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EVALUATION OF SOLAR ARRAY FLIGHT EXPERIMENT RESPONSE DURING FLIGHT FOR EXTENSION/RETRACTION PHASE

By Jerry Slaby

Systems Dynamics Laboratory
Science and Engineering Directorate

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16. ABSTRACT

This is a post flight evaluation of the Solar Array Flight Experiment's (SAFE) deployment dynamics that explains the encountered resonances.

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TECHNICAL MEMORANDUM

EVALUATION OF SOLAR ARRAY FLIGHT EXPERIMENT RESPONSE DURING FLIGHT FOR EXTENSION/RETRACTION PHASE

INTRODUCTION

The Solar Array Flight Experiment (SAFE) is a deployable space structure. It consists of a mast and a blanket. The mast is wound in a coil and is stored in a container. The blanket is composed of 87 hinged panels that are folded and stowed in a separate box. Mast and blanket are connected at the top and at the bottom. As the mast unwinds, the pleated blanket deploys, creating an ultra light structure.

One of the experiment's objectives was to record the extension/retraction phase for later evaluation. Such an experiment in a gravitational environment would be impossible.

Before the flight, a study of the longitudinal vibration of the blanket was made, in order to determine its natural frequency. If the mast and blanket frequency coincided, a possible cross-coupling might occur, causing a response problem.

The study indicated that at 60 percent deployment, a potential cross-coupling was possible, but SAFE's deployment speed was too high (1.65 in./sec) to permit that.

During the retraction phase, there was a strong cross-coupled resonance between the mast and the blanket. It occurred at 10 percent deployment at a frequency of 0.75 Hz.

The subsequent report evaluates this phenomena.

ANALYSIS

The objective of this evaluation is to simulate the SAFE's extension/retraction dynamics in order to assess the observed flight resonant response and its potential problem for future arrays.

The SAFE was instrumented with accelerometers and viewed by the Orbiter video system.

One set of xyz-accelerometers was placed at the base of the mast to record a low frequency disturbance. Whereas a set of xy-accelerometers was mounted on the tip of the mast, to register the acceleration of the mast in deployed condition (0.06 to 0.04 Hz at 0 to 8 mg). For the extension/retraction phase, the video recorders were registering a higher activity of the system than anticipated.

All the video recordings that displayed the extension/retraction phase show that SAFE was constantly responding to deployment mechanisms disturbance. Tape 1 of the video recordings has been singled out because it exhibits an increase in oscillation. Especially during retraction, at a 10 percent mast length, SAFE's dynamic activity intensified. The mast tip started to rock and to twist, causing the blanket's upper panels to oscillate up and down. A cross-coupling between the lateral and longitudinal axis was evident.

Only the xy-accelerometer set that was mounted on tip of the mast recorded that vibration distinctly (Figs. 3,4,5).

This analysis will use the x-axis recordings even though they were clipped, because the accelerometer was designed for 70 and 100 percent deployed condition and operated somewhat out of its frequency and sensitivity range. Valid Power Spectrum Density (PSD) plots could be made from the not affected oscillogram's portions. The missing information will be supplemented with video recordings and simulations.

Figure 1 shows an isoplot for the extension. It depicts a set of PSD plots. Each PSD plot shows a time slice of 50 sec indicating the magnitude of a particular frequency that prevailed at that time. Figure 1 shows two rows of peaks, one at 0.75 Hz and one at 1.5 Hz. These two rows of peaks indicate that the tip of the mast responded mainly to two distinct frequencies; the deployment mechanisms rotational rate (0.75 Hz) and its first harmonic (1.5 Hz).

At this point a single assumption must be made to conclude this analysis: The resonance seen at 10 percent extension was caused by the system's first bending mode as it coincided with the fundamental frequency of the deployment mechanism.

This assumption is justified by the available data shown on Figure 7. The 100 percent and 70 percent deployment first mode frequencies were both determined by analysis and test. This first mode is predominantly a cantilever bending mode. It responded at 10 percent, 70 percent, and at 100 percent deployment to a frequency of 0.75 Hz, 0.06 Hz, and 0.038 Hz, respectively.

An additional resonance is noticeable on Figures 3 and 4 at 60 percent deployment. It is the resonance of a higher order mode that responded to the first harmonic disturbance frequency. The same mode responded later to the fundamental frequency at 90 percent deployment (compare Figs. 6 and 7).

THE MATH MODEL

A math model was developed in an attempt to simulate the extension/retraction phenomenon.

A simplified version of SAFE can be visualized as a cantilever of varying length, whose base is disturbed periodically.

Since the first bending mode frequency of the cantilever is a function of its length, the frequency will change as the cantilever extends or retracts. At some length the natural frequency of the cantilever will coincide with the disturbing frequency, causing a resonance.

To simulate that event, a linear second order differential equation was chosen with a time dependent coefficient, since time is directly proportional to the cantilever's length.

The time dependent frequency $\omega_n(t)$ was derived from the modified cantilever equation whose total mass is concentrated at the tip. The modification function was obtained by curve fitting the deployment points at 10 percent, 70 percent, and 100 percent as seen on Figure 7.

