System Identification of a Nonlinear Flexible Mode for the Shuttle Radar Topography Mission

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Abstract

In this paper we present the results of a study to identify a nonlinear bending mode for a 60 meter space structure. This study was done in support of the Shuttle Radar Topography Mission (SRTM). For this purpose, one linear model and three nonlinear models were considered and evaluated. The best selected model was used in the final Kalman filter that reconstructed the state associated with the relative radar antenna motion for the SRTM interferometer payload. High accuracy of the relative state estimates are needed because they are used by the motion compensation algorithm in the radar interferometry processor when calculating the desired topographic maps. The accuracy of this nonlinear modal bending model was critical in meeting the final desired performance requirements of the mission.

Keywords: system identification, nonlinear system, flexible modes, large space structure,

1. Introduction

In February 2000, the Shuttle Radar Topography Mission (SRTM) was flown on board of the Space Shuttle Endeavour to collect topographic data of the Earth (between 60 degrees north latitude and 54 degrees south latitude). This data will allow creating the first near-global high-resolution topographic maps of the Earth.

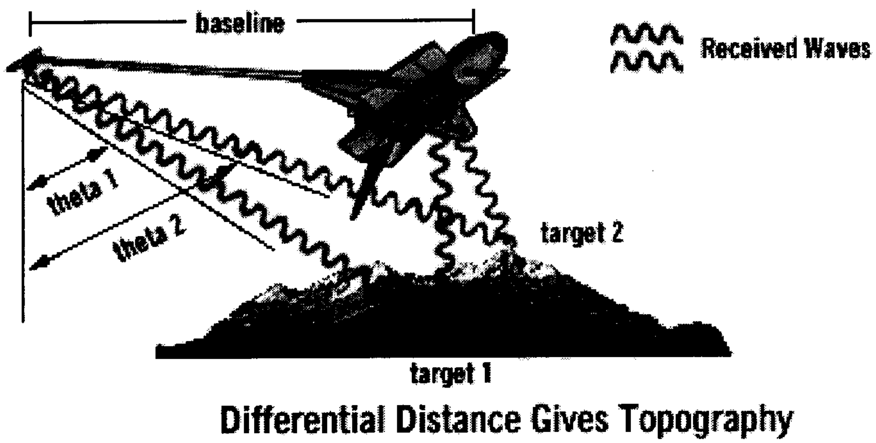

Figure 1. SRTM

To acquire the topographic data, SRTM used a technique called radar interferometry. This technique allows extracting elevation data from differences between two radar images taken from two different locations given that the relative position and orientations of the radar antennas are known with respect to the surface. For this purpose the SRTM payload had two sets of radar antennas (one on the Shuttle bay and one at the end of a 60-meter deployable mast), and a suit of high precision instruments (Attitude and Orbit Determination Avionics, AODA) to measure the position and orientation of the radar antennas with respect to the Earth. GPS receivers measured the position of the payload with respect to the Earth surface, and a Star Tracker and an Inertial Reference Unit were used to measure the orientation of the antenna located on the Shuttle bay. To measure the relative orientation and position of the outboard antenna located at the tip of the 60-meter boom with respect to the Shuttle, a Target Tracker and laser rangefinder were used. The Target Tracker measured the relative orientation by tracking an array of LEDs mounted on the outboard antenna. The laser rangefinder measured the relative distance between the Shuttle and a corner cube mounted on the outboard antenna. An overview of the system is given in Figures 1 and 2.

