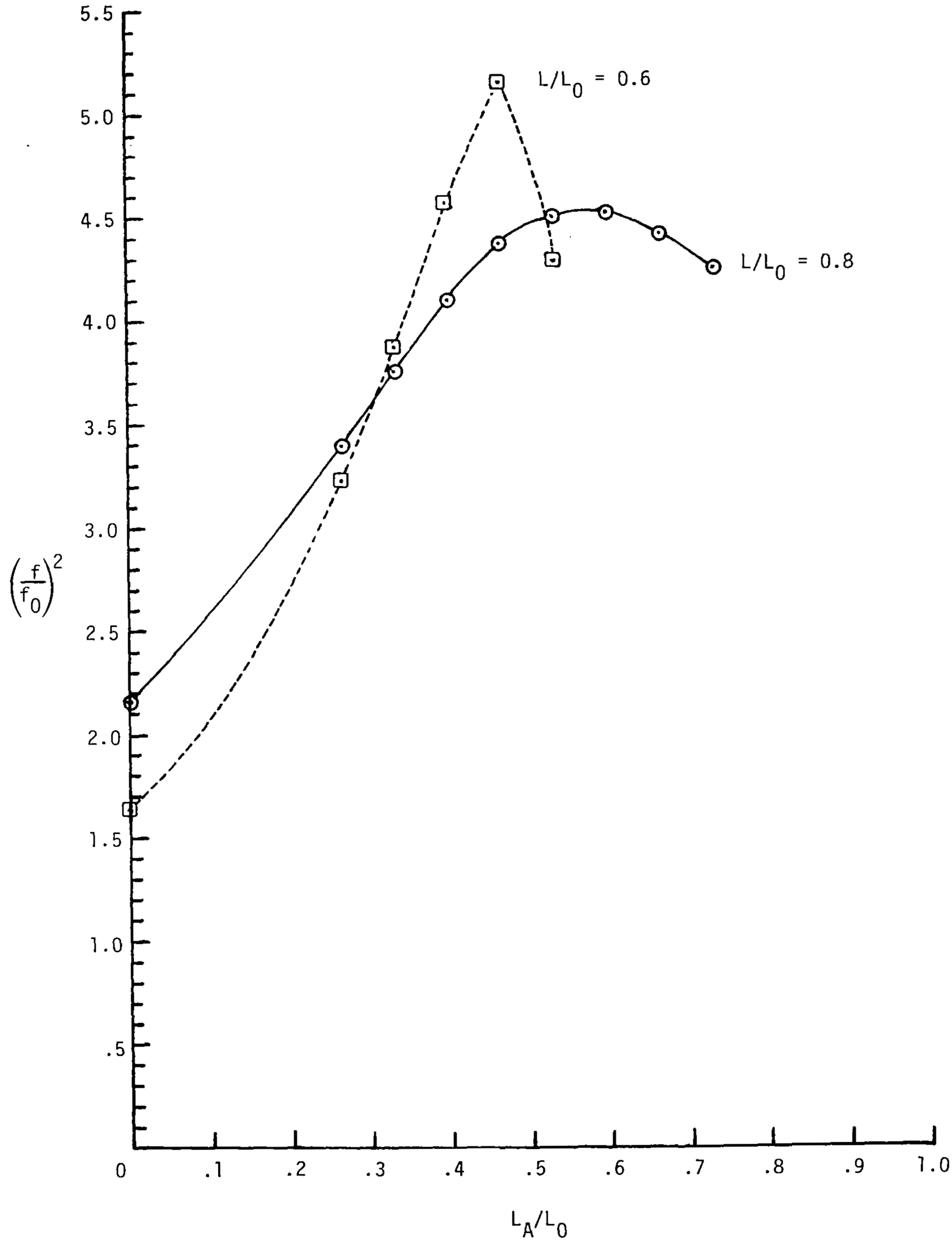


Figure 15.- Frequency ratios for selective deployment/retraction of quadratically tapered truss. $\lambda = 0.1$.