To duplicate the oscillograms, the information from Figures 1 and 2 was used.

The disturbing function is on the right hand side of the differential equation. It consists of the fundamental frequency and its first harmonic.

$$\ddot{X} + 2 * \xi * \omega_n(t) * \dot{X} + \omega_n^2(t) * X = P * (\cos \omega t + A * \cos 2\omega t) \tag{1}$$

The time dependent frequency consists of the cantilever equation multiplied by a modifying function

$$\omega_n(t) = \sqrt[2]{\frac{3 * EI}{m * Z_0^3}} * \frac{0.125}{(Z(t)/Z_0)^{1.15}} \quad . \tag{2}$$

For simulation, the cantilevers length was replaced with time, it is $Z(t) = v*t$. To avoid a division by zero the simulation started at t=1 sec and equation (2) becomes:

$$\omega_n(t) = \sqrt[2]{\frac{3 * EI}{m * Z_0^3}} * \frac{0.125}{(v*t/Z_o)^{1.15}} \quad , \tag{3}$$

$t = 534$ sec	Time needed to deploy 70 percent
$Z_0 = 1$ in.	Normalization constant
$m = 1$ lb-sec^2/in.	Lumped mass at the mast tip
$EI = 18 * 10^6$ lb-in.^{2}	Flexural stiffness of the cantilever
$Z = 1260$ in.	Total length of the cantilever (100 percent deployed)
$P = 4$ mg $= 1.5$ in./sec^2	Average acceleration from Figure 3
$\zeta = 0.05$	Chosen structural damping
$A = 0.6$	Estimated multiplication factor (Fig. 1)
$v = 880$ in./534 sec	SAFE's deployment speed (Fig. 7) (from 0 to 70 percent)
$\omega = 4.72$ rad/sec	Disturbance frequency (constant)
$\omega_n(t) = 0.2$ to 6 rad/sec	Natural frequency of the first bending mode (a function of deployment, see eq. (3))

Figure 5 shows the extension record with the relevant details.

The simulation shown in Figures 8 and 9 matches the raw data except at short mast length. In that portion the simulation shows a clear 1.5 Hz response.

This discrepancy means that for short mast length the model fails to represent accurately the hardware. Or in physical terms, SAFE appears to have a higher rate of change of stiffness at shorter mast length than the linear model.

This idealisation uses a single degree of freedom math model and simulates SAFE's first bending mode, consequently a higher order mode is not included. Resonances No. 3 and No. 4, shown on Figure 7, are caused by a higher order mode which is not simulated.

DISCUSSION

A finer tuning of the parameters would give a higher fidelity in simulating the flight data. However, the main objective is to understand what happened during the extension/retraction period and to explain the flight data as is shown on Figures 3, 4, and 6.

Since extension is a mirror image of the retraction, only one event needs to be discussed and simulated. If one chooses to explain the extension (Fig. 3), the main resonance is at 10 percent deployment. Comparing Figures 5 and 7, the history of that event becomes clear. As the mast extends, the first bending mode curve crosses the region of 1.5 Hz and subsequently 0.75 Hz; encountering resonance No. 1 and No. 2 at crossover points (Fig. 7). The linear model simulation (Figs. 8 and 9) reproduced properly the envelope of the main resonance at 10 percent deployment, but it failed to duplicate in detail the oscillograms shape and frequency at that point.

The choice of the structural damping factor was made by trying to duplicate the over-all shape of the signal. But the simulation shows that a ten fold decrease in damping causes an amplification of the maximum up to three times. It is known from tests that the structural damping is between 2 and 8 percent. Since this simulation uses 5 percent damping, the true maximum can be, at the most, two times higher than the simulation (peak-to-peak 1 to 2 in. lateral displacement).

The oscillogram's unsymmetry about the axis of oscillation is caused by the superposition of the frequencies 0.75 Hz and 1.5 Hz (Fig. 2). The lower parts of the signal are subtracted and added to the upper parts. That effect makes the signal appear unsymmetrical.

The induced longitudinal oscillation of the panels, during the resonance at 10 percent deployment, was estimated to be 0.75 Hz and to have a panel displacement of 0.5 ft peak-to-peak. Counting from top, only the fifth and sixth panel-pair were actively participating in that oscillation.

This study indicates that a coincidence between the first bending mode and the rotational rate of the deployment mechanism is unavoidable. As long as that coincidence occurs at a short mast length the resulting resonance will not cause a dynamic response problem, because the deployment speed is too high to allow an oscillatory build-up.

CONCLUSIONS

1) For oscillatory extendable structure, dynamic coupling will most probably exist.

2) The response can be minimized by a high excitation frequency.

3) Extendable structures using an oscillatory mechanism to deploy, should be dynamically evaluated to insure that local deployment problems do not exist.