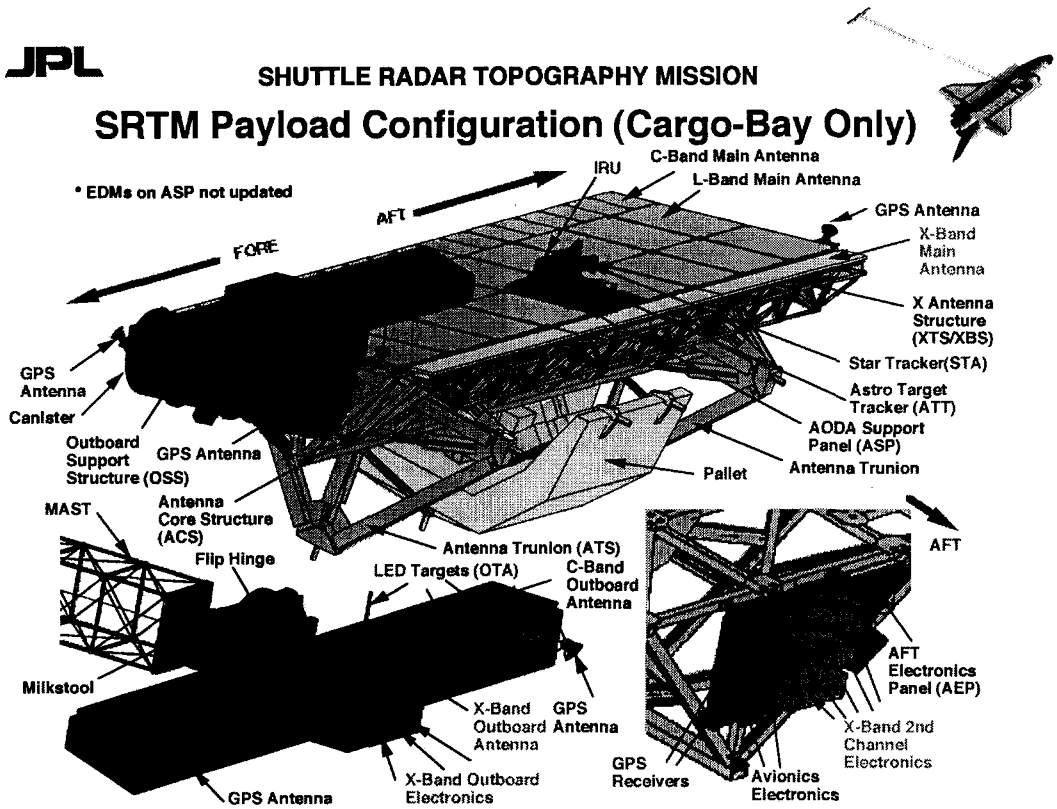

Figure 2. SRTM attitude and orbit determination avionics

Achieving the objective of creating topographic maps with an absolute height error of 16m every 30 postings, required estimating the position of the Shuttle with respect to the ground at the 1-meter level, the orientation of the antennas to the 1-arcsecond level, and the relative position/orientation of the antennas to the 1-mm/100-arcsecond levels. A general overview of the calibration and estimation, used to process the AODA measurements to the desired accuracies, is given in [1]. A description of the SRTM mast is given in [2], and a study on the damper failure is given in [3].

In this paper we are going to present a study to identify a model for the nonlinear roll bending mode of the 60-meter mast. Figure 3 and 4 show the mast deployed during the mission. This model was critical in achieving the required accuracies for the relative position and orientation of the antennas. This model was used by a Kalman filter to estimate the relative position and orientations of the antennas. Inputs to this Kalman filter were the Target Tracker and rangefinder measurements, and recorded time-histories of the Shuttle thruster firings during radar mapping. Outputs of the Kalman filter were time histories of estimates of the relative position and orientation of the radar antennas.

