MEASUREMENTS OF THE STS ORBITER'S ANGULAR STABILITY DURING IN-ORBIT OPERATIONS[1]

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ABSTRACT

We report on measurements of the angular stability, commonly called "jitter", of the STS Orbiter during normal operations in space. Measurements were carried out by measuring optically the Orbiter's roll and pitch orientation relative to the solar vector as the Orbiter was held in a $-Z_0$ solar inertial orientation (orbiter bay oriented toward the Sun). We also report observations of an interesting perturbation to the Orbiter's orientation noted by the crew during the STS-60 mission. These data may be useful in analyzing the in-orbit response of the Orbiter to thruster firings and other applied torques, and may aid in the planning of future experiments that require fine-pointed operations by the Orbiter.

INTRODUCTION

The Orbiter Stability Experiment (OSE) is a "Get-Away Special" payload designed to characterize the angular stability ("jitter") of the STS Orbiter about its X-axis (pitch) and Y-axis (roll) when the Orbiter's $-Z_0$ axis is pointed to the Sun. during its operation in space (ref. 1). The original motivation for these observations was to obtain a database for designing an image motion compensation system for a solar extreme ultraviolet imaging instrument that would use the orbiter as a platform for solar observations during an STS mission. Although the solar instrument that was planned was never implemented and flown, the Get-Away Special was flown as the flight equipment had already been prepared. The observational results, which cover angular amplitudes of Orbiter motions from about two degrees to the sub-arc second range, may be of use to other STS users. The OSE was flown on two shuttle flights, STS-40 and STS-60, during which observations were made and on a third flight, STS-64, when the proper STS attitude for OSE observations was not scheduled.

DESCRIPTION OF THE ORBITER STABILITY EXPERIMENT

Angular deviations from the solar vector were observed with two Lockheed Intermediate Sun Sensors (LISS) which can detect deviations about the two axes normal to the solar vector of as little as 0.1 arc sec. Each sensor therefore provided both Orbiter pitch and roll information, and one unit was rotated about the Z_0 axis by 180 degrees relative to the other so that actual STS motions would result in opposite polarity signals from the two LISS sensor outputs, thereby distinguishing Orbiter motions from any possible in-phase electronic system noise. The four analog signals from the LISS were each sampled 58 times per second, filtered, multiplexed, processed by a 16 bit analog to digital converter, stored in shift registers, and recorded on a Lockheed Model 4200B tape recorder. Measurements were made over the frequency range of 0.01 to approximately 10 Hz, the high frequency cutoff of the 12 db/octave filter beginning at 11 Hz to avoid aliasing. Ancillary data channels provided calibration voltage levels, a nominally 100 Hz clock signal, and three temperature sensor outputs. These were interleaved with the primary data stream.

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ANGULAR SENSITIVITY OF THE OSE SENSORS

The nominal angular field of view (FOV) of the Lockheed Intermediate Sun Sensor (LISS) used on OSE is +/- 2 degrees, appropriate for its usual application as a Sun pointer on suborbital sounding rockets. On OSE, this FOV was subdivided with a 16-bit scalar to yield a sensitivity (the change in the offset of the solar vector corresponding to the least significant bit of the scalar output) of 0.23 arc sec. For the STS-40 mission, the FOV of one of the two LISS was increased (thereby reducing the sensitivity) to +/- 3 degrees to increase the likelihood of obtaining data even if the offset of the instrument's line of sight (LOS) from the Sun, via the Orbiter's navigational base, were as great as three degrees. For the STS-60 flight, we increased the sensitivity of the second LISS by a factor of more than ten, yielding 0.036 arc sec per LSB, comparable to the noise level from the LISS itself. System electronic noise, introduced by the A/D circuitry, was typically 0.75 LSB. This noise level was measured during STS flight by operating the OSE in the absence of sunlight, i.e., during the nighttime portion of the orbit.

OSE ALIGNMENT TO THE GAS BRIDGE AND THE STS STRUCTURE

Angular alignment to the STS navigational system was critical as the total FOV of the OSE sensors was never greater than +/- 3 degrees. Prior to flight, we estimated the limits of potential misalignment of the LISS to the Orbiter's navigational base, based on the machining tolerances of the LISS sensors and their attachment to the GAS mounting plate, and the machining tolerances of GAS container, the GAS bridge, and the mounting points of the GAS bridge to the STS. The largest potential contributor to OSE-solar alignment was the alignment of the GAS bridge to the Orbiter structure and the deformation of that structure, relative to the guidance system mounted in the nose of the STS. Given published Orbiter tolerances (ref. 2) , this misalignment could amount to several degrees. However, from earlier solar pointing measurements made on STS-3 during flight of the OSS-1 payload, it was known that experiment-Orbiter misalignments could be held to 0.1-0.2 degrees.

Each LISS's reference optical surface was optically aligned to a precisely machined mounting plate (the LISS Alignment Plate (LAP)) mounted externally on the sunward end plate of the GAS container. Optical co-alignment of the two LISS reference surfaces to 0.2 arc min in pitch and 2.8 arc min in roll was achieved. The LAP was then shimmed, using an inclinometer and precision bubble levels, to bring it into alignment with the GAS bridge structure and the trunnions by which the GAS bridge attaches to the STS Orbiter sills. Using these techniques, the total misalignment of the LISS to the GAS bridge was held to a few (5-10) arc min in both pitch and roll, based on alignment measurements carried out before and after flight of both STS-40 and STS-60.