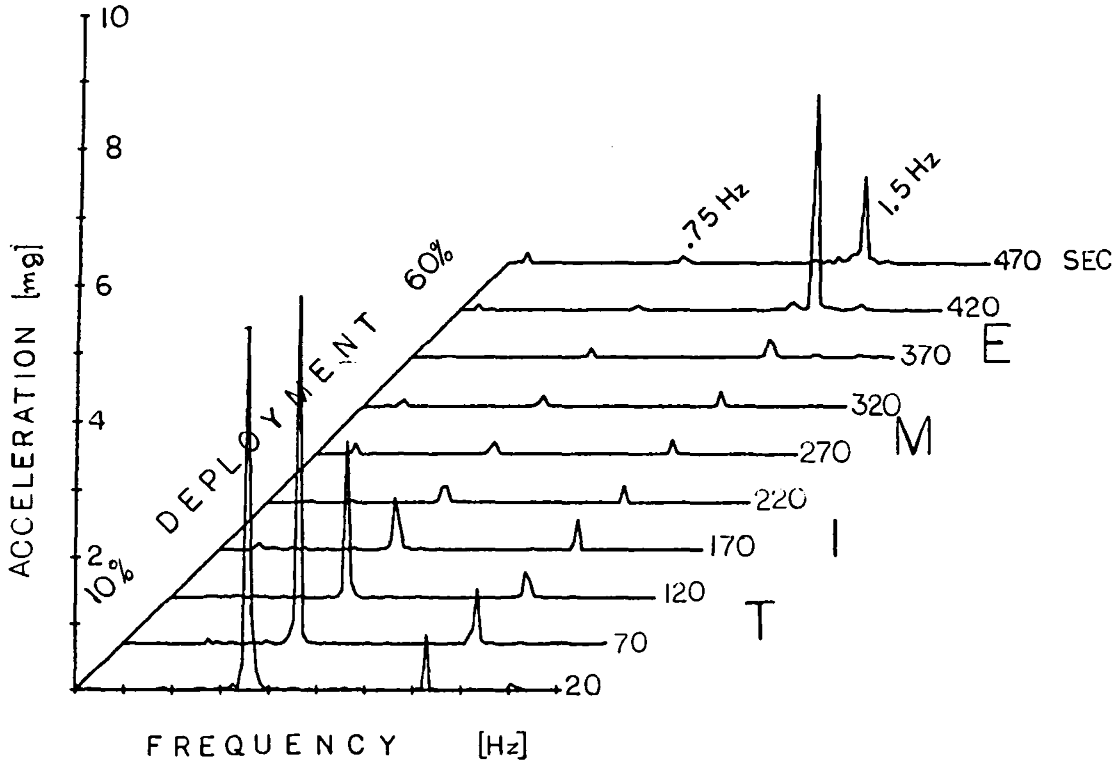

Figure 1. A typical isoplot for the second extension. The first row of peaks represents the disturbance frequency. The second row of peaks is the first harmonic of the disturbance frequency.

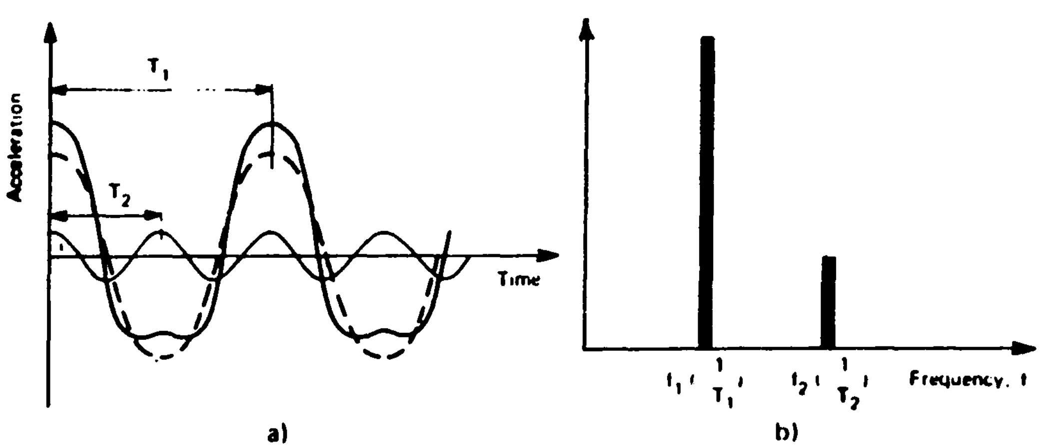

Figure 2. The profile of the disturbance function used in simulation. (a) Time domain. (b) Frequency domain.