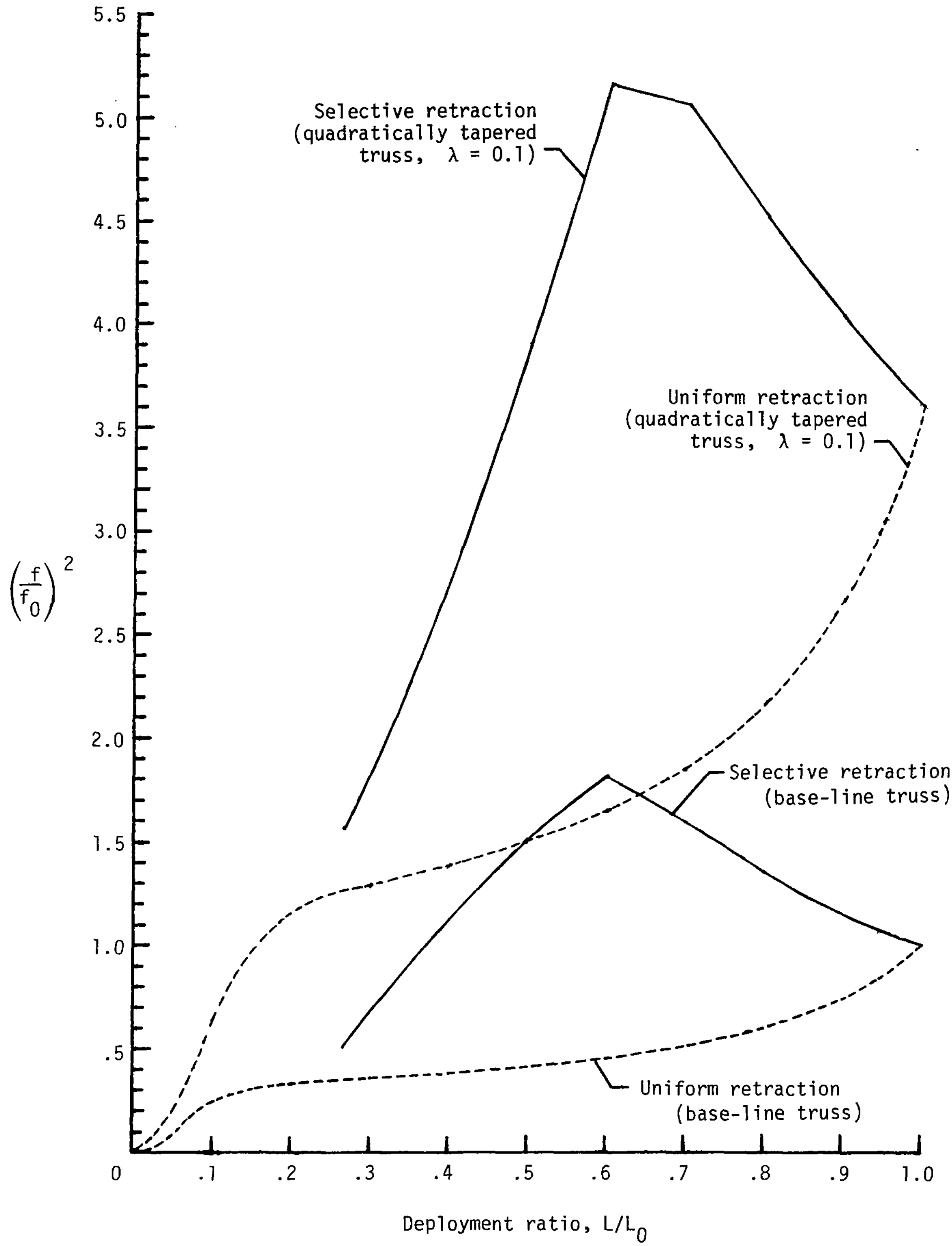


Figure 16.- Maximum frequency ratios with selective deployment/retraction.

Truss With Tip Mass

One limit on the selective deployment/retraction scheme is obtained by allowing the length of the retracted section (section B) to go to 0. This gives the configuration shown in figure 17, where all of section B is retracted and locked, in which