No direct measurements of alignment of the LISS to the Orbiter X and Y axes were made. From the machining tolerances of the LISS mounting system to the GAS container, we estimated that the alignment errors of the GAS Bridge to the Orbiter Trunnion system were no greater than 1 degree and therefore acceptable for the observations to be made.

Overall alignment of the LISS LOS to the solar vector after establishing a $-Z_0$ solar inertial attitude was extremely good on STS-40, amounting to offsets of at most 4 arc min in pitch and 5 arc min in roll. On STS-60, on the other hand, the alignment in roll was again about 5 arc min, but in pitch it was 35-38 arc min, which placed the solar LOS out of the FOV of the high-gain pitch channel. This significant misalignment is within the limits given in the ICD quoted above, but is inconsistent with the performance achieved on STS-40. We suggest that it may be due to a long-term drift in the STS inertial attitude control system, which is updated by reference to the inertial reference from of bright stars. On STS-40, an IMU recalibration was carried out two hours before OSE operations and accurate alignment to the Sun was achieved. On the other hand, on STS-60, the most recent IMU alignment was carried out 67 hours before OSE operation and the Orbiter navigational base may have drifted by up to 0.6 degrees in pitch in that period of time.

ON-ORBIT OBSERVATIONS

The OSE was operated for approximately two hours on STS-40 and for nearly one hour on STS-60. In this paper we incorporate results obtained on both of these mission, as neither data set has been fully analyzed and compared with ancillary data on Orbiter operations. During the OSE observations on STS-60 the Orbiter was stabilized in the -Z_0 solar inertial mode with a +/- 0.2 degree deadband. Maintaining this deadband required firing of vernier thrusters, and the reversals of Orbiter motion produced by such firing are the most prominent feature in the OSE data stream. Figure 1 illustrates the overall motions of the Orbiter during the solar observing period on STS-60. A slow but steady drift of the mean pointing direction relative to the Sun during the observing period during both missions. On STS-60 this drift amounted to 9 arc min/hr in pitch (about the Orbiter Y_0 axis) and 3 arc min/hr in roll (about the Orbiter X_0 axis). The corresponding rates observed on STS-40 were 3.8 arc min/hr in pitch and 2.5 arc min/hr in roll.

A double differentiation of the LISS sensor data, which yields the angular acceleration of the Orbiter about its Y_0 or X_0 axis, clearly demonstrates the pitch or roll rate changes associated with each vernier thruster firing. A short interval of LISS pitch channel data analyzed for the STS-40 flight is shown in Figure 2. The times of vernier thruster firings are also marked (with a different symbol for each thruster) and combinations of such firings have repeatable results in the OSE pointing data. An unanticipated effect was the appearance of a pitch deviation when thrusters were commanded to accomplish an Orbiter roll maneuver. It is known that minor imbalances in thrust between pairs of thrusters can result in cross-coupling of movements about the roll and pitch axes and we apparently have observed the cross-coupled body motions of the vehicle that are the result.

We also detected perturbations that are not associated with thruster firings, but which may be due to crew activities or the operation of mechanical systems on the STS. No crew exercise activity was scheduled during the time period shown in Figure 3 (a sub-interval of that shown in Fig. 2) but angular accelerations (and decelerations) not related to thruster firings are clearly detectable. As the OSE was directly attached to the Orbiter sill via the rigid GAS Bridge, we believe that the observed angular rates truly represent the body motions of the Orbiter and are not vibrations of intermediate mechanical structures.

OSE was operated during an exercise period during the STS-60 mission, so that some of the smaller fluctuations in pointing shown in Fig. 1 may be attributable to torques on the vehicle as the crew operated the exercise equipment.

OBSERVATION OF AN ANOMALOUS ATTITUDE PERTURBATION

We have detected an attitude perturbation, reported by the crew as a "shudder," just prior to shut down of the OSE on STS-60. Although barely detectable in comparison to the normal motion of the Orbiter within its specified deadband, this event is interesting in that it exhibits a spectrum of rotational (in pitch and roll) vibrations of the Orbiter that are characterized by sharp resonances and that are of longer duration in time than the duration of vernier thruster firings used to maintain the Orbiter's orientation (usually 1-2 sec long). The onset of the event, at MET 07/03:45.4 +/- 1 minute, coincides with small changes in Orbiter's pitch and roll rotation rates, suggesting that one or more thruster firings may have occurred. Rogers and Delombard have reported (ref. 3) that although this event has been ascribed by propulsion teams at the Johnson Space Center to three vernier engines firing simultaneously, data from the NASA/JSC Mission Evaluation Workstation System shows no such event at the time of the peak of a vibration recorded by the Shuttle Acceleration Measurement System (SAMS) and no significant vibration signature appeared in the SAMS data during several firings of three thrusters within six minutes of the event. Figures 4 and 5 illustrate those portions of the OSE data stream in during which this vibration event was observed in pitch and roll. The consistency of the OSE observations is demonstrated, in Figure 5, by the similarity of observations in our low gain (upper curve) and high gain (lower curve) roll channels, after applying the relevant sensitivity scaling and accounting for the rotation by 180 degrees of one LISS relative to the other on the LISS Alignment Plate. In this plot an electronic disturbance internal to the OSE would have produced out-of phase rather than in-phase variations of the two OSE signals.