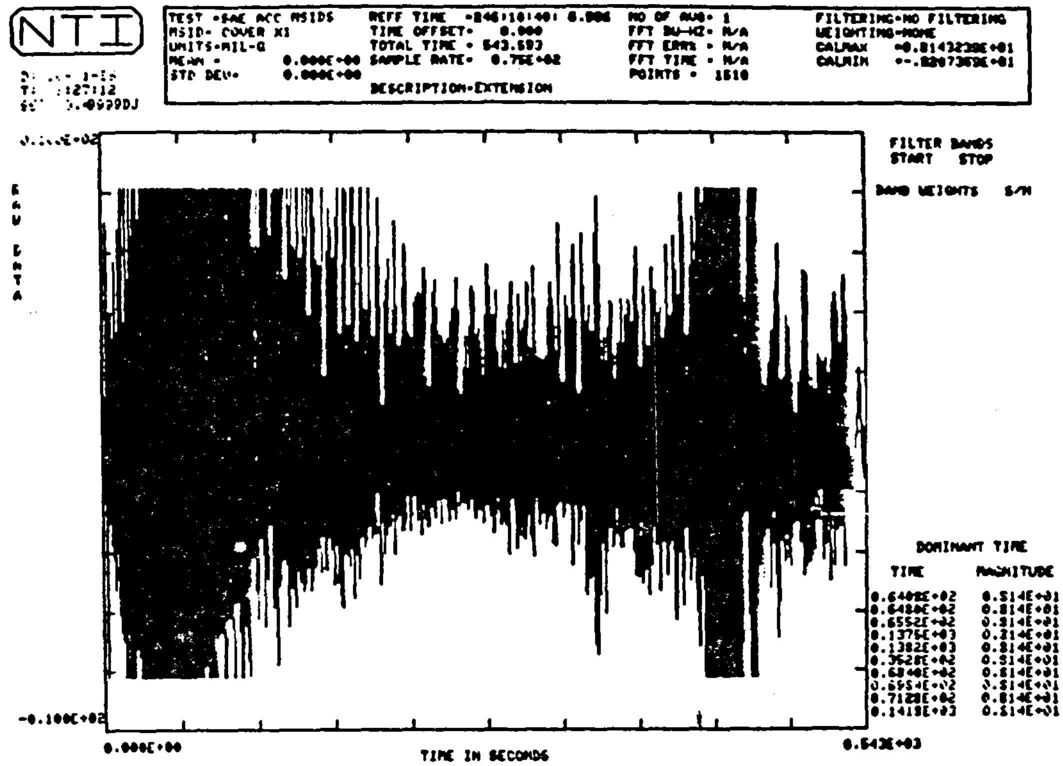

Figure 3. Oscillogram made during the extension from 0 to 70 percent at the tip of the mast in X-axis.

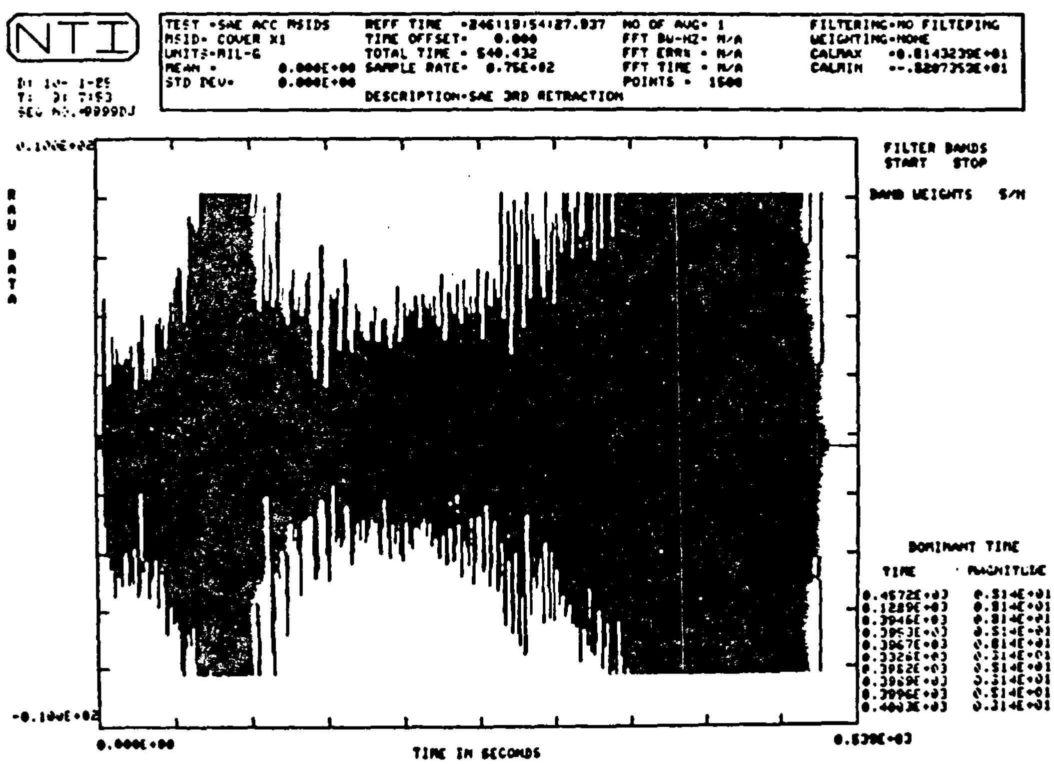

Figure 4. Oscillogram made during the retraction from 70 to 0 percent at the tip of the mast in X-axis.

(Note that the retraction is a mirror image of the extension.)

