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On-Orbit Evaluation of the Control System/Structural Mode Interactions on OSO-8

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The Orbiting Solar Observatory-8 experienced severe structural mode/control loop interaction problems during the spacecraft development. Extensive analytical studies, using the hybrid coordinate modeling approach, and comprehensive ground testing were carried out in order to achieve the system's precision pointing performance requirements. A recent series of flight tests were conducted with the spacecraft in which a wide bandwidth, high resolution telemetry system was utilized to evaluate the on-orbit flexible dynamics characteristics of the vehicle along with the control system performance. This paper describes the results of these tests, reviewing the basic design problem, analytical approach taken, ground test philosophy, and on-orbit testing. Data from the tests was used to determine the primary mode frequency, damping, and servo coupling dynamics for the on-orbit condition. Additionally, the test results have verified analytically predicted differences between the on-orbit and ground test environments. The test results have led to a validation of both the analytical modeling and servo design techniques used during the development of the control system, and also verified the approach taken to vehicle and servo ground testing.

Introduction

THE influence of flexible-body dynamics on the design of spacecraft control systems is becoming increasingly important as the vehicle configurations become more complex and control requirements become more severe. The bulk of the activities involved in the design and analysis of control systems with flexible plant dynamics has been limited to analytical modeling of both the vehicle structural characteristics and the dynamic interaction of the structure with the control system. Verification and validation of the analytical techniques developed over the last several years with ground and on-orbit testing has been quite limited.[1] On-orbit determination of mode shape, frequency and damping (system design parameters which always have a high degree of uncertainty) using specialized instrumentation, testing, and telemetry is typically a luxury a program office is not willing to support.

The dual-spin Orbiting Solar Observatory-8 (OSO-8) is a spacecraft which experienced severe structural dynamics interaction problems during the control system development.[2] The wide servo bandwidths, dictated by the precision (1 arcsec) pointing requirement of the despun platform, in conjunction with the relatively low-frequency bending modes of the lightweight despun structure, led to extensive design, analysis, and ground test activities during spacecraft development. The nominal on-orbit performance of the control system (following launch in June 1975), in which no structural mode coupling problems were observed, was initially the only indication that there were no significant flaws in the design.

Recently, however, interest in this topic on the part of the Jet Propulsion Laboratory (regarding the Galileo program) resulted in a NASA sponsored series of on-orbit tests[3] (conducted in Oct. 1978). These tests attempted to obtain on-orbit data to evaluate both the actual flexible dynamic characteristics of the spacecraft and the servo interaction characteristics, for comparison with prelaunch analytical and ground test predictions. This paper presents the results of these tests, reviewing first the basic design problems for OSO-8, and the analytical and ground test data developed prior to launch. The approach to on-board testing is described and the data obtained from the test program is presented. Comparisons are presented of the on-orbit and ground test environments and their relationship to the observed on-orbit characteristics.

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The OSO-8 Spacecraft and Servo Design Problem

The OSO-8 spacecraft was designed and built by Hughes Aircraft for NASA Goddard Space Flight Center. Spacecraft components used by the control system for attitude determination and control are illustrated in Fig. 1 The inertially despun platform (the Sail) is comprised primarily of a solar panel and the Pointed Instrument Assembly (PIA). The two primary experiment packages making up the PIA rely on solar oriented telescopes (spectrometers) to collect scientific data concerning variation of the ultraviolet lines on the solar disk, particularly in the chromosphere.

The PIA has two degrees of rotational freedom to permit solar pointing. Azimuth motion is achieved by rotating the entire despun platform about the despin bearing axis (DBA) while elevation motion of the PIA alone is facilitated by an elevation bearing assembly (EBA). Both bearing assemblies house electric torque motors used for control. Two sets of attitude sensors are provided. For eclipse periods (one per 90 min orbit), a rate integrating gyro and a microsyn gimbal angle sensor detect azimuth inertial angle and elevation gimbal angle. The primary sun sensors, for use when the sun is visible (day), are located on the front faces of the PIA experiment packages, one sensor on each experiment.

Low-bandwidth servo loops hold attitude during the eclipse periods. At sunrise, control is automatically transferred to high-bandwidth "day" servos. In addition to highly stable sun center and offset pointing, these servos provide a raster scan capability. The entire despun platform is scanned back and forth in azimuth while the PIA is repetitively stepped in elevation. This creates a raster which may cover the entire sun (large raster) or a 150 by 150 arcsec portion (small raster)

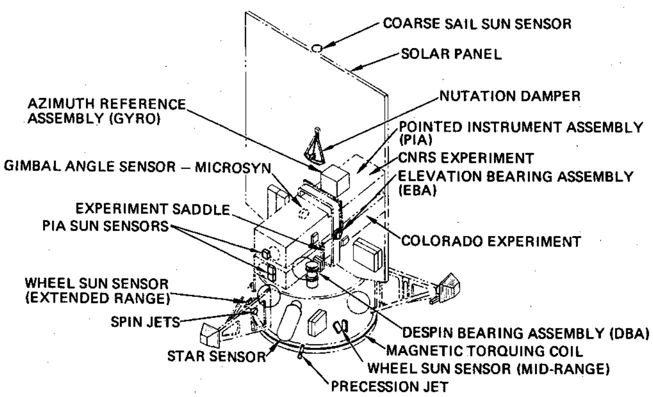

Fig. 1 OSO-8 components for control and aspect determination.