The disturbance produced a modulation in the Orbiter's pitch rate for at least ten seconds, but a modulation of the roll rate could be detected for 20 seconds. The oscillatory motion superimposed on the Orbiter's slow rotational motion within its pointing deadband is best displayed by first subtracting a polynomial fit from the LISS data in each channel. The residual components, after suitable polynomial fits have been subtracted, are shown in Figures 6 and 7. The quality of the observations are clearly better in roll than in pitch, as the high gain pitch channel was saturated due to the pitch offset noted earlier.

ANALYSIS OF THE ATTITUDE DISTURBANCE

Spectral analyses of the pitch and roll excursions were carried out in two second increments for the first twelve seconds of the event using an IDL Discrete Fast Fourier Transform defined by:

$$F(u) = \frac{1}{N}\sum_{x=0}^{N-1} f(x)\exp\left[-j2\pi ux/N\right]$$

This function differs by $(N)^{-1/2}$ from the transform typically used in the analysis of Orbiter vibration data and in the microgravity requirements document for the space station, Space Station Freedom Microgravity Environment Definition-Rev B (ref. 4). Power Spectral Densities, in units of (arcsec sec^{-2}) Hz^{-1}, are shown in Figure 8 for pitch and roll data taken during the first four seconds of the event.

Power is present at frequencies that are are reasonably well correlated with the principal modes of vibration of the vehicle, as summarized by Bergemann (ref. 5). A vibration at 3.5-4 Hz observed in both pitch and roll channels may correspond to a fuselage torsional mode associated with wing and fin bending and another, at 5 Hz, may correspond to a fuselage first normal bending mode expected at 5.2 Hz. A rapidly damped oscillation at about 7 Hz in roll is matched most closely in Bergemann's tabulation by a fuselage first lateral bending mode at 7.4 Hz. Spectral power in both pitch and roll channels at 1-2 Hz and at 2-3 Hz in pitch at the onset of the event may correspond to structural frequencies of the Orbiter's radiators and cargo bay doors, but we have no way of discriminating among such possibilities.

The spectral power as a function of time at each significant frequency is shown in Figure 9 for both pitch and roll. These data enable us to estimate the damping constant associated with each major vibrational mode. The results are summarized in Table 1. We have not been able to identify the impulse which initiated the event, but changes in the pitch and roll rates of the vehicle at the beginning of the event suggest that on-orbit maneuvering jets were involved.

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(2) STS Interface Control Document, Vol. XIV, Paragraph 3.3.1.2.1 and Table 4.1.2-3, p. 3-27.

(3) Rogers, M.J.B., and Delombard, R., "Summary Report of the Mission Acceleration Measurements for STS-60, Spacehab-2," NASA Lewis Research Center, Cleveland Ohio, 1994.

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Table 1. Damping Constants of Orbiter Pitch and Roll Vibrations (sec)

Pitch		Roll	
1-2 Hz	0.6	3.9 Hz	2.95
2-3 Hz	0.7	5.0 Hz	0.67
3.9 Hz	2.14	7.0 Hz	1.35
5.0 Hz	2.85		