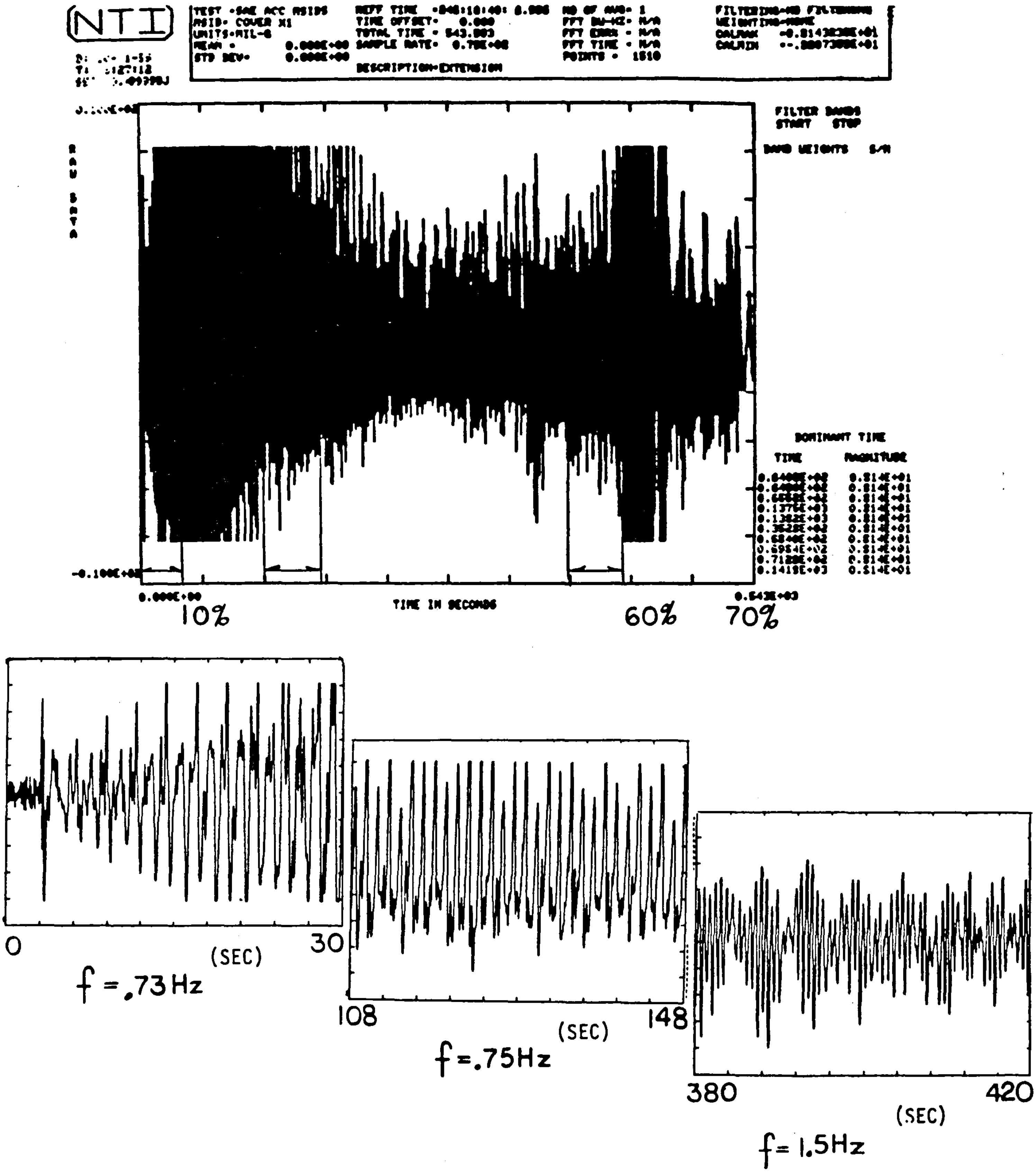

Figure 5. Close-up of Figure 3. Note a 180° phase shift in the 10 percent deployment region, indicating a single resonance.