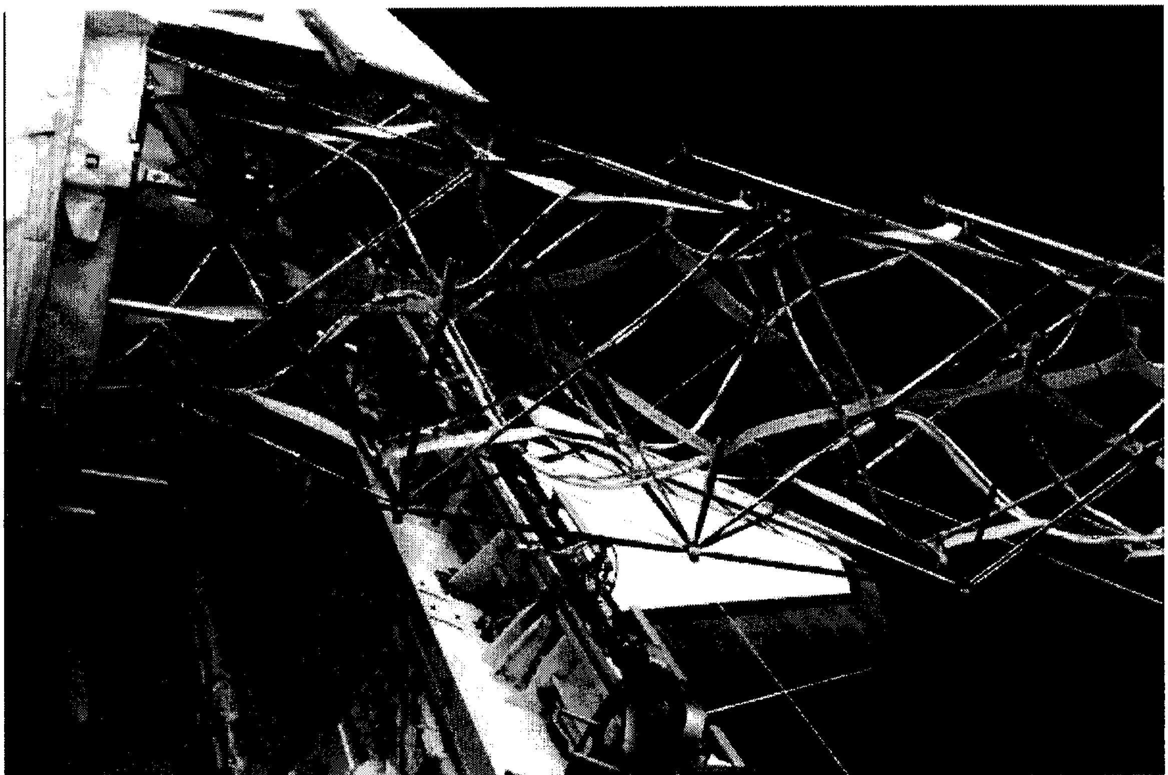
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Figure 3. View of the Mast from the Shuttle during the mission.

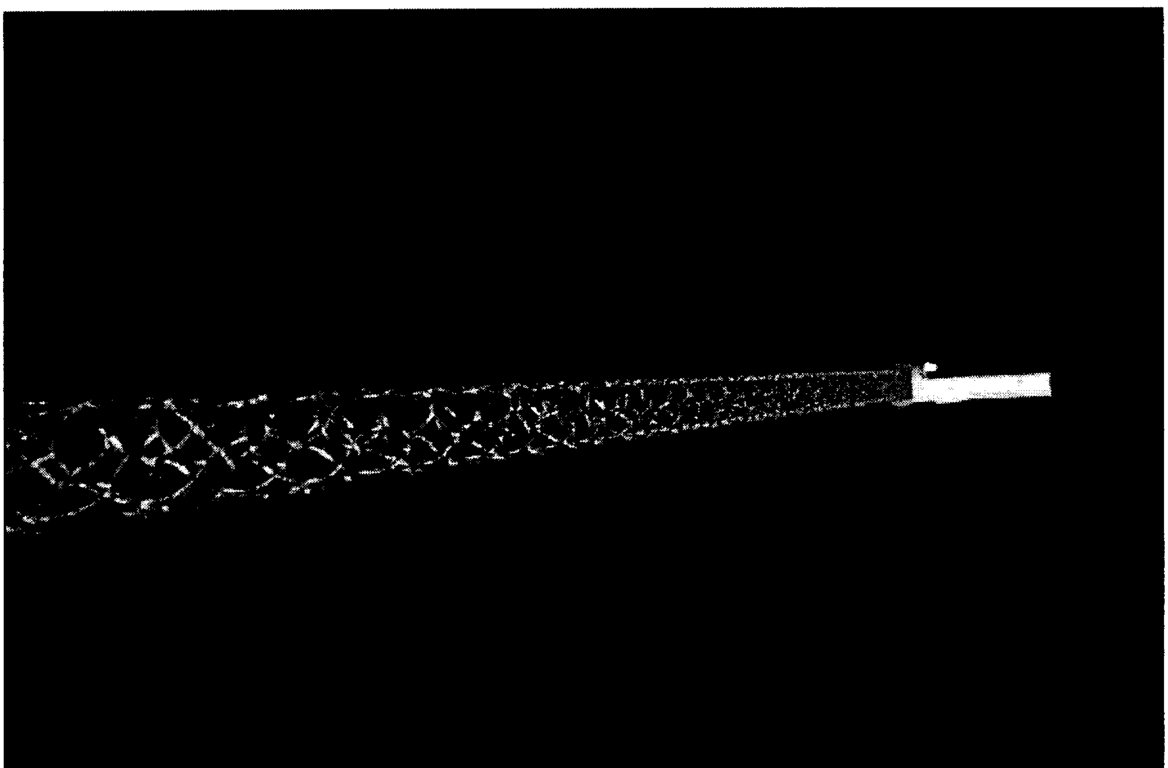
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Figure 4. View of the Mast and outboard antenna from the Shuttle during the mission.