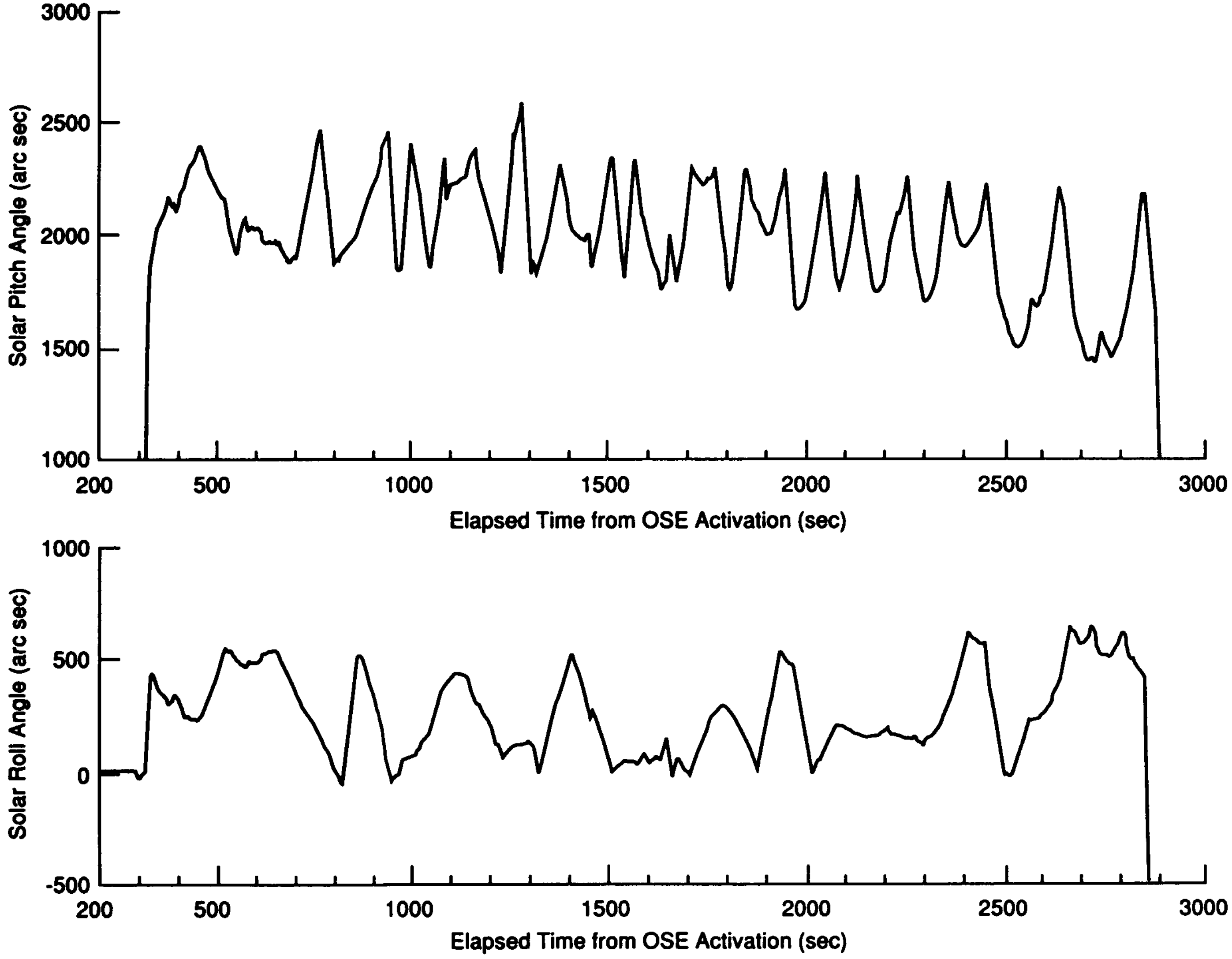

Figure 1. Angular deviations of the Sun's position relative to the reference directions of the Orbiter Stability Experiment's sun sensors as a function of time during operation of the instrument on STS-60. These deviations are interpreted as motions of the Orbiter in pitch and roll relative to a line between the Sun and the Orbiter.

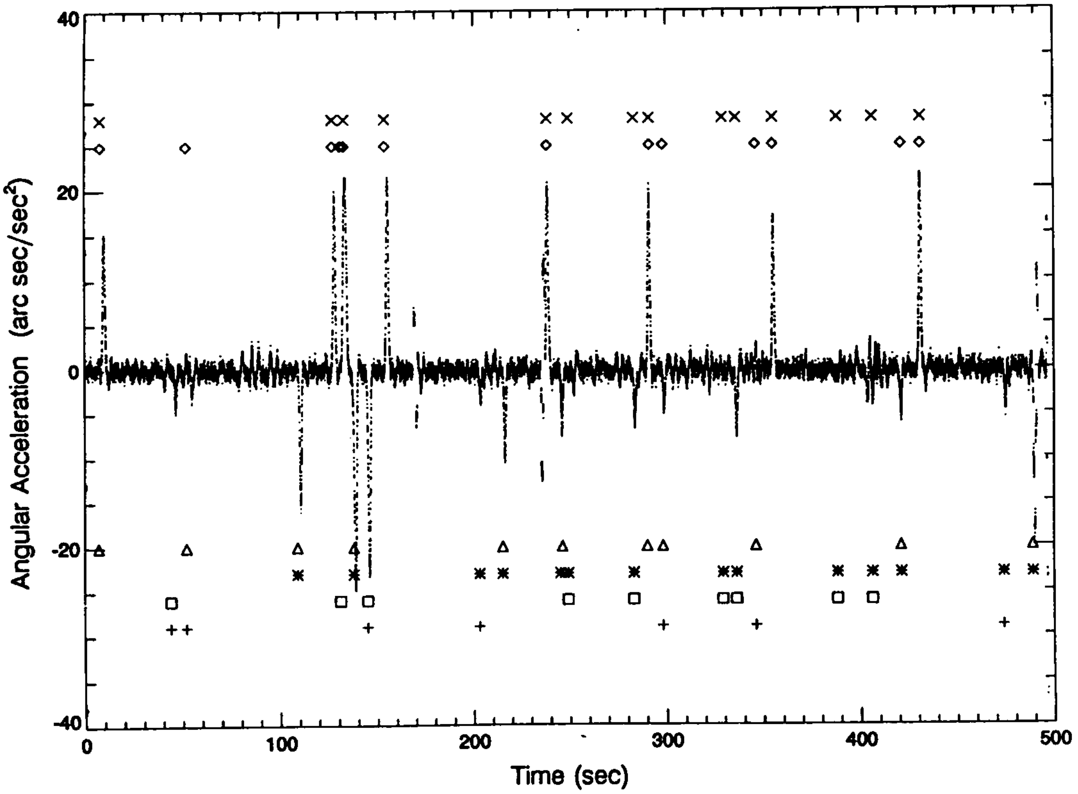

Figure 2. Angular accelerations of the STS in pitch in response to vernier thruster firings on STS-40. Coincidence of crosses and diamonds mark times of vernier thruster firings to accomplish pitch maneuvers.