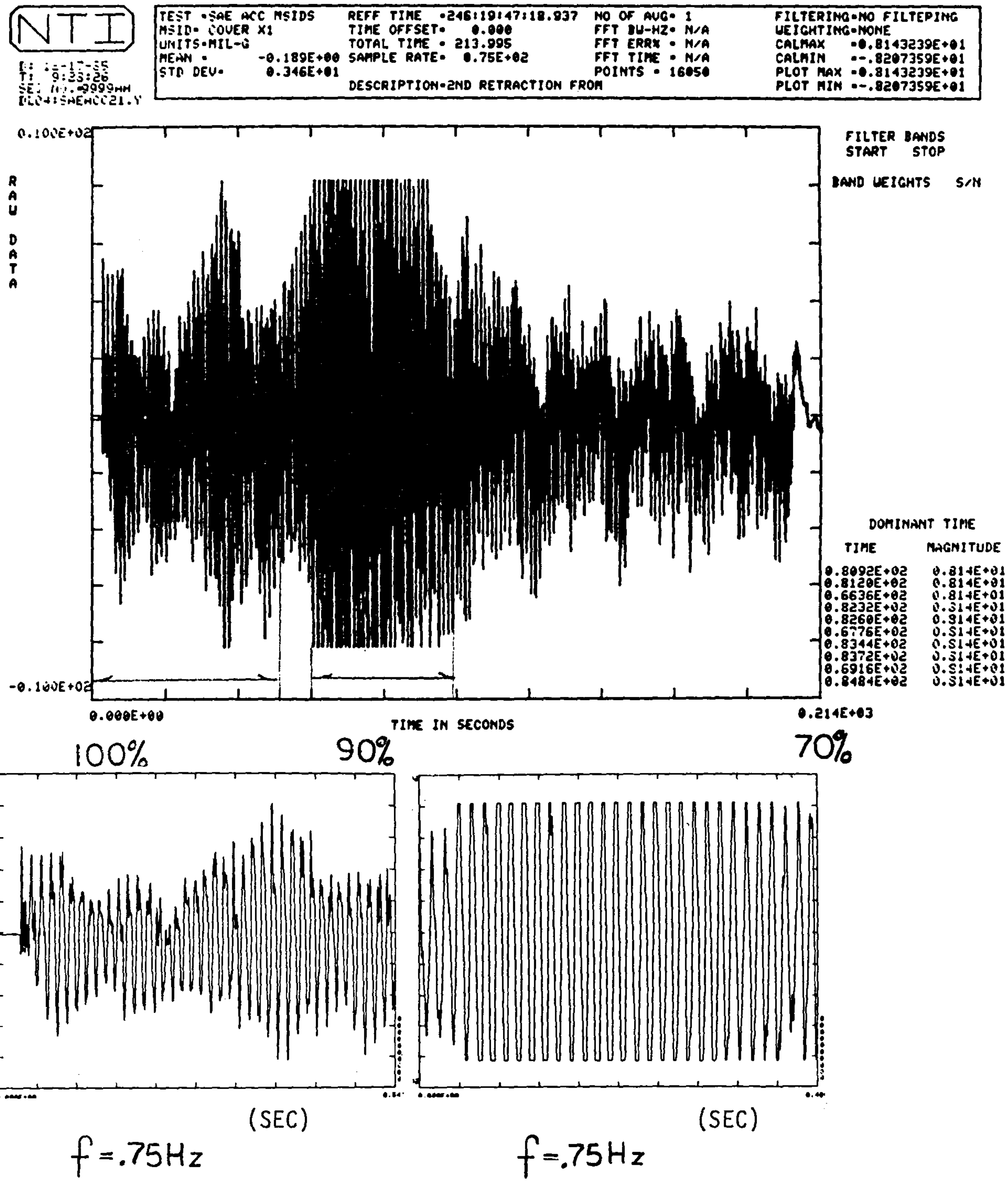

Figure 6. Oscillogram made during retraction from 100 to 70 percent at the tip of the mast in X-axis.

(NOTE: The resonance at 90 percent deployment is on Figure 7 marked as the intersection No. 4.)