2. Problem description: nonlinear bending mode

The main Roll bending mode showed a nonlinear behavior. This nonlinear behavior manifested itself in several ways:

- Its frequency was amplitude dependent. At high amplitude it tended to oscillate at a higher frequency, giving about a 10% frequency variation going from high to low over a given response.
- Its damping profile exhibited a linearly decaying envelope.
- The mean value over each cycle tended to have two different values: one occurring at medium to high amplitudes, and another at lower amplitudes.

These nonlinear behaviors were apparent by inspection of the ASTROS Target Tracker (ATT) measurements of the boom motion. The ATT is a camera mounted on the inboard antenna, which took pictures of three LEDs in a triangle configuration mounted on the outboard antenna. Figure 5, shows the motion in the vertical axis of an LED with respect to time. The vertical axis is the more sensitive to the roll bending mode.

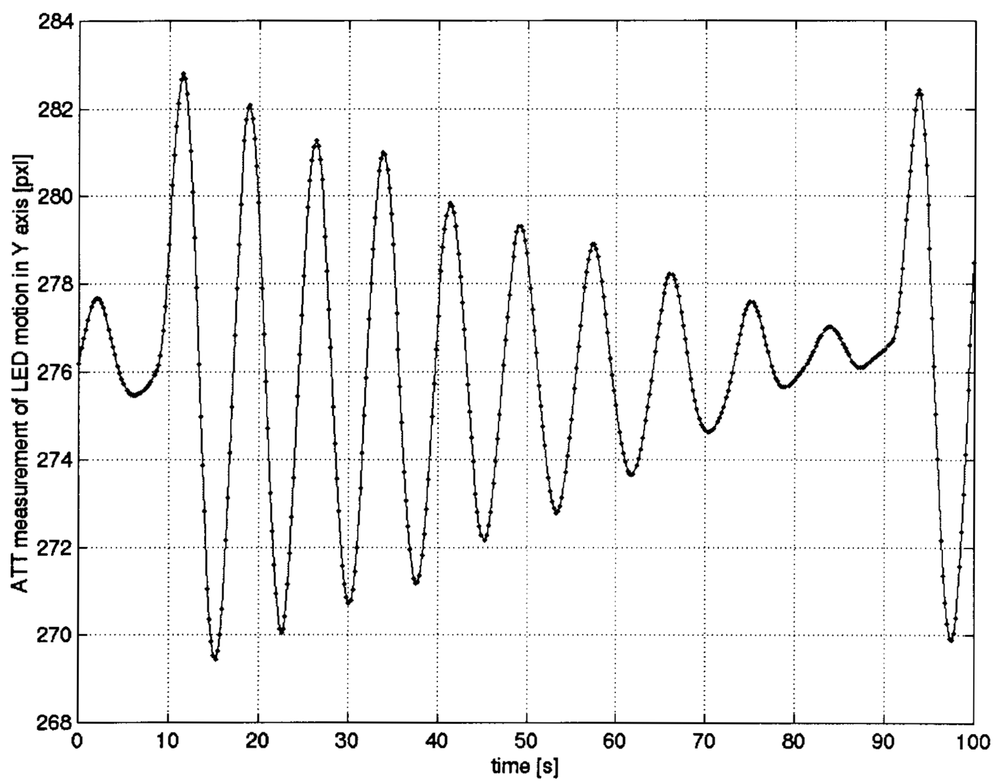

Figure 5. Nonlinear roll bending mode as seen by the ATT.