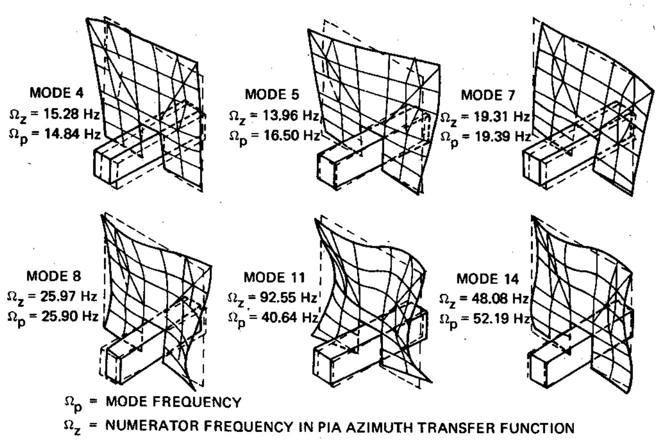

Fig. 2 Shapes of predominant azimuth coupled flexible modes.

located arbitrarily on the sun's disk. A 1 arcsec pointing stability is maintained throughout, except during the raster scan turnarounds.

The requirements to both maintain the PIA pointing stability at 1 arcsec in both control axes, and also to achieve a short (750 ms) turnaround time at the end of each raster scan line, led to servo bandwidths (3 dB) of 3 Hz for the azimuth loop and 5 Hz for the elevation loop. The orbit "night" control loops, which had only 0.1 deg pointing accuracy requirements, had bandwidths of less than 0.5 Hz. The desire to minimize the overall spacecraft weight led to a lightweight despun structure with the first bending mode frequency at 6 Hz.

The key flexible modes and mode shapes which coupled into the control loops are illustrated in Fig. 2. These were developed from a standard finite-element model of the despun platform.

A significant complication in the design of the two control loops is the separation between the sensors (at the forward end of the PIA) and the actuators (contained in the bearing assemblies). Thus the OSO-8 design problem was not the simpler one of controlling a central rigid core (containing the sensors and actuators) with flexible appendages, but rather a problem in which the flexible element itself was to be controlled (with considerable structural flexibility between the sensors and actuators). This effect causes more unpredictable behavior of the coupled dynamics, with sensor/actuator phase reversals causing reversed stability criterion for adjacent modes.

With the requirements of precision pointing and an essentially fixed structural design with bending modes within the control loop bandpass, the OSO-8 control system design problem became one of designing the loop dynamics to accommodate both constraints, i.e., to fix the interaction problem in the electronics.

Analytical Approach and Ground Test Philosophy

Control System Design Approach

The analytical approach taken in the design of the control system utilized the Hybrid-Coordinate modeling technique developed by Likins.[4] The analysis effort was augmented with a comprehensive series of ground tests carried out at various stages of the control system and spacecraft development. As detailed in Ref. 2, specialized software was developed to integrate the output of the Structural Dynamics group finite-element mass model of the entire despun structure with the rigid-body dynamics of the spinning section to generate the composite (flexible- and rigid-body) linearized equations of motion of the spacecraft. Using this basic dynamic model of the spacecraft, and additional analytical models of the control loops, time and frequency domain analyses were carried out to evaluate system performance and stability. The final configurations and parameters which were developed for the azimuth and elevation control loops are shown in Fig. 3.

The resulting analytically predicted interaction between control system and structural dynamics is summarized in the Bode and Nichols graphs for the orbit day azimuth and elevation control loops—Figs. 4 and 5. These graphs show the open-loop frequency response characteristics of each control loop and its plant dynamics. The graphs provide the information necessary to determine stability margins and individual mode coupling strength. The Nichols graph (open-loop gain plotted against open-loop phase) was used extensively in the design because it provided the maximum visual information regarding modal coupling without explicit use of the frequency variable. On a Nichols graph, each flexible mode is characterized by a circle (generated by a quadratic pole-zero pair in the frequency domain) which modulates the basic rigid-body dynamics curve. The size of the circle is a function of both the assumed modal damping ratio and the strength of the coupling of the structural mode to the control loop. The direction of the circle is determined by the nature of the flexible mode itself. Appendage modes, in which the sensors and actuators are contained in the rigid body, generate loops whose trajectories move initially to the right in the gain-phase plane. For systems in which the sensors and actuators are separated on the flexible element, circles of either direction can develop with loops having trajectories which move initially to the left, occurring when the sensor and actuator are out of phase in the mode.

Mode stability is determined (on the Nichols graph) by the position of the mode circle relative to the "-1 point" stability boundary, i.e., the conditions of unity open-loop gain (0 dB) and an open-loop phase angle of -180 deg.

As can be seen in the frequency response plots for the azimuth and elevation servos (Figs. 4 and 5), the azimuth control loop exhibits the most severe structural dynamics coupling, with the fourth and fifth bending modes (at $\sim$15 Hz) well within the loop bandpass. Because of the performance constraints, it was necessary for the azimuth control loop to stabilize these two modes. To accomplish this, a phase lead narrowband filter was added to the loop shaping to place the mode dynamics loop to the right of the -1 point of the Nichols graph. An additional gain notch filter was added toward the end of the development phase to reduce the mode coupling in the 40-50 Hz frequency region.

The effect of the "nonappendage" characteristics of the flexible mode coupling with the azimuth control loop can be seen in the reversal in the direction of the Nichols graph loops which correspond to structural modes 8 and 9 (at $\sim$29-30 Hz).

The predicted elevation loop coupling (Fig. 5) with spacecraft flexibility is much weaker than that experienced by the azimuth loop. This effect is attributed to the elevation gimbal which effectively isolates the PIA elevation sensor from the spacecraft.