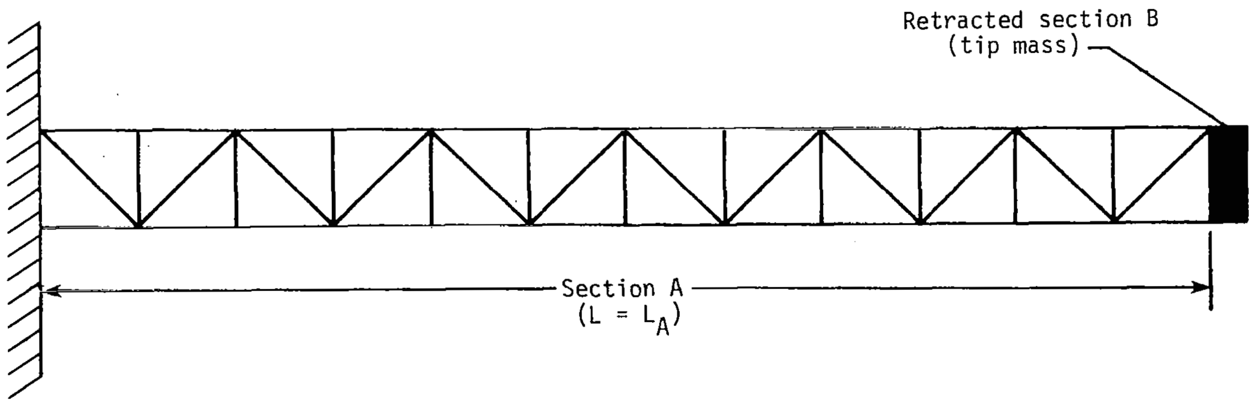


Figure 17.- Sketch of base-line truss with tip mass.

a tip mass is formed at the end of a fully deployed truss with length $L = L_A$. For purposes of the finite-element analysis, a rigid mass was placed at the free end of the truss to represent the retracted and locked section B.

Frequency Envelope

The frequency envelope of the base-line truss is summarized for axial operation in figure 18. The lower bound on the truss frequency ratio (solid line) is given by the uniform deployment/retraction scheme for all values of deployment ratio. Truss configurations with fundamental frequencies which fall below this line are possible, but they would not be used because for any deployment ratio, because the truss can always be configured so that the frequency ratio is at least the value given by the uniform case.

Two other curves which appear in figure 18 are the selective-retraction curve for the base-line truss (taken from fig. 16) and the curve for a truss with a tip mass. These two curves, which cross at a deployment ratio of 0.667, form the upper bound of the frequency envelope. For $0.667 < L/L_0 \leq 1.0$, the selective-retraction curve gives the upper bound on $(f/f_0)^2$; and for $L/L_0 < 0.667$, the truss with a tip-mass curve gives the upper bound.

The final curve in figure 18 illustrates a special selective deployment/retraction case within the total frequency envelope. Here, $L_A/L_0 = 0.267$ (see fig. 14) so that the number of bays in the fully deployed section A is 8. As section B is retracted from its fully deployed position, $(f/f_0)^2$ begins a gradual climb from its value of 1.0 at $L/L_0 = 1.0$. At a deployment ratio of 0.6, $(f/f_0)^2$ reaches a maximum value of 1.018; then, it begins to decrease and passes through 1.0 again near $L/L_0 = 0.45$. These results show that the frequency of the truss can be held nearly constant (within 2 percent of 1.0) for $0.45 \leq L/L_0 \leq 1.0$ by using this particular selective scheme.