The Kalman filter which was designed to estimate the relative motion of the outboard antenna with respect to the inboard one, used a linear model for the mast flexible dynamics. The model was extracted from a NASTRAN model of the combined Shuttle with the SRTM payload in the radar-mapping configuration (mast deployed, dampers caged). This model included the five lowest frequencies modes of the mast: the first and second roll and yaw bending modes, and the twist mode. Each of these modes was modeled as a second order system. This implied that the modal frequency was constant and the modal damping was exponential. Given the nonlinear behavior of the roll bending mode, the linear model was not good enough. The linear damping and nonlinear mean value could be accommodated by using a moderate processed noise in the Kalman filter, but the frequency-amplitude nonlinearity could not. Therefore, a model for the frequency-amplitude nonlinearity was needed to achieve the desired performance.

3. Experimental realization of the frequency-amplitude curve

An experimental realization of the frequency-amplitude curve was obtained by running a moving windowed least squares estimator on the roll bending mode amplitude state. At each time, a time-window was centered at that point in time and was taken to have a duration of about 90% of the average wavelength of the mode. Within this window a best-fit sinusoid (phase, amplitude and frequency) was determined by numerically minimizing a least squares error. Then, this window was moved by about 2% of the average wavelength, and another best-fit sinusoid was determined, and so forth. An experimentally generated plot of modal amplitude versus squared-frequency (as determined by the moving window technique) is shown in Figure 6. This curve was generated using data that spanned several hours and contained multiple transients (in response to thruster firings).

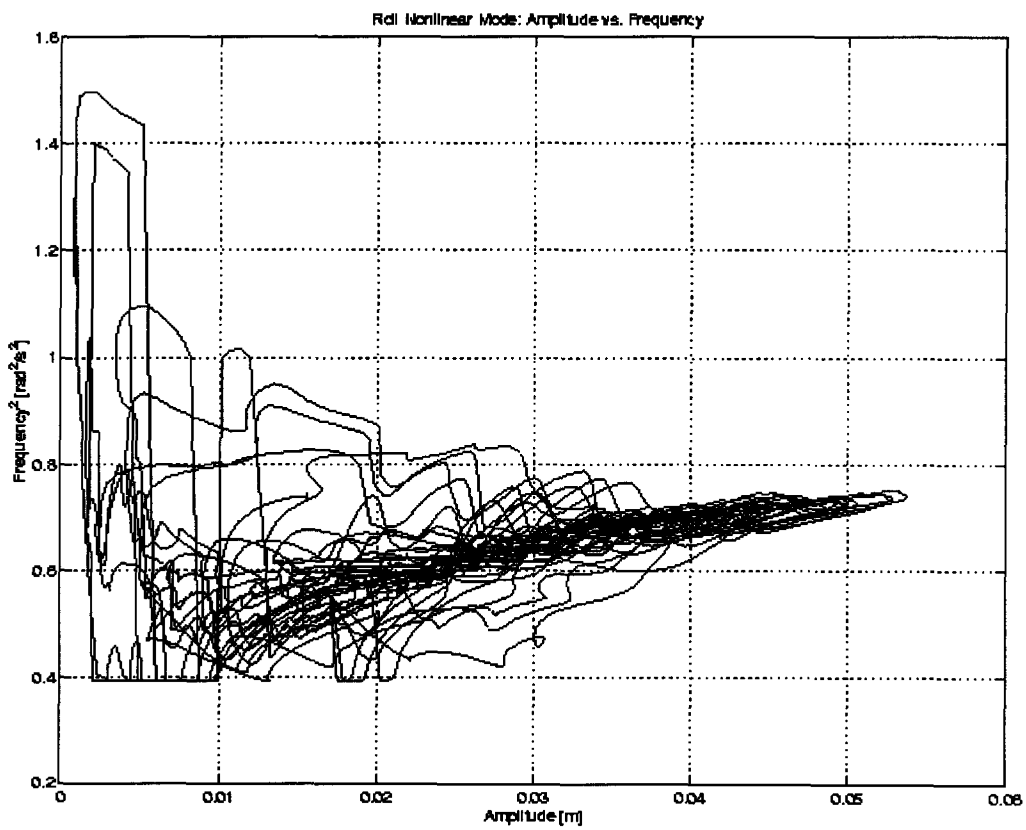

Figure 6. Experimental frequency-amplitude curve.