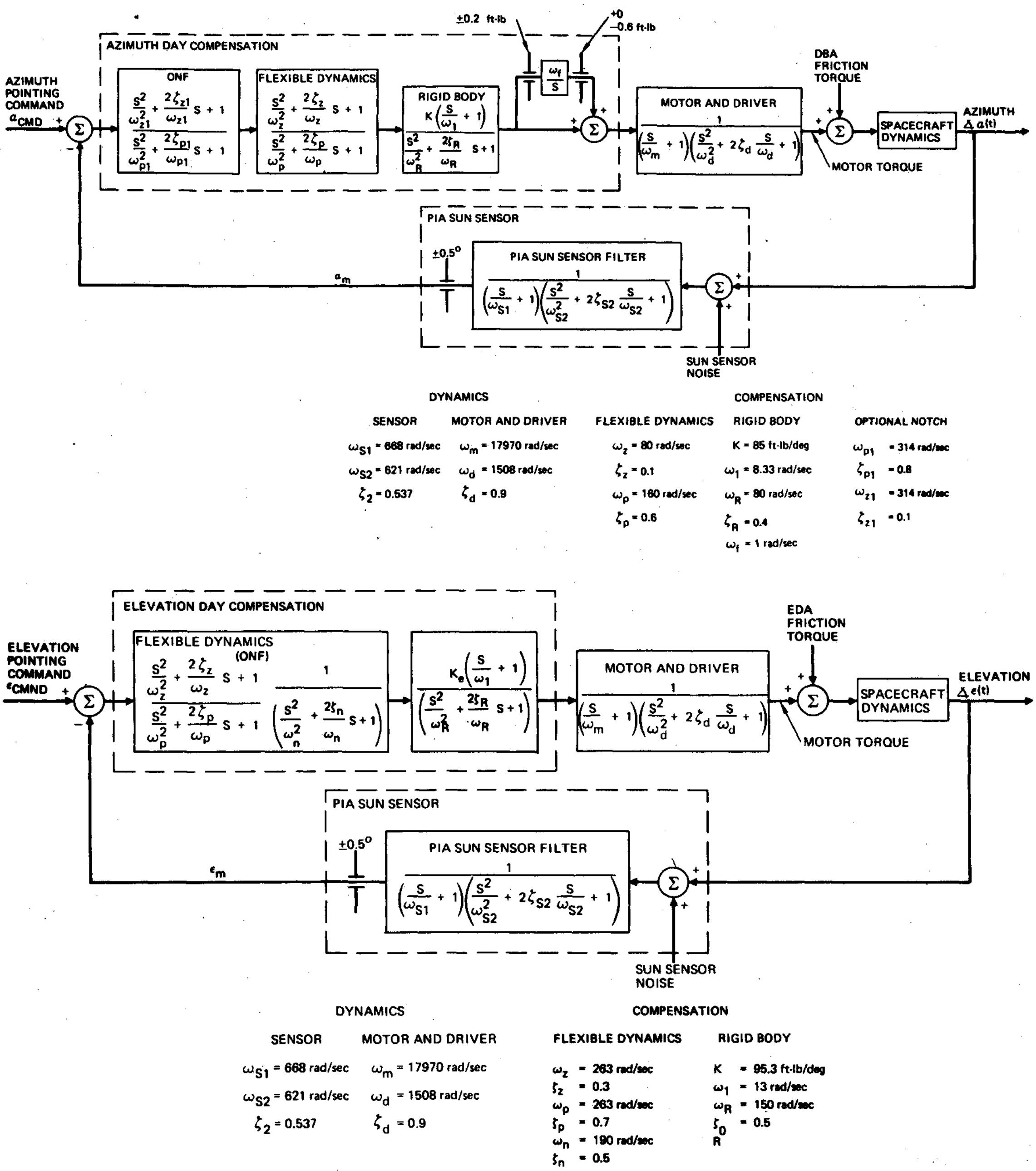

Fig. 3 Azimuth (top) and elevation (bottom) control loop block diagrams.

Ground Testing for Design Verification

Because of the critical dependence of the control loop design on the Sail and PIA flexible dynamics, a series of extensive ground tests of the despun structure were conducted with the basic objective of verifying the stability of the control system at the structural mode frequencies. Three test phases, carried out over a 1½ yr time span, comprise the ground test program. These tests included initial testing of a mass model mockup of the structure, flight structure testing, and a final structural response test using the full, flight configuration Solar Observatory. Detailed descriptions of the test techniques and results can be found in Ref. 2.

The azimuth and elevation control loop (structure plus servo) open loop Bode plots, obtained during ground testing, are given in Figs. 6 and 7. These figures compare the predicted and measured dynamics. For the azimuth control loop, a single dominant Sail torsional mode is observed at 15 Hz as predicted by the analytical model. The higher-frequency (30-60 Hz) modes appear in the test data with their coupling strength reduced by the servo dynamics. Ground test data for the elevation control loop (Fig. 7) shows the anticipated weaker mode coupling with only one strongly coupled mode observed (at ~35 Hz) which represented bending of the PIA experiments in elevation (dubbed the "alligator mode").