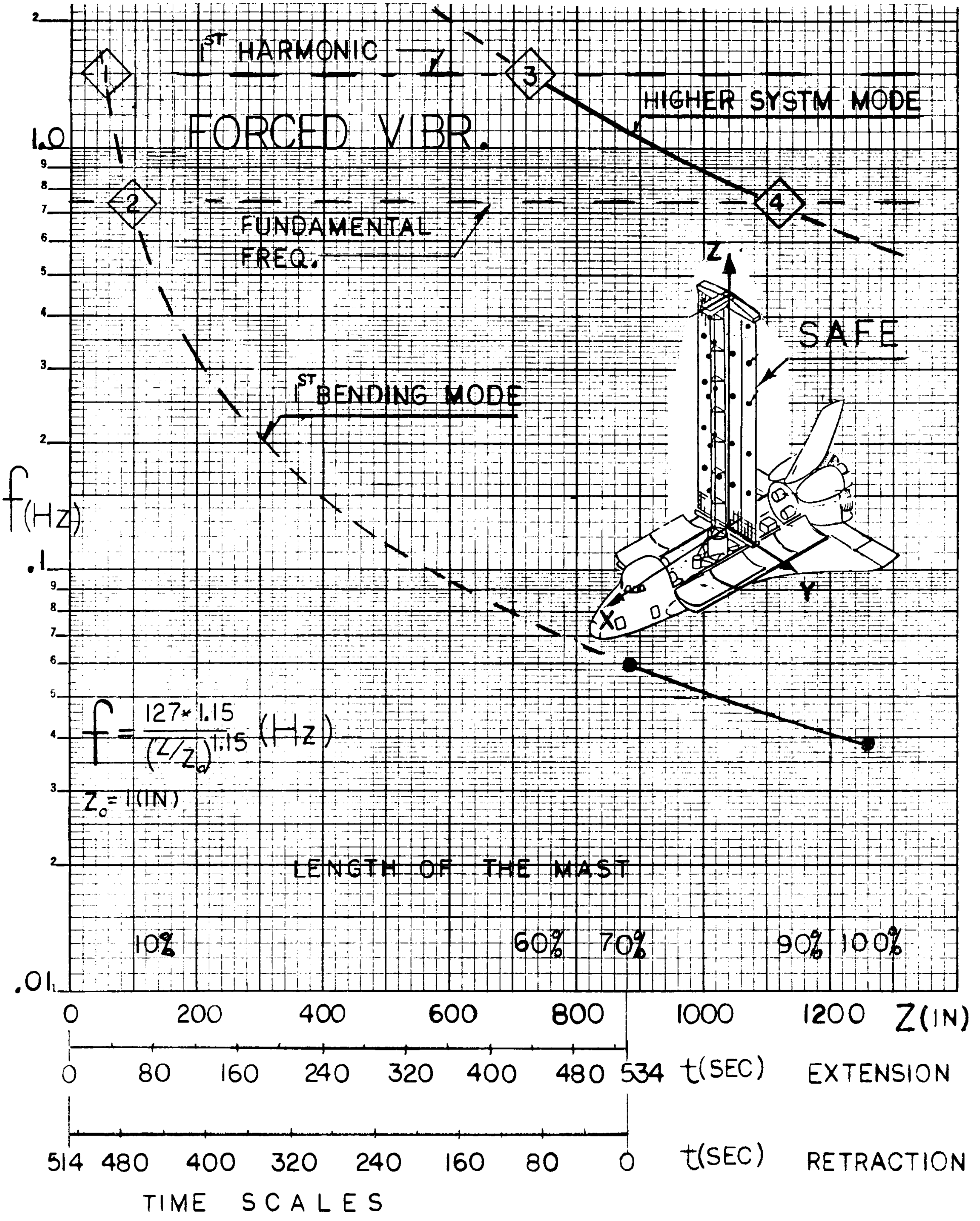

Figure 7. SAFE's frequency response curve for the first bending mode and a higher system mode.