4. System Identification

Three parameterizations were considered for the frequency-amplitude nonlinearity. The parameters of each of these parameterizations were fitted using experimental frequency-amplitude curves generated by the method given in section 3.

The parameterizations are the following:

1) Frequency-amplitude curve fitting.

$$\ddot{x} + \xi\dot{x} + K(x,\dot{x})x = 0$$

$$A(x,\dot{x}) = \sqrt{x^2 + \left(\frac{\dot{x}}{\overline{K}(x,\dot{x})}\right)^2}$$

$$K(x,\dot{x}) = a + bA(x,\dot{x}) + cA(x,\dot{x})^2$$

with parameters: a, b, c

The optimal parameters were calculated by a least squares fit. The optimal parameters are: $a = -0.714041, b = 1.151121, c = 0.282855$. Figure 7 shows the experimental curve and the fitted model.

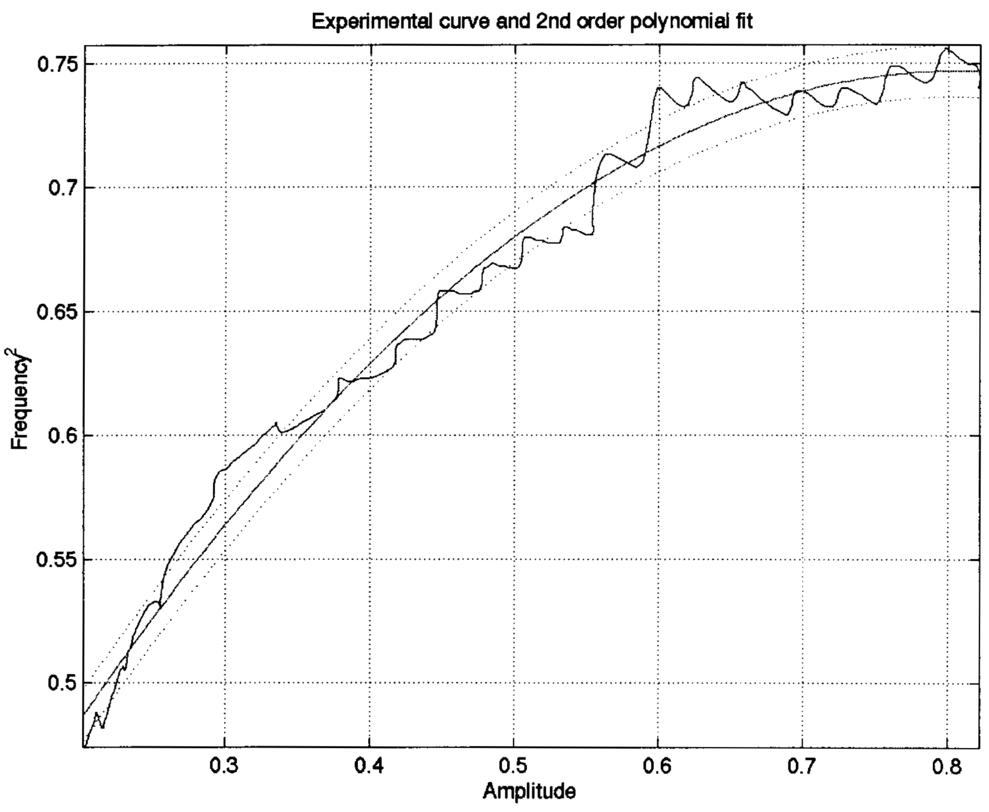

Figure 7. Frequency-amplitude curve fitting

2) Duffing model [4].

$$\ddot{x} + \xi\dot{x} + K(x,\dot{x})x = 0$$

$$K(x,\dot{x}) = a + b|x| + cx^2$$

with parameters: ξ, a, b, c

This Duffing model was fitted. The optimal parameters are the following $\xi = 0.051, a = 0.2731, b = 1.407143, c = -1.002551$.