On-Orbit Interaction Predictions vs Ground Test Data

As the critical nature of the structural dynamic coupling became evident, a major concern developed over possible differences between the ground test and on-orbit environments. All ground testing was carried out with essentially fixed-base conditions, with the despun platform cantilevered from the spinning section which was fixed to the test floor. Flexible dynamic testing with a "soft base" to simulate the "free-free" on-orbit conditions was not feasible. In order to investigate possible differences in the coupling dynamics, an analytical model of the ground test environment was developed for comparison with the on-orbit spacecraft model characteristics. Using the same finite-element model of the despun structure, the structure/control loop interaction was evaluated in the ground test condition using the frequency

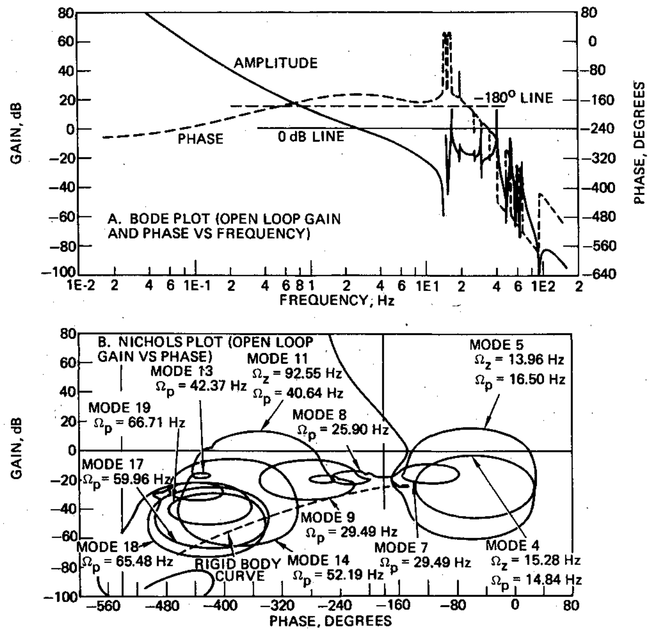

Fig. 4 Azimuth day servo open-loop frequency response.

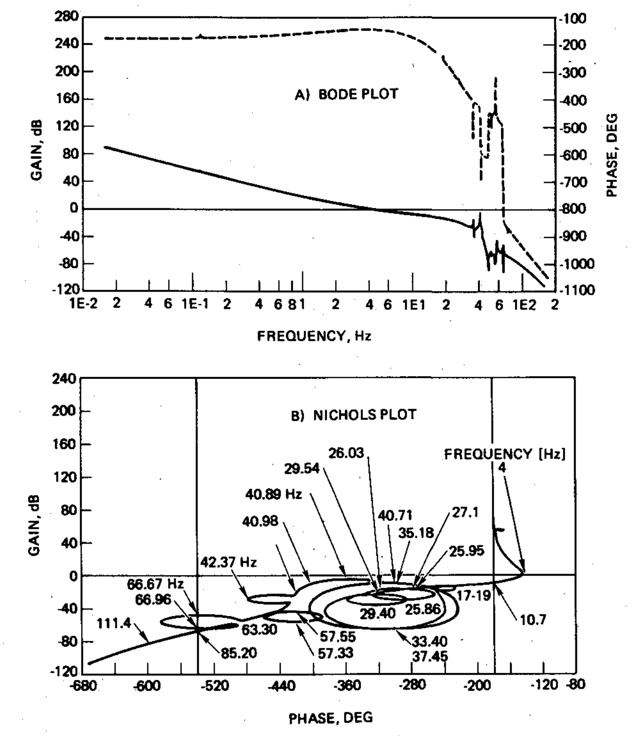

Fig. 5 Elevation day servo open-loop frequency response.

domain stability analysis technique discussed previously. The resulting Nichols plots are presented in Figs. 8 and 9, comparing the azimuth and elevation servo coupling for the two conditions.

The azimuth orbit day control system dynamics are shown in Fig. 8. A conservative structural mode damping ratio of 0.15% has been used for all modes. This has the effect of accentuating the modal coupling, giving a stronger structural interaction that was determined from the response tests. The most significant difference in azimuth response characteristics betweeen the ground test and on-orbit conditions occurs in the low-frequency band, around the "15 Hz" mode. For the on-orbit condition, the mode is seen to be composed of two distinct modes (at 16.5 and 14.8 Hz) which appear to merge into a single mode (at 16.5 Hz) with the fixed base constraint.

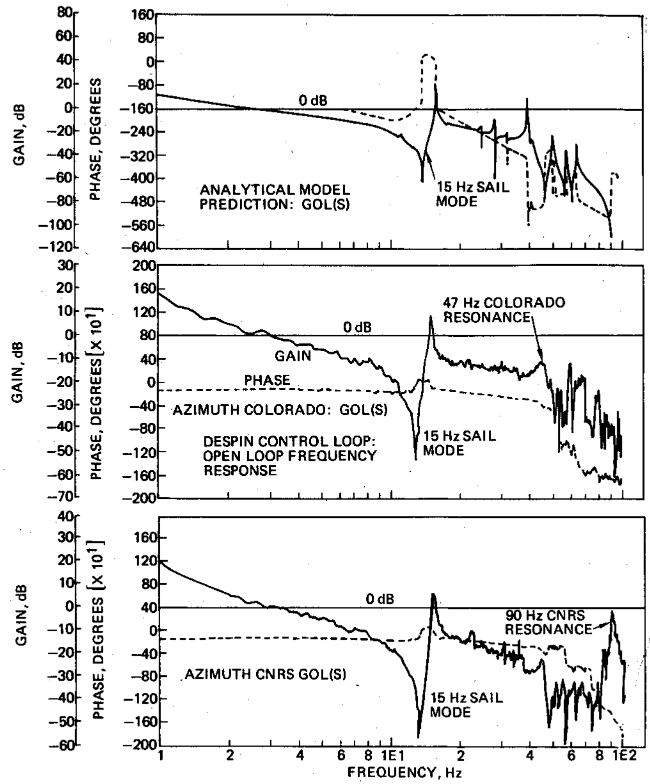

Fig. 6 Predicted and measured azimuth day open-loop transfer functions.