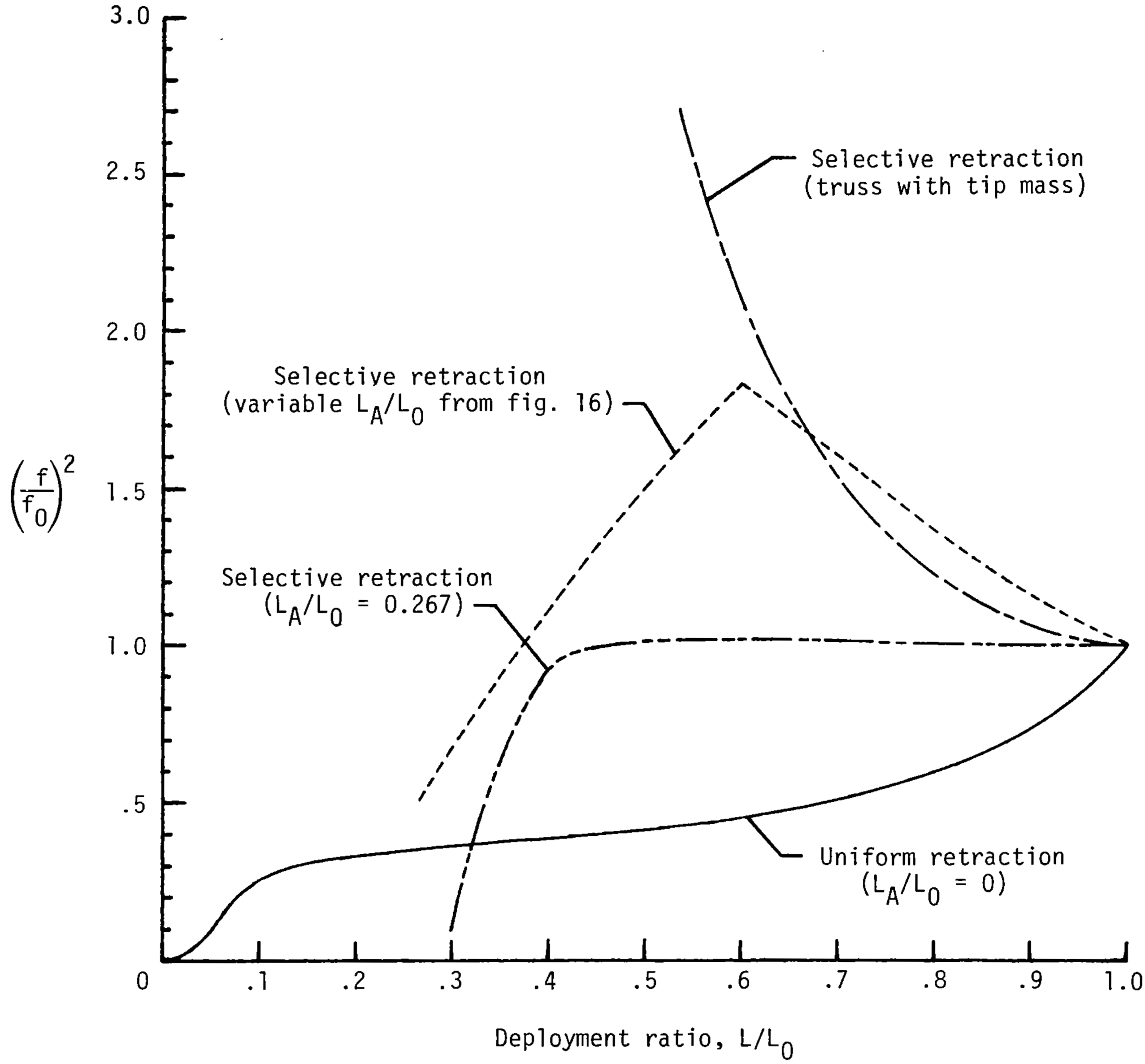


Figure 18.- Summary of frequency envelope of base-line truss for axial operation.

Serpentine Operation

The first type of serpentine operation investigated was the straight, lateral geometry shown in figure 7. The variation in first frequency ratio as a function of θ_t is shown in figure 19 for the base-line truss and the quadratically tapered