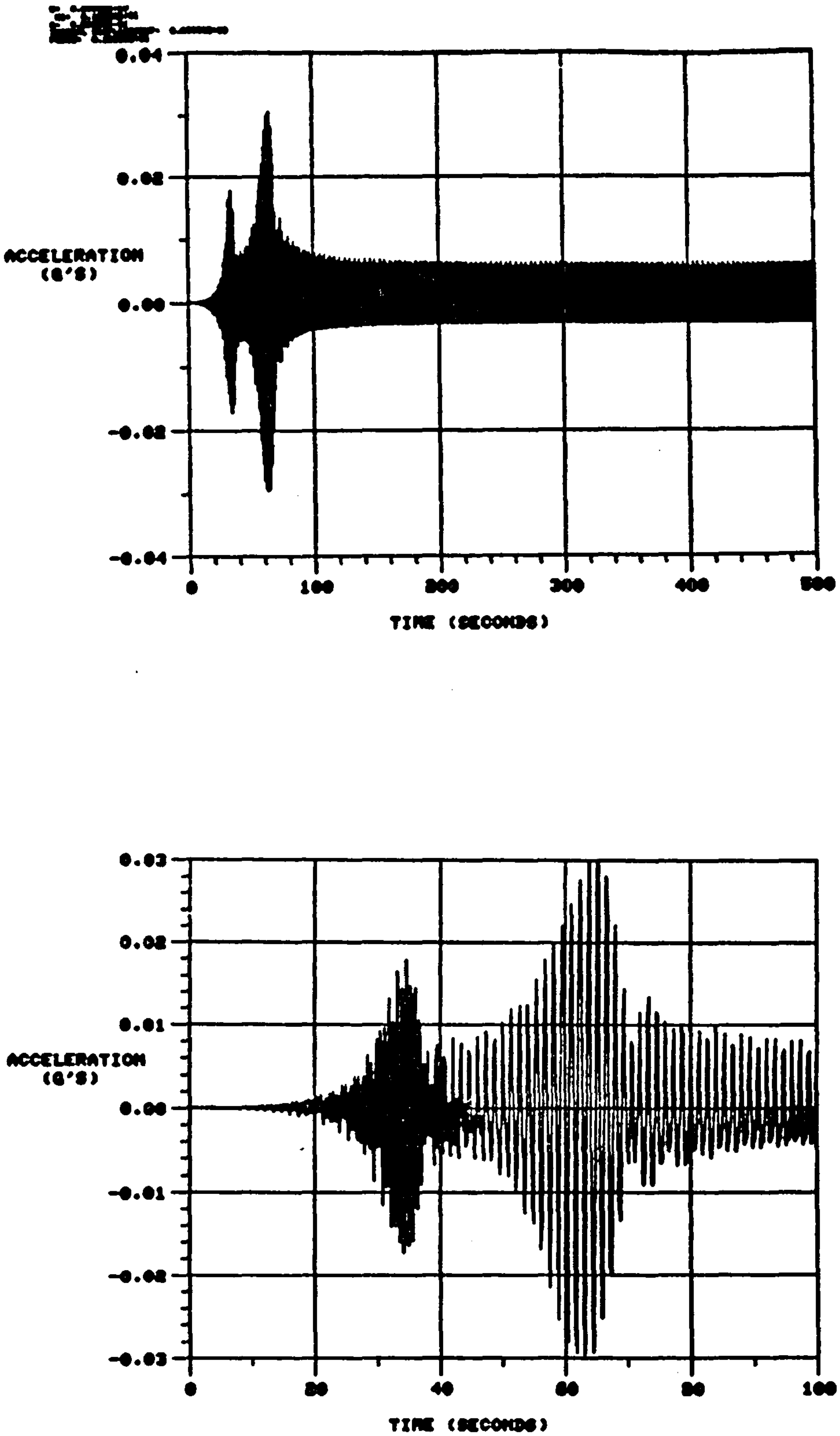

Figure 8. Simulated acceleration in X-axis at the mast tip during 0 to 70 percent extension.

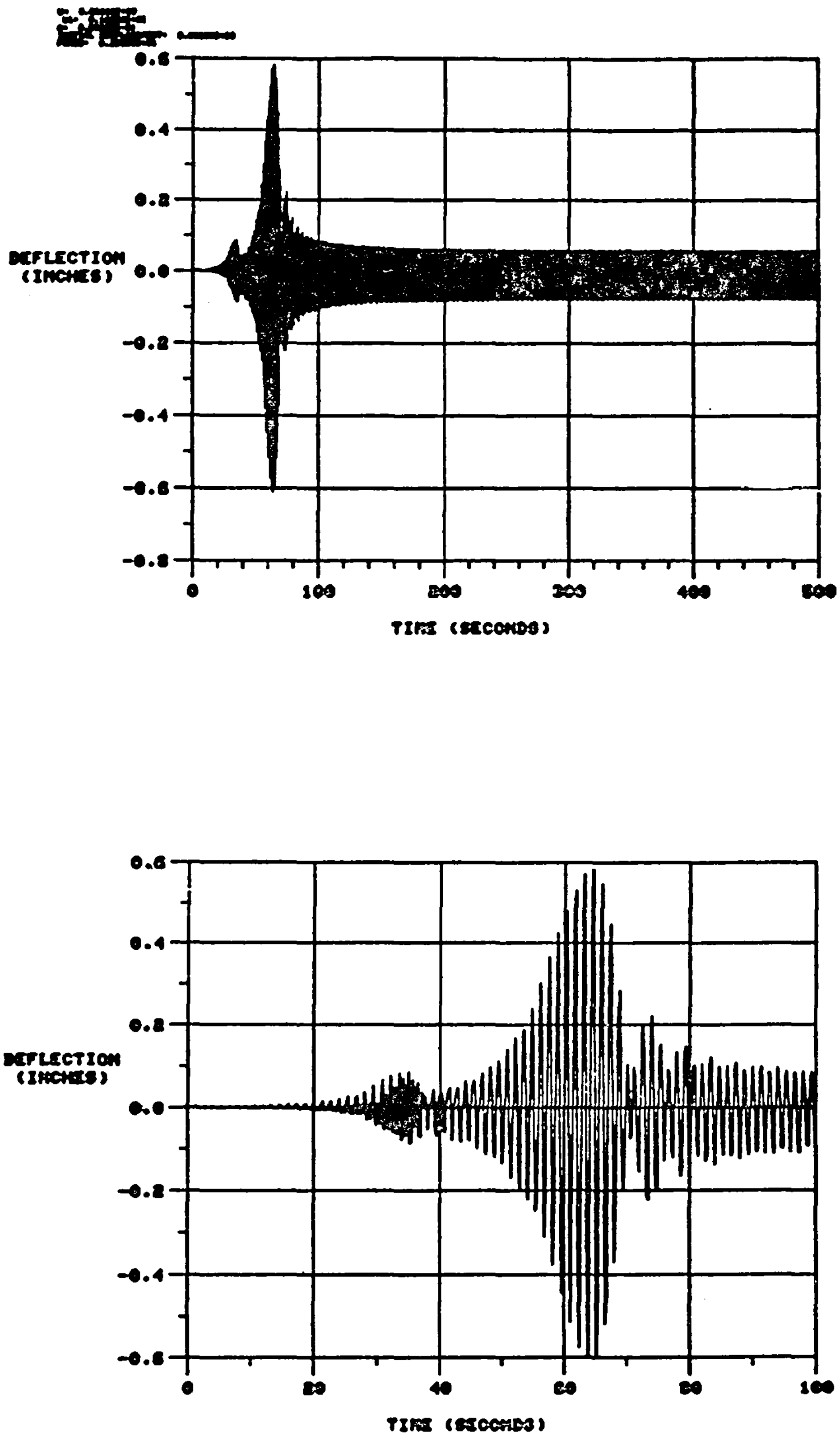

Figure 9. Simulated deflection in X-axis at the mast stip during 0 to 70 percent extension.

APPROVAL

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By Jerry Slaby

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

for G. F. McDONOUGH
Director, Systems Dynamics Laboratory

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