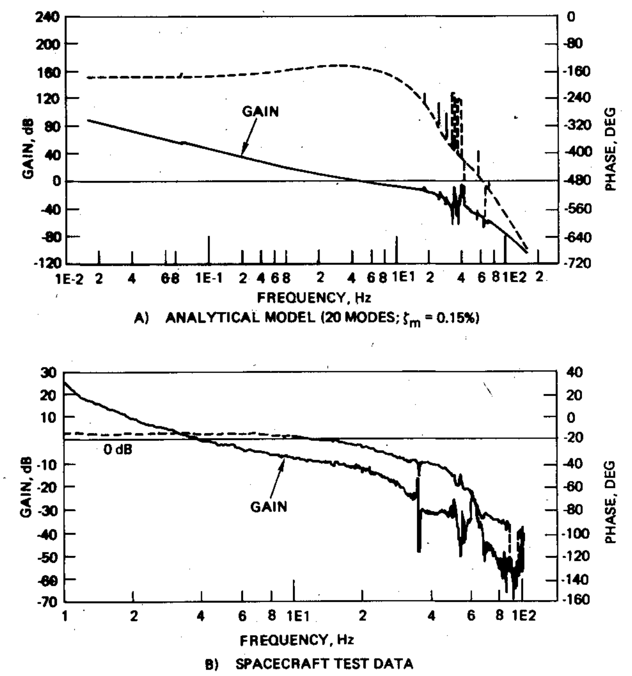

Fig. 7 Predicted and measured elevation day open-loop transfer functions.

Since the frequencies of both modes are centered in the range of the control shaping dynamics which were designed to phase stabilize the modes, this structural difference has no impact on the control system stability margins. This can be observed directly by a comparison of the two Nichols charts.

An additional difference in the azimuth loop between the on-orbit and ground test conditions is the appearance of a weakly coupled 19 Hz mode in the "free" configuration. This mode is gain stabilized by the control system with ~10 dB of

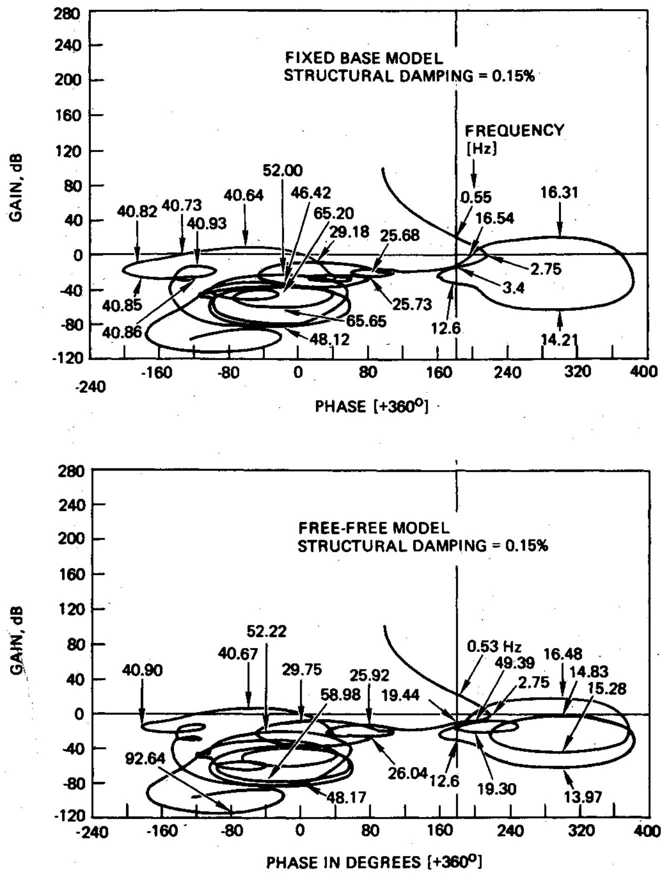

Fig. 8 Comparison of ground test and on-orbit azimuth open-loop dynamics.

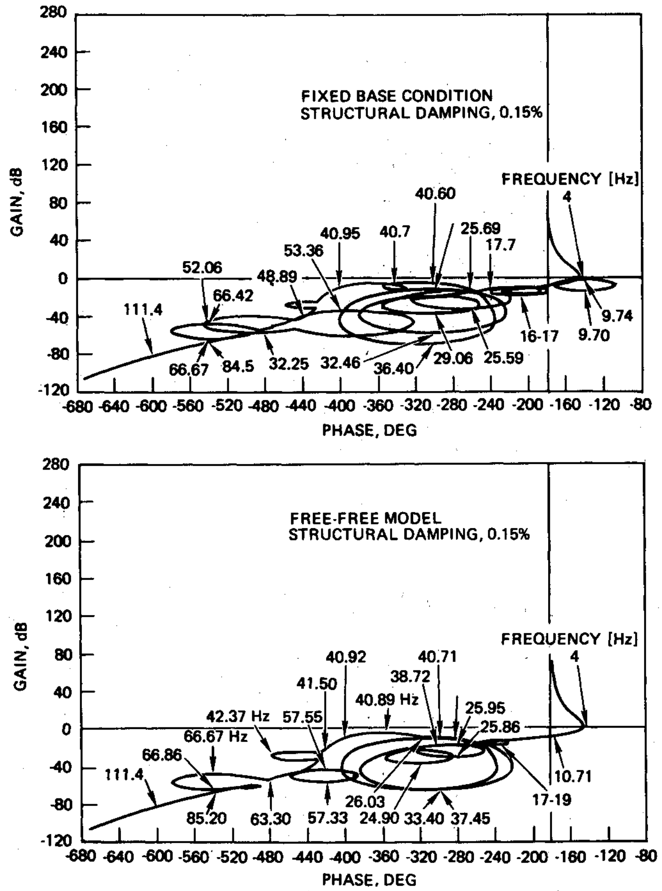

Fig. 9 Comparison of ground test and on-orbit elevation open-loop dynamics.