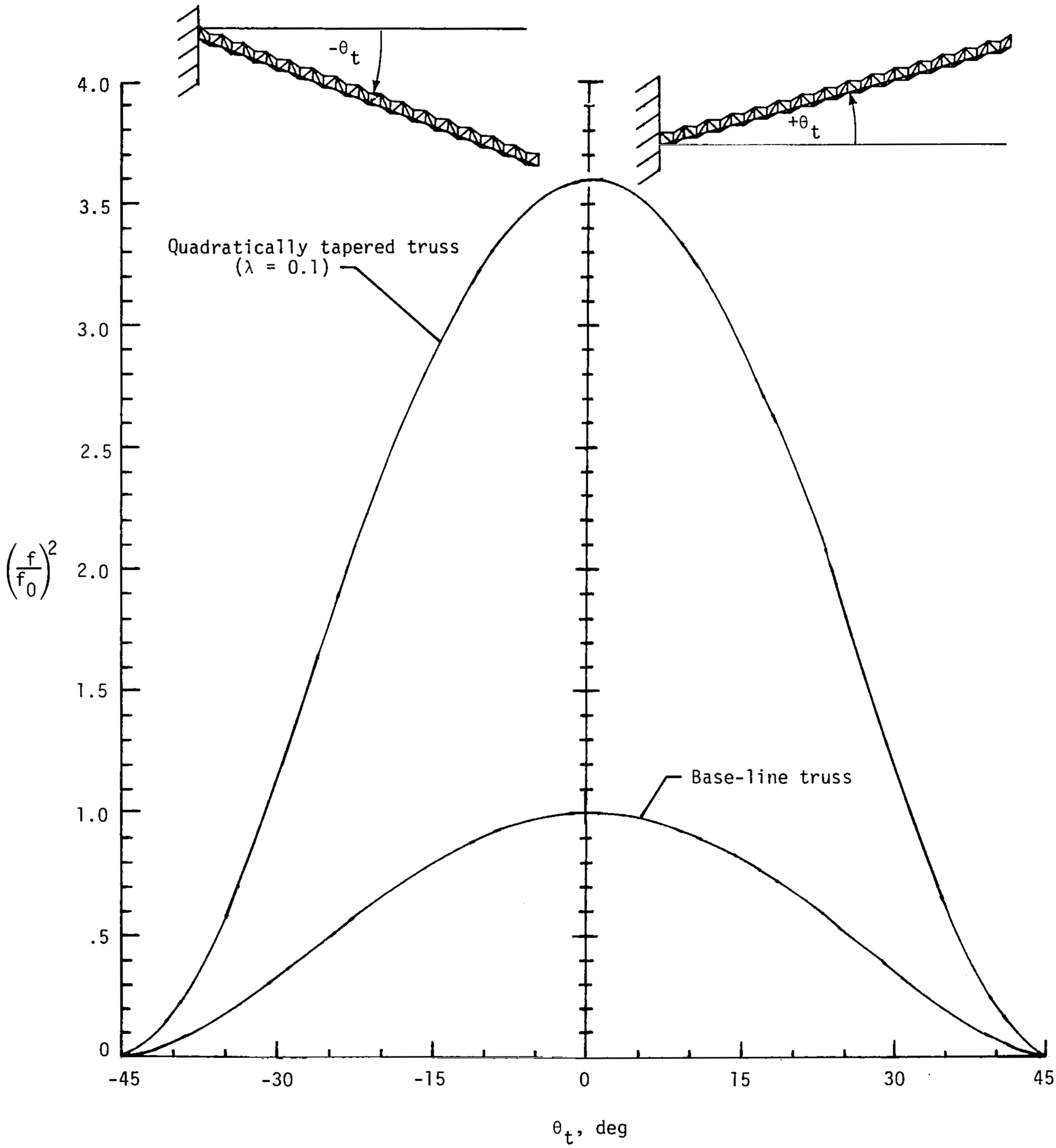


Figure 19.- Fundamental frequency of base-line and quadratically tapered ($\lambda = 0.1$) trusses during straight, lateral serpentine operation.

truss with $\lambda = 0.1$. In both cases, the frequency ratio is at its maximum at $\theta_t = 0°$. At $\theta_t = \pm 45°$, every other bay of the truss is fully retracted which means that these bays have no stiffness. Thus, the frequency ratio for both the untapered and tapered trusses goes to 0 at ±45°. The frequency behavior is very nearly symmetric, with $(f/f_0)^2$ for negative θ_t ranging between 0.8 and 6.1 percent less than the corresponding values for positive θ_t. The reason for this result is that for the negative θ_t configuration, the first bay is partially retracted and the second bay is fully deployed; whereas in the positive θ_t configuration, the first bay is fully deployed and the second bay is partially retracted. The extra stiffness provided by the fully deployed bay at the root of the truss, thus, results in slightly higher frequencies for the positive θ_t configuration.

The second type of serpentine geometry studied was the curved, lateral geometry shown in figure 20. For this case, θ_b has been made 0 by having the first three