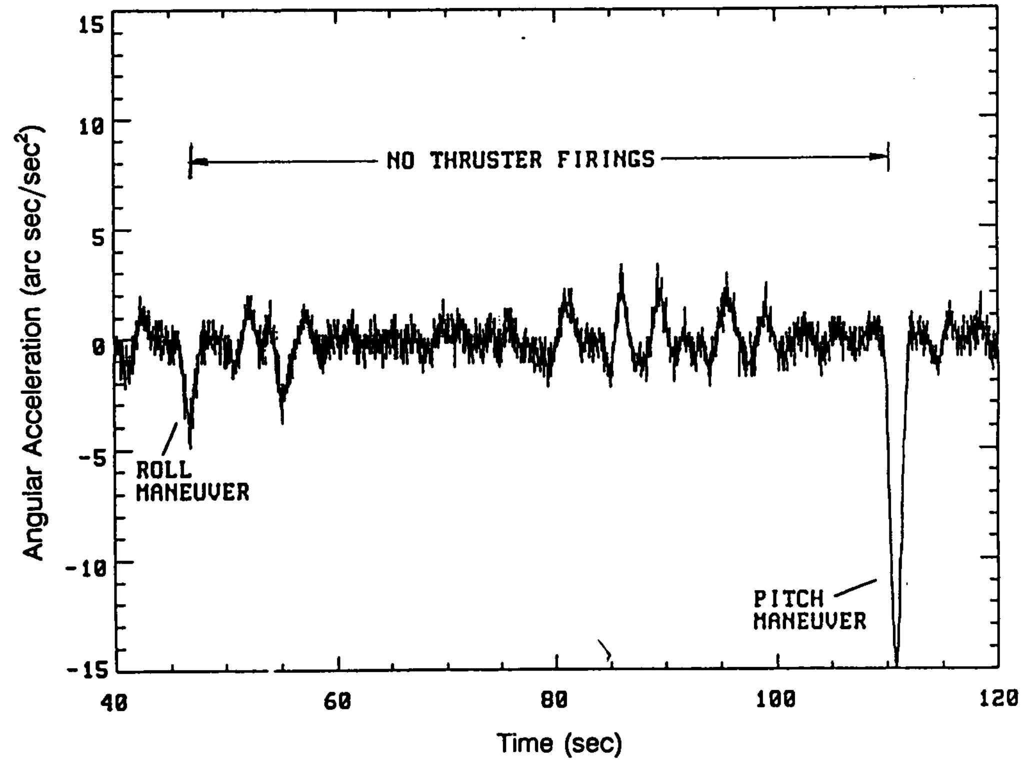

Figure 3. A short interval of data from the STS-40 mission illustrating perturbations in STS pitch orientation when no vernier jets were being fired. One pitch maneuver is obvious at the end of the data interval shown, and a roll maneuver at the beginning of the interval also produces a slight acceleration in pitch at the beginning of the data interval.

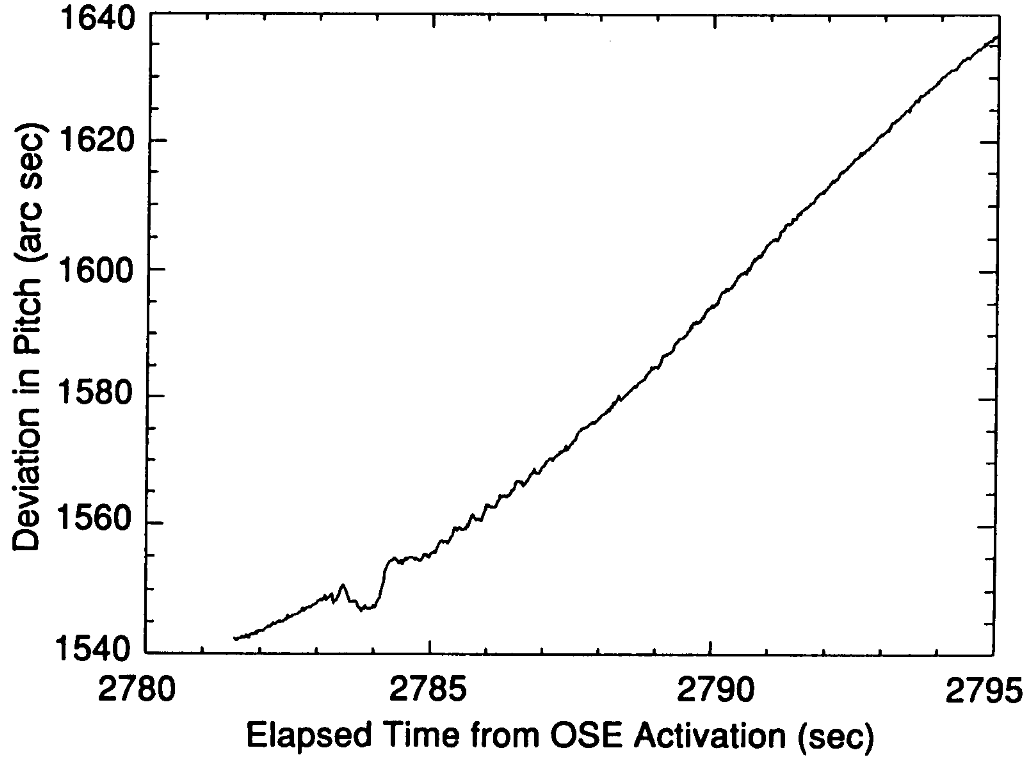

Figure 4. Detection of an anomalous attitude perturbation about the Orbiter's pitch axis at 2784 sec after initiation of OSE Operations on STS-60. This perturbation occurred near the end of OSE operations on that mission.