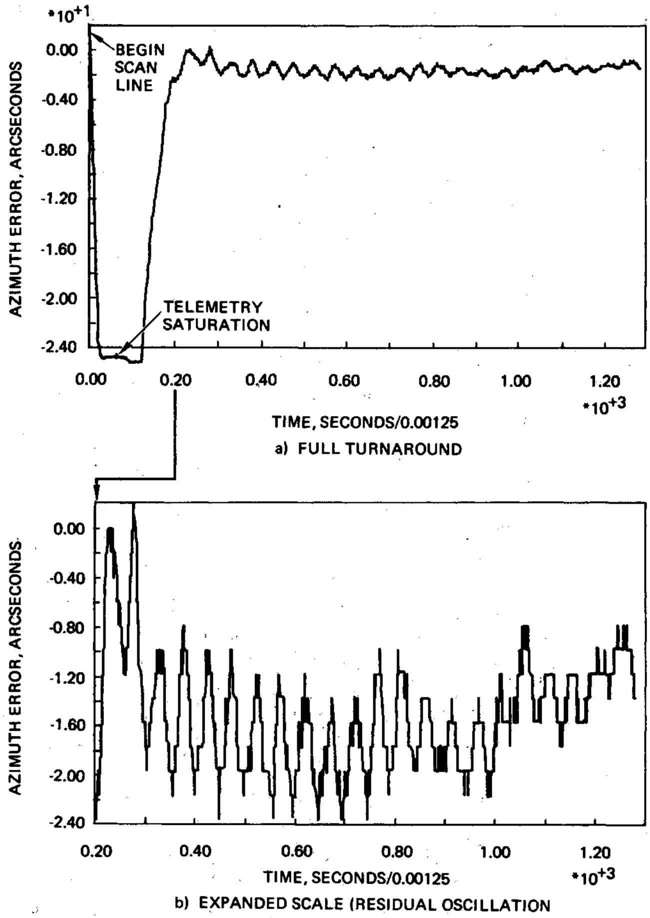

Fig. 10 Azimuth servo loop error during raster turnaround; on-orbit test—raw data.

margin with the 0.15% modal damping ratio. Because of an error in the PIA mass model, it would be expected that the actual structure mode frequency would be slightly lower, between 17 and 18 Hz. This would tend to add phase stability to the mode. The weak coupling of the mode even with the light damping assumed should result in no interaction problem once on-orbit.

The only other differences observed in the azimuth response characteristics are slight shifts upward in mode frequencies in the "free" condition. All basic mode shape characteristics remain unchanged.

As is expected, elevation structural coupling exhibits more differences than are observed in azimuth. The elevation dynamics are shown in Fig. 9. Several modes (below ~20 Hz and around 40 Hz), which are weakly coupled to the control system, become uncoupled for the "free-base" orbital condition. Again, slight frequency increases are observed in most of the modes for the on-orbit configuration. However, the dominant interaction characteristics remain unchanged between the two conditions.

On-Orbit Testing

Approach

The approach taken for on-orbit flexible mode evaluation was to excite the structure through the servo torque motors and use a wide band width dwell telemetry mode to monitor the output of the precision sun sensors. To excite the Sail flexible modes, the control system was operated in the large fast raster scanning mode in which the entire despun platform is slewed in azimuth at a 44 arcmin/5.12 s rate. At the end of each scan line, the scan direction is reversed by applying a 2-3 ft-lb motor torque pulse to the Sail for approximately 0.25 s. The control loop will reacquire the scan profile and track to the 1 arcsec requirement within 0.75 s. Simultaneous with the

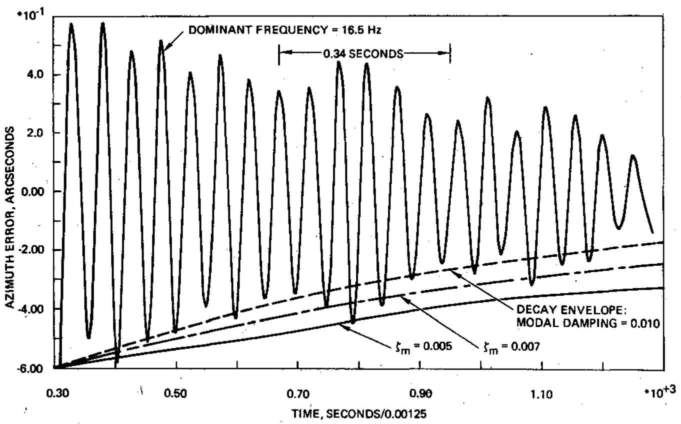

Fig. 11 Filtered on-orbit test data (raster turnaround).

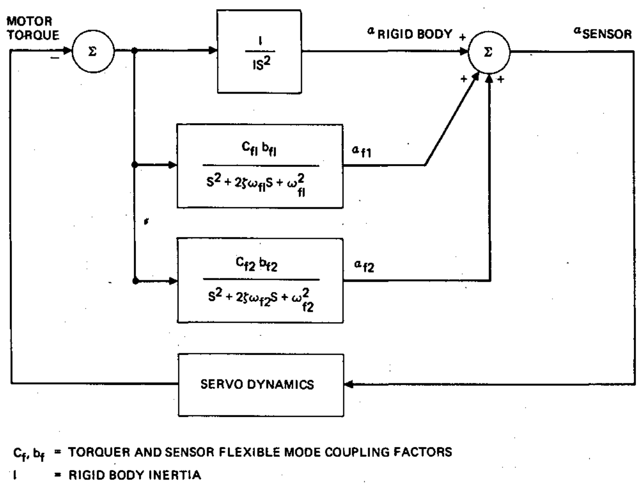

Fig. 12 Simplified analytical model of primary Sail modes.