Figure 8 shows how the duffing model fits some data.

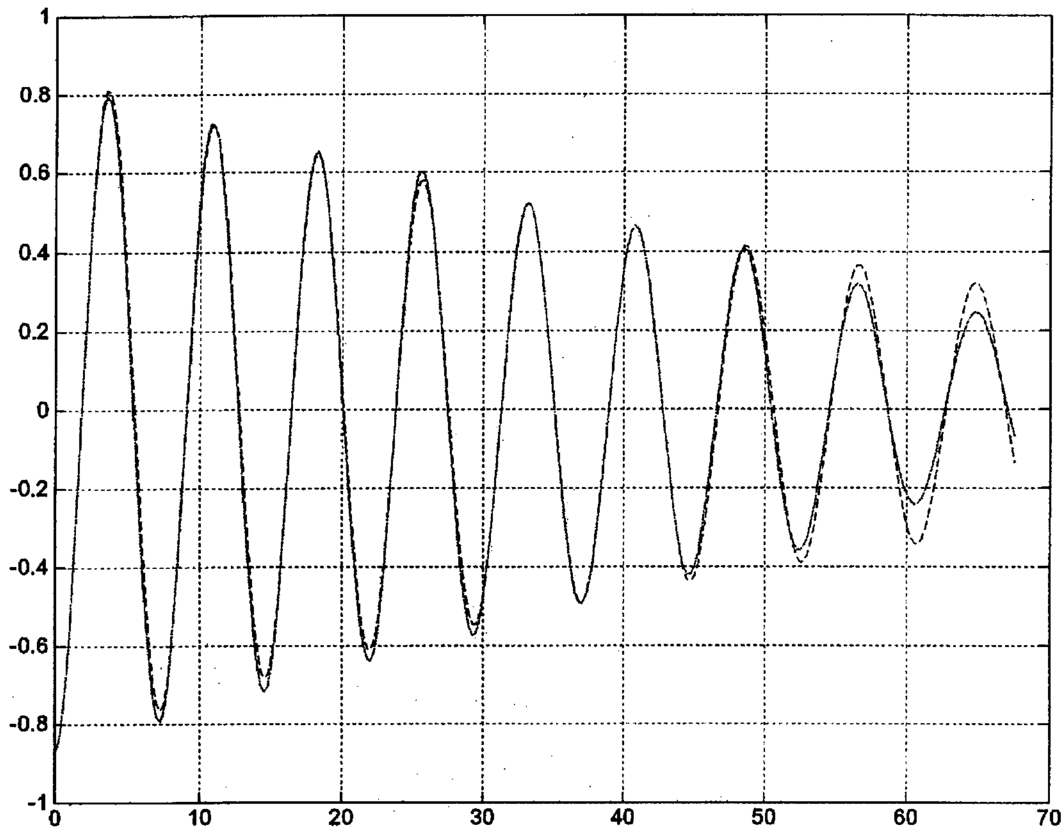

Figure 8. Duffing model fit to data

3) Modal expansion.

$$\ddot{x} + M(x,\dot{x}) = 0$$

$$M(x,\dot{x}) = \sum_{j=0}^{3} \sum_{\substack{i=0 \\ no: i=0, j=0}}^{3} p_{ij} x^i \dot{x}^j$$

with parameters: $p_{ij} \begin{cases} i = 0,\ldots,3 \\ j = 0,\ldots,3 \end{cases}$ no i = 0 and j = 0

The optimal parameters were: [0.078883, 0.575785, -0.020779, -0.094683, 0.013407, 0.306406, -0.182583, 0.137373, 0.166841]. Figure 8 shows how this model fits the data.