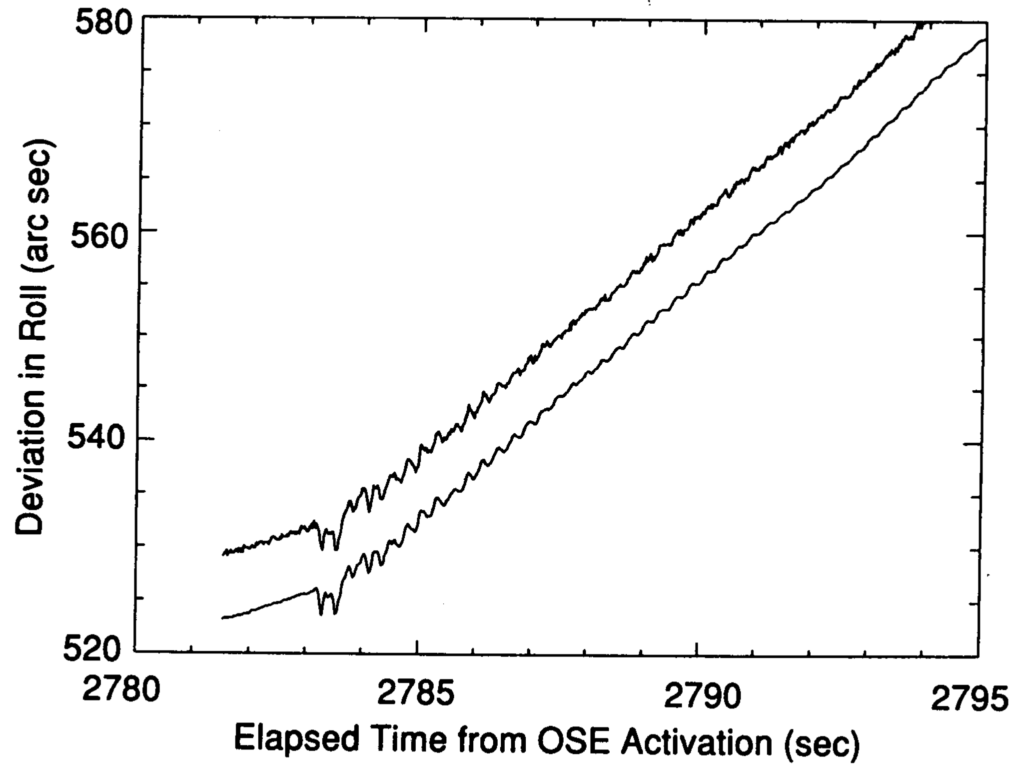

Figure 5. Detection of the same perturbation, in this case about the Orbiter's roll axis, as observed in the OSE's low-gain (upper curve) and high gain (lower curve) roll channels. Note the change in Orbiter roll rate at the beginning of the event, suggesting that a vernier thruster firing may be associated with this event.

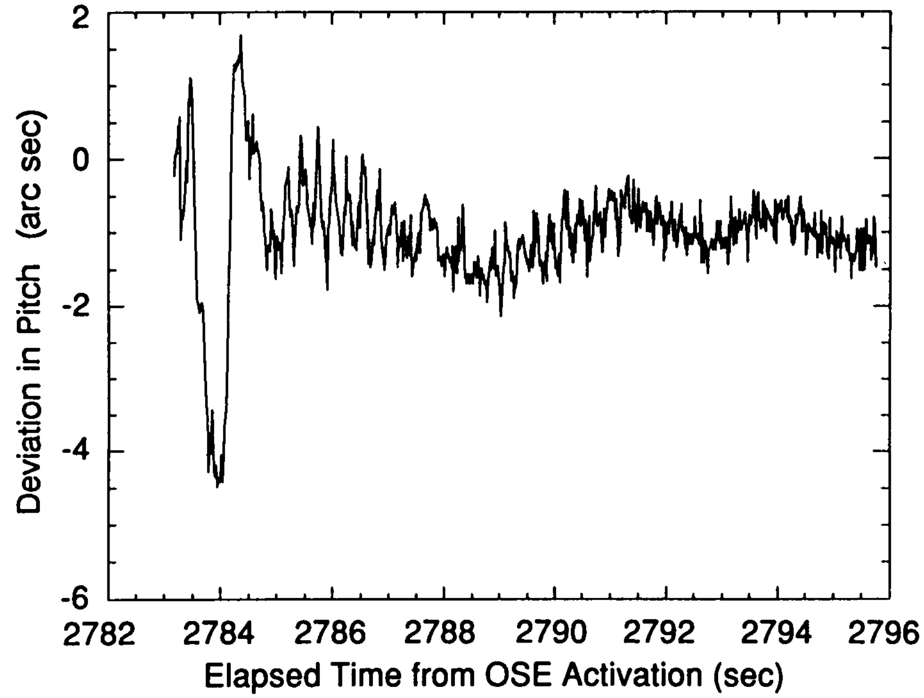

Figure 6. Pitch deviations from a polynomial fit to the OSE data at the beginning of the attitude perturbation shown in Figure 4.