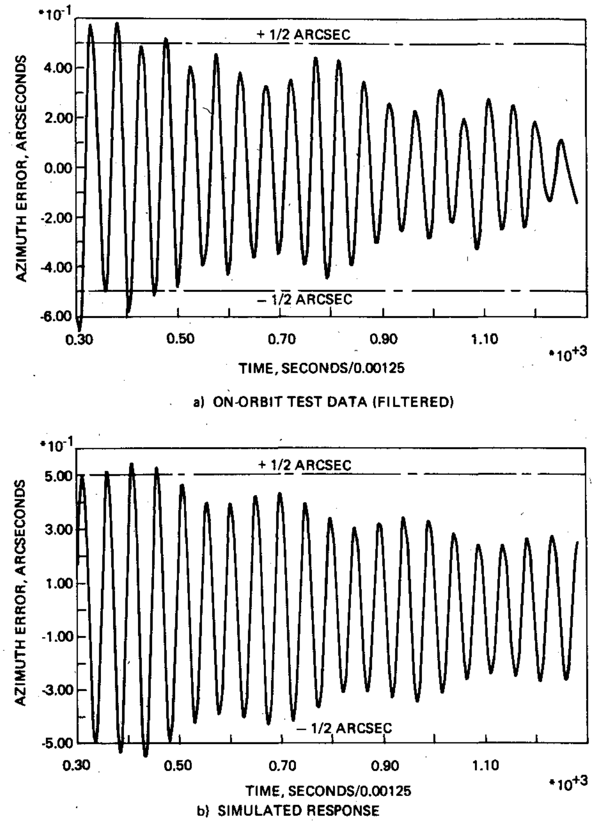

Fig. 13 Comparison of measured and predicted azimuth servo error during raster turnaround.

torque reversal, the PIA is stepped down in elevation (37.5 arcsec) using the elevation torquer (with a ½ ft-lb capability).

The OSO-8 telemetry system contains a dwell operating mode in which a selected telemetry word can be continuously monitored with a sampling rate of 800 Hz. This gives a half-sample frequency (for coherent data) of 400 Hz, which is well beyond the 50 Hz maximum frequency of interest. For flexible mode testing, the high resolution (0.2 arcsec) servo loop error telemetry points were recorded in dwell mode while the control system was operated in the large, fast raster scan mode.

Results

The raw telemetry data showing a typical end of scan line azimuth loop turnaround time history is presented in Fig. 10. The large initial error at the start of the plot represents saturation of the telemetry and the interval over which the 3 ft-lb of motor torque is applied to the Sail. This transient settles out within 0.25 with a residual oscillatory response of ~1.2 arcsec (peak-to-peak) which decays over the 1.5 s interval shown in the figure. The dominant frequency of oscillation seen in the figure is 16.5 Hz. To eliminate the effects of noise and quantization and highlight the oscillation, data shown in Fig. 10 was processed through a digital filter. The resulting filtered time response is given in Fig. 11. The response is characterized by two modes, the dominant being the 16.5 Hz oscillation, and a modulation due to a second, more weakly coupled mode. The modulation frequency of ~3 Hz indicates the second mode frequency is 13.5 Hz. As measured on the graph, the decay rate of the oscillation results from a damping ratio of between 0.7% and 1%.

These results correlate well with the analytical predictions developed from the hybrid-coordinate analytical modeling approach discussed earlier, and validates the expected differences between ground test and on-orbit environments. The anticipated dominant coupling of the "15 Hz" Sail mode with the azimuth control loop is seen in the data. The predicted splitting of the single mode observed during ground test (and predicted for the fixed-base ground test environment) into two modes which are close in frequency is also verified. The analytically predicted dominant Sail mode frequency of 16.5 Hz is identical to the mode frequency measured on-orbit. The only discrepancy between the measured and predicted data appears to be the frequency of the second, more weakly coupled mode. Based on the 3 Hz beat frequency observed in the on-orbit test, the second mode frequency appears to be at 13.5 Hz, whereas the analytically determined mode frequency is 14.5 Hz (as shown on the servo Nichols graph in Fig. 8). The anticipated closed loop modal damping of 0.7% (as measured during the closed-loop destabilization testing-see Ref. 2) was also realized on-orbit.

In addition, the lack of any higher frequency modes observed in the data is consistent with both the analysis and ground test data in which the expected modal damping of ≥1%, along with the dynamics of the control loop shaping (with the notch filters and high-frequency rolloff), result in weak higher frequency coupling. With nominal structural parameters for the higher frequency modes, the expected sensor output would be below the 0.2 arcsec quantization of the telemetry.