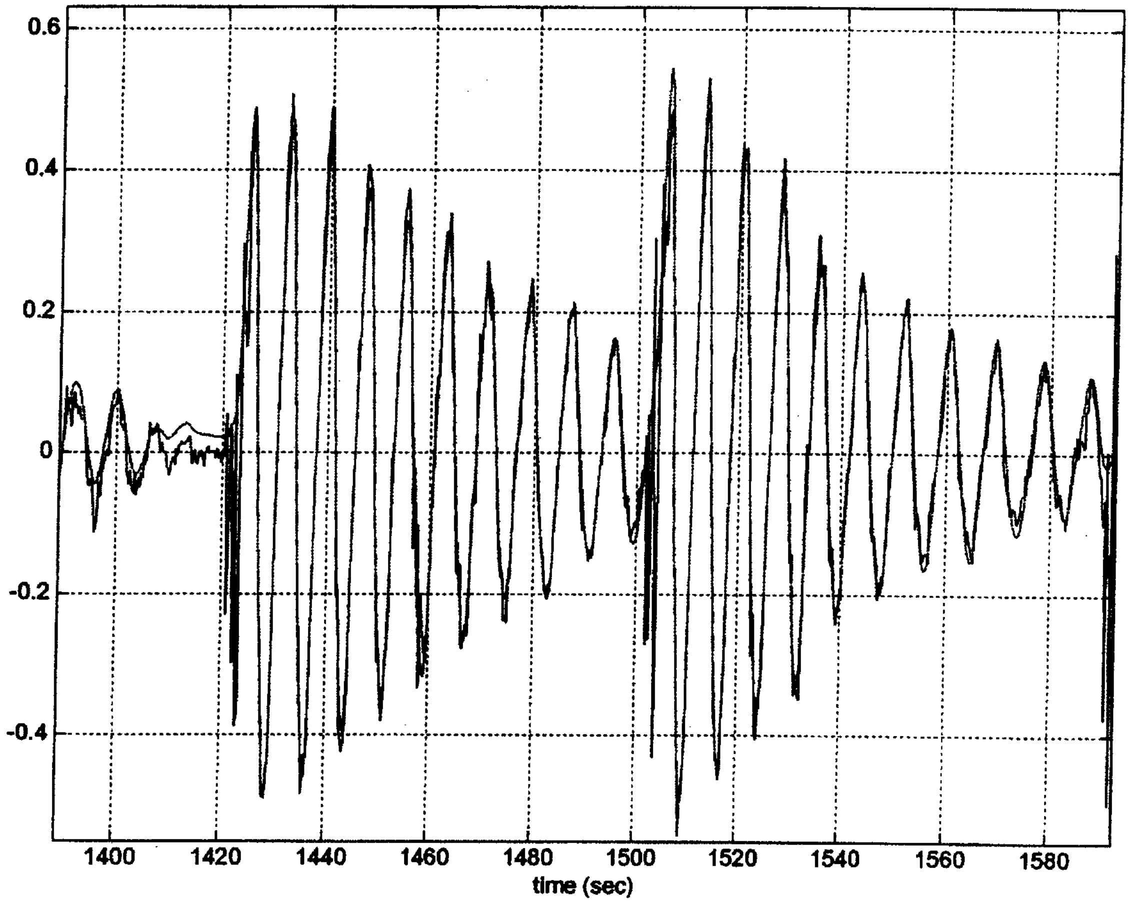

Figure 9. Modal expansion fit to data

5. Validation

Each of the three models was evaluated by implementing them in the Kalman filter and comparing residuals at the 0.12-0.14 Hz frequency band. The modal expansion model when implemented in the Kalman filter was numerically sensitive and was discarded. The results from the curve fitting and Duffing model are shown in the following table. The RMS value given in the second column is the RMS of the a-priori residual, and it has been transformed to an equivalent height error over the ground in meters.

Method	RMS
Linear mode	0.680
Curve fitting	0.457
Duffing model	0.498

The best performance was achieved by the curve fitting approach. This approach was selected and used for the processing of the final delivered Shuttle Radar Topography Mission data.

6. Conclusions

In this paper we present the results of a study to identify a nonlinear bending mode for a 60 meter flexible mast in space. This study was done in support of the Shuttle Radar Topography Mission. The model obtained in this study was used in a Kalman filter that estimated the relative motion of the radar antennas, which in turn was used by the motion compensation algorithm in the radar interferometry processor which produces the topographic maps. The accuracy of this model was crucial to meeting the desired mission performance.

Acknowledgments

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