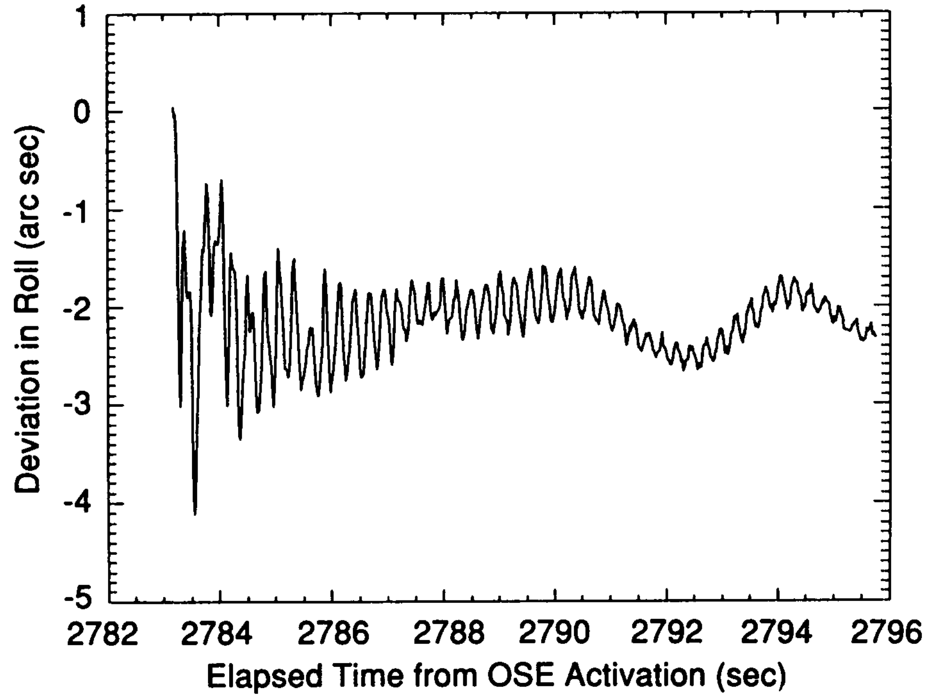

Figure 7. Roll deviations from a polynomial fit to the OSE high-sensitivity roll channel at the beginning of the attitude perturbation.