In order to compare the strength of the measured coupling of the Sail torsional modes with the predicted coupling strength, a simulation of the dominant mode dynamics was developed. The analytical model used in the simulation is shown in Fig. 12. The intent here was to excite an analytical model of the two flexible modes with a torque impulse containing the same energy as was developed during the on-orbit testing, and to observe the magnitude of the oscillation

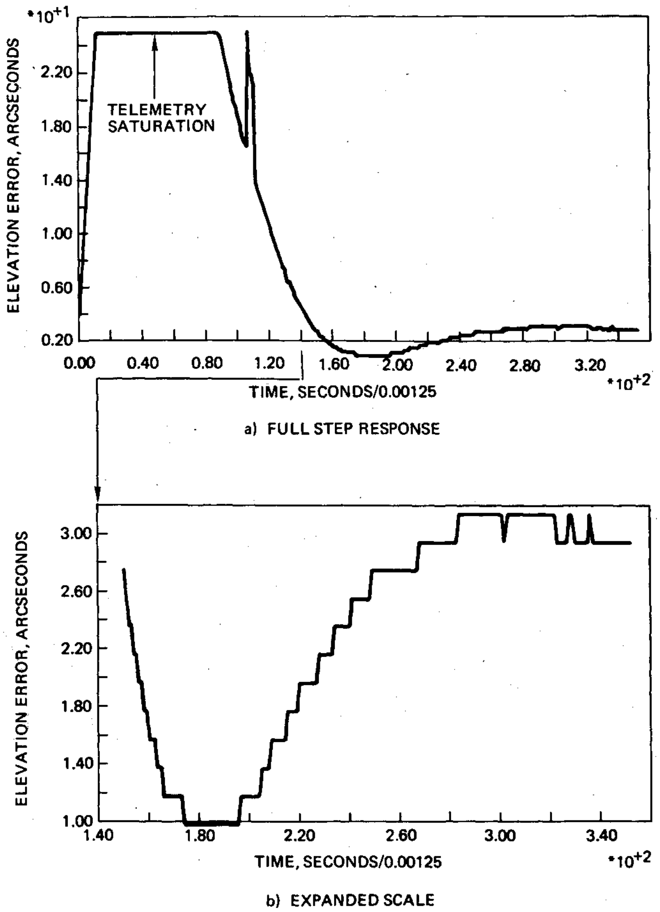

Fig. 14 Elevation servo loop error during line step; on-orbit test —raw data.

appearing on the servo error signal. A high correlation between the oscillation amplitude developed on the simulation and the amplitude observed during the tests would validate the modeling approach in which the predicted coupling factors are crucial in analyzing loop stability.

The resulting simulation time history is given in Fig. 13b, with the on-orbit data given in Fig. 13a. The peak modal oscillation amplitude predicted following the torque impulse is ~0.6 arcsec. This is extremely close to the measured oscillation amplitude shown in Fig. 13a.

A second series of measurements taken while the control system was operating in the raster scan mode involved observation of the elevation servo error using the wide bandwidth dwell telemetry mode during the 37.5 arcsec elevation line step transient. A time history of the loop servo error is given in Fig. 14. During the first 0.15 s, the loop torquer is saturated (at ½ ft-lb), after which the servo loop error is nulled. For the elevation loop, only the rigid-body dynamics are observed. No oscillations develop as a result of the transient. Again, these results are consistent with both the analytical models and ground test data described previously in which the elevation gimbal acts to isolate the servo from spacecraft flexibility.

Conclusions

The results obtained from the OSO-8 on-orbit flexible mode interaction testing confirmed the existence of the flexible mode coupling problem and verified the analytical and ground test approaches taken during the control system development phase. The data suggests that had the control system been designed with only a rigid-body dynamics model, the azimuth day control loop would have been unstable and the required system performance would not have been achieved. (The problem itself would probably have been detected at spacecraft level testing and would have required a redesign of the already built control electronics with a severe cost and schedule penalty.) The use of the hybrid coordinate modeling approach along with frequency domain analysis techniques accurately modeled the behavior of the primary model coupling dynamics. While the fidelity of the analytical model at higher frequencies (where finite-element models tend to become less accurate) was not verified, it was shown that there were no significant errors in the predicted coupling strength of the higher frequency modes. The predicted weak interaction at "reasonable" modal damping (~1%) was inferred from the on-orbit testing by the lack of higher frequency mode coupling in the data. The system design approach, which required an accurate analytical model for low frequency modes, developed servo dynamics (and electronics capability) to accommodate significant uncertainty and errors at higher mode frequencies. The azimuth loop dynamics were designed to stabilize the "15 Hz" Sail mode, requiring an accurate analytical description of the mode characteristics, while the remaining loop dynamics were used to gain stabilized modes in the 40-60 Hz region in which substantial errors in structural damping and mode characteristics would be tolerated without an instability. Overall, the measured system pointing stability was well within the required 1 arcsec (rms).

The inclusion, during the spacecraft development phase, of a comprehensive ground test program (which included analytical modeling of the test environment) to augment the analysis activities, proved to be a valuable (and necessary) asset in developing confidence in the system design and structural model accuracy. The final system design parameters which were developed from both analysis and test activities, achieved the required system performance while accommodating a complex flexible structure.

Acknowledgments

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References

[1] Sincarsin, G.B. and Hughes, P.C., "Dynamic Ground Testing of the Hermes (CTS) Development Model Solar Array: Theory and Experiment," *Proceedings of the Symposium of Dynamics and Control of Large Flexible Spacecraft,* Blacksburg, Va., June 13-15, 1977, pp. 75-86.

[2] Yocum, J.F. and Slafer, L.I., "Control System Design in the Presence of Severe Structural Dynamics Interactions," *Journal of Guidance and Control,* Vol. 1, March-April 1978, pp. 109-116.

[3] Welton, P., Slafer, L., and Hofmann, G., "OSO-8 On-Orbit Test of October 1978—Final Report," Jet Propulsion Laboratory, Pasadena, Calif., Contract BP690629, March 1979.

[4] Likins, P.W., "Dynamics and Control of Flexible Space Vehicles," Jet Propulsion Laboratory, Pasadena, Calif., Technical Rept. 32-1329, Revision 1, Jan. 1970.