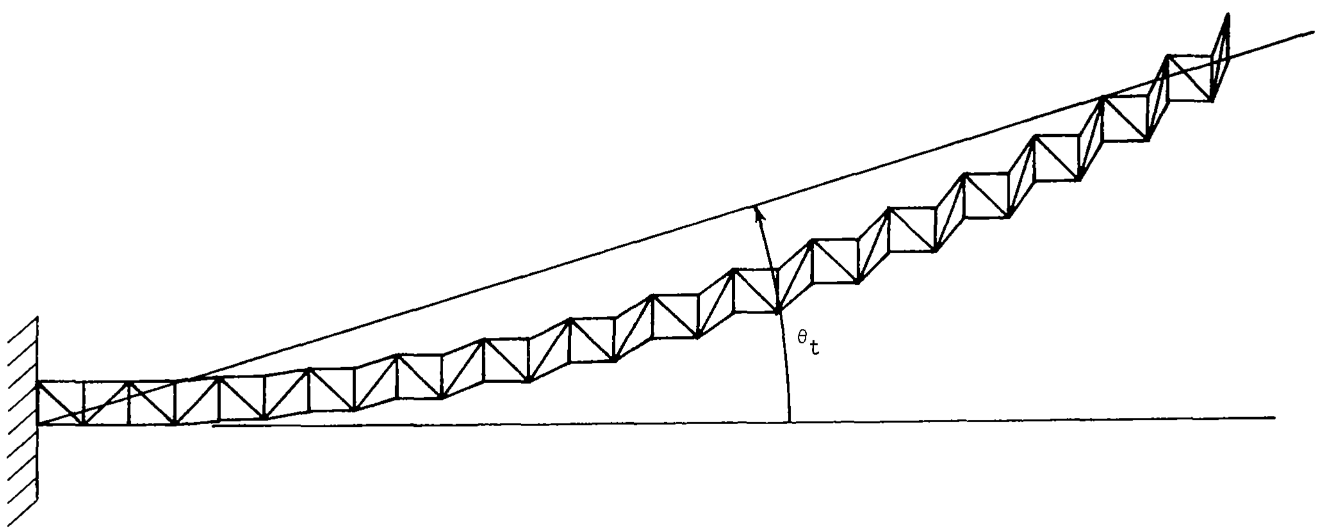


Figure 20.- Representative curved, lateral serpentine geometry. $\theta_b = 0°$.

bays always remain fully deployed. The frequency ratio $(f/f_0)^2$ as a function of the tip angle θ_t is shown for the base-line and quadratically tapered truss in figure 21. Since θ_t is limited by full extension of the diagonal in the outermost bay, values of θ_t for the curved geometry extend only to 23° (when $\theta_b = 0°$). The data show that for $\theta_t < 23°$, the curved serpentine truss will give a higher frequency ratio than a straight serpentine truss. The reason for this result is that the three bays at the base of the curved truss are fully deployed, thus giving the curved truss more root stiffness than the straight truss. The importance of retaining root stiffness for maintaining or increasing the frequency ratio has already been established in the selective deployment/retraction study, and it is shown to be applicable for serpentine operation also.