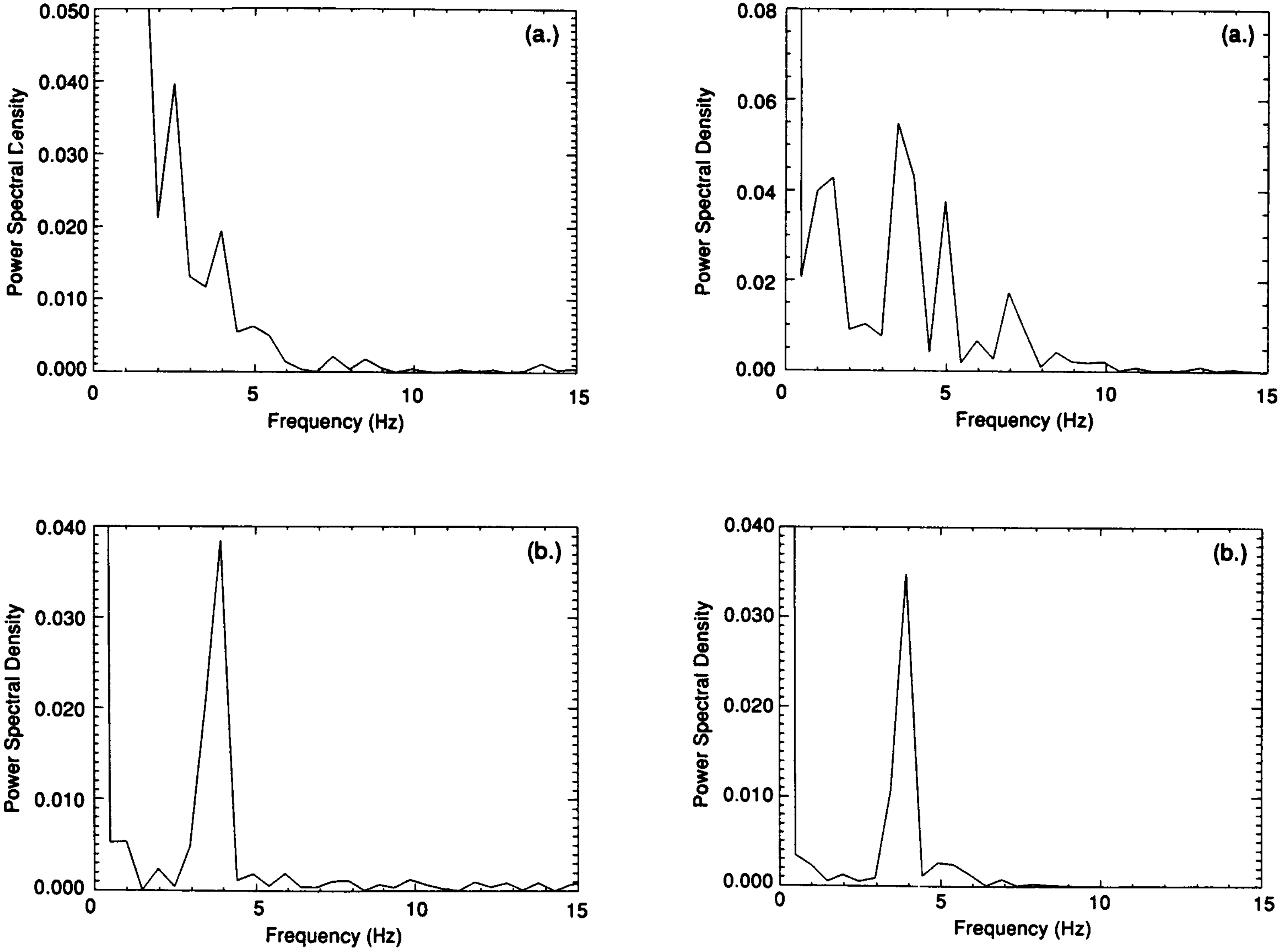

Figure 8. Power spectra of pitch deviations (left panel) and roll deviations (right panel) from polynomial fits to each data channel as a function of frequency at (a) 0.0-2.0 and (b) 2.0-4.0 sec after the beginning of an attitude perturbation on the STS-60 mission.

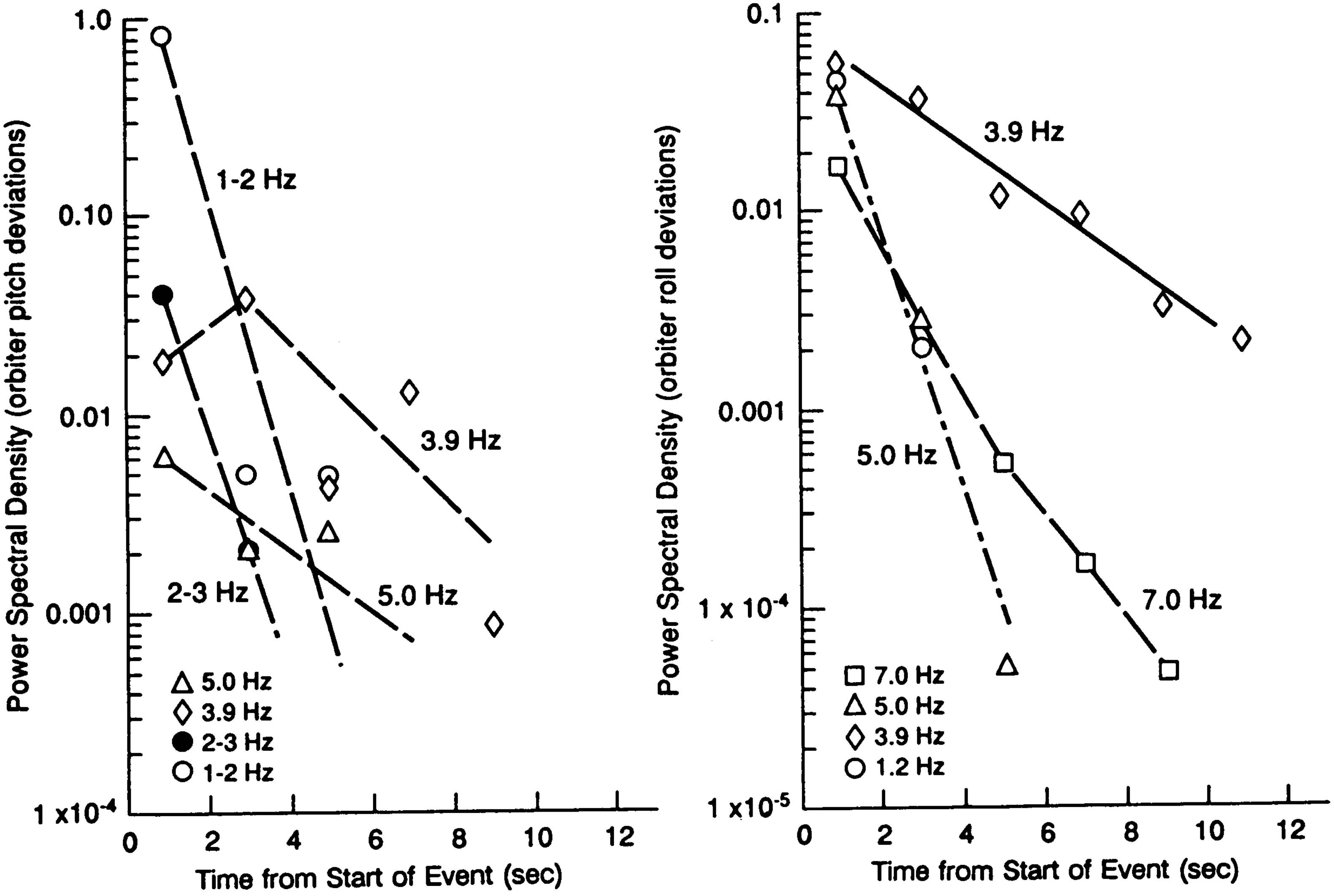

Figure 9. Spectral Power as a function of time for selected frequencies of Orbiter motions during the attitude perturbation shown in Figures 6 and 7.