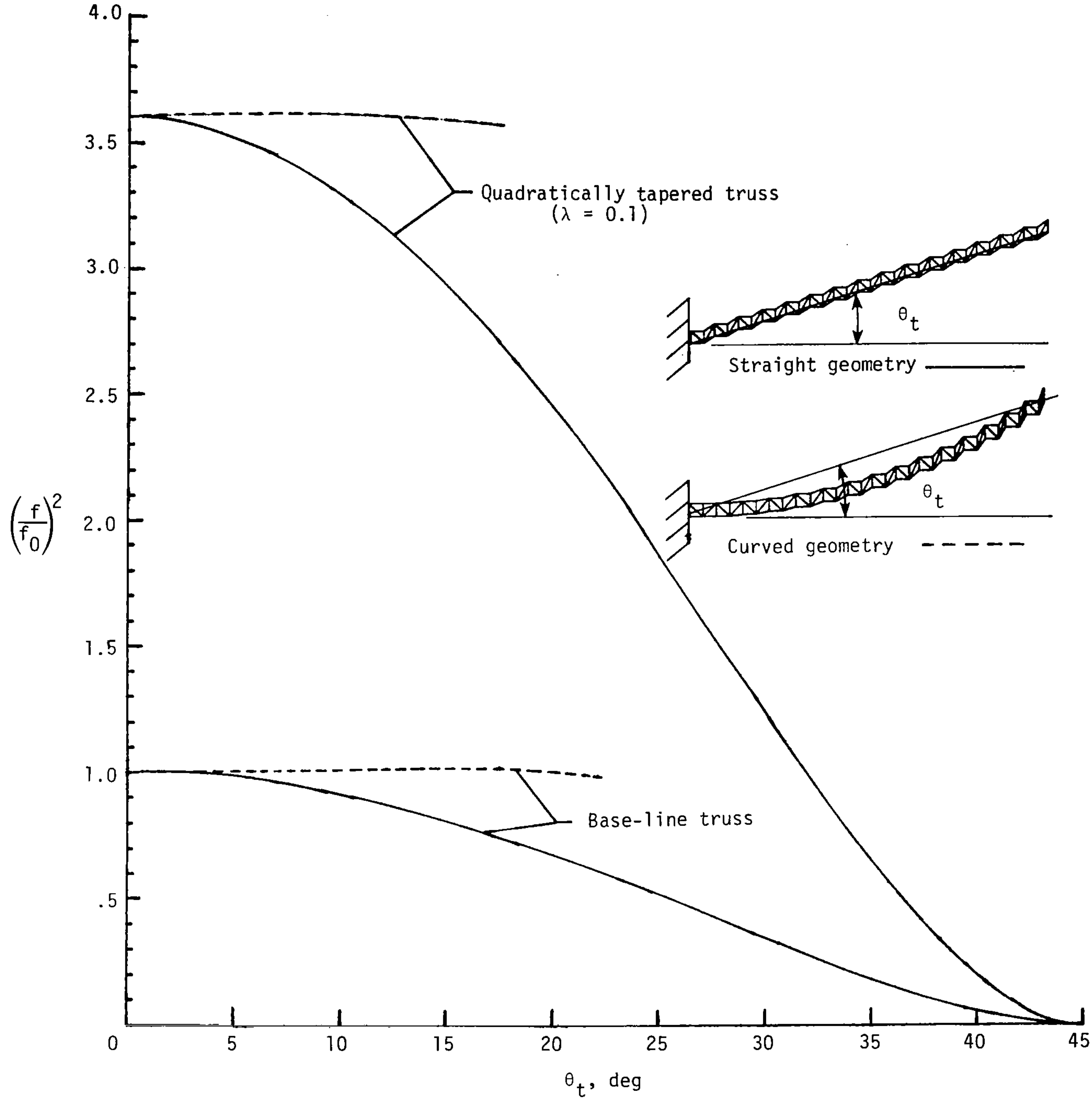


Figure 21.- Fundamental frequency of base-line and quadratically tapered (λ = 0.1) trusses during curved, lateral serpentine operation.

CONCLUDING REMARKS

An analytical study was made to evaluate the fundamental frequencies of a two-dimensional cantilevered truss boom at various stages of deployment. Each bay of the truss had an independently controlled actuator in the diagonal member. By extending and retracting these diagonals, the truss could be axially retracted or deployed and undergo lateral serpentine operations. The truss evaluated in this study was 30.48 m long, 1.016 m deep, and had 30 bays.

Two truss models with the aforementioned dimensions were examined. In the first (base-line) model, all the truss members (battens, diagonals, and longerons) had equal cross-sectional areas and, thus, each bay was identical. In the second (tapered) model, the areas of the members varied from bay to bay but were uniform within each bay. For this tapered model, the member areas were largest in the bay at the cantilever root and decreased in each successive bay from the root to the tip. When fully deployed, a quadratically tapered truss, in which the area of the members in the tip bay was 10 percent of the area in the root bay, had a fundamental frequency which was 3.6 times that of the base-line truss and approximately one-half that of the mass. The tapered truss, however, no longer met the requirement on tip deflection because of an applied load, which was the criterion used to size the base-line truss.

A significant reduction in the fundamental frequency of both models took place as the truss was uniformly retracted from a fully deployed position. The largest decrease in frequency occurred at the beginning of truss retraction for a small change in the diagonal-member lengths. During uniform retraction, the fundamental mode changed from pure bending (at full deployment) to a combination of bending and axial vibration, and then to a pure axial mode (near full retraction).

Significant increases in fundamental frequency for the base-line and tapered trusses are possible if a selective rather than uniform deployment/retraction scheme is used during axial operation. The frequency increase occurs with the selective operation because stiffness is maintained at the root of the cantilever by selecting a number of bays there to stay fully deployed during truss maneuvers. Similar frequency increases are noted during serpentine operation when a curved, lateral geometry, rather than a straight, lateral geometry, is used. The frequency increases for the curved geometry are due, again, to requiring that a number of bays near the truss root remain fully deployed during serpentine maneuvers.

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16. Abstract

An analytical study was made to evaluate changes in the fundamental frequency of a two-dimensional cantilevered truss boom at various stages of deployment. The truss could be axially deployed or retracted and undergo a variety of controlled-geometry changes by shortening or lengthening the telescoping diagonal members in each bay. Both untapered and tapered versions of the truss boom were modeled and analyzed by using the finite-element method. Large reductions in fundamental frequency occurred for both the untapered and tapered trusses when they were uniformly retracted or maneuvered laterally from their fully deployed position. These frequency reductions can be minimized, however, if truss geometries are selected which maintain cantilever root stiffness during truss maneuvers.

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