JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 18, No. 4, July–August 1995

Vibrations of the Low Power Atmospheric Compensation Experiment Satellite

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The Low Power Atmospheric Compensation (LACE) satellite dynamics experiment has measured vibrations of an orbiting satellite from a ground site and has observed the excitation of satellite vibrations by a sequence of boom movements. The preprogrammed boom movements were initiated by commands from a ground control site and observed by the Massachusetts Institute of Technology Lincoln Laboratory Firepond laser radar facility located in Westford, Massachusetts. In the tests, a narrow-band heterodyne CO_2 laser radar, operating at a wavelength of 10.6 μm, detected vibration-induced differential Doppler signatures of the LACE satellite. Augmentation of vibration amplitudes was achieved through timing of repeated boom movements. Evidence of open-loop vibration damping by this method of repeated boom movements was also obtained, although the data were not conclusive since only a single attempt at open-loop damping was observed. The tests have demonstrated the feasibility and advantages of using relatively low cost ground-based observation techniques for vibration measurements and health monitoring of orbiting structures and for improving the accuracy of mathematical models for the structural dynamics of light, flexible space structures.

Background and Description of Low Power Atmospheric Compensation Experiment Dynamics

KNOWLEDGE of the vibration response of orbiting systems to disturbances is crucial to the analysis, design, and construction of light, flexible spacecraft and for the development of precision pointing mechanisms on space platforms. The large size and lightweight construction of space structures requires space verification of structural models derived from computer models and ground tests. Furthermore, the effects of the space environment, such as weightlessness, cannot be replicated on the ground. However, only two previous experiments have been dedicated to on-orbit vibration measurements: the Solar Array Flight Experiment[1,2] (SAFE) and the Middeck Zero-Gravity Dynamics Experiment[3] (MODE). Both of these experiments were on the Space Shuttle. The Low Power Atmospheric Compensation Experiment (LACE) dynamics, performed on a free-flying satellite, has provided an opportunity to achieve valuable on-orbit structural dynamics information at relatively low cost. First, the dynamics experiment rode "piggy-back" as an experiment secondary to the primary objective of the LACE satellite. Second, the novel technique of using ground-based measurements of vibrations of the orbiting satellite was employed. The measurements were accomplished by targeting retroreflectors on the satellite with a ground-based laser radar. Two series of tests have been performed, the first series was in January 1991[4] and a series in late August 1992, described in this report. Both tests used the Lincoln Laboratory Firepond CO_2 laser radar. The only on-board hardware needed for the measurements are germanium retroreflectors. The January 1991 ground-based tests demonstrated the feasibility of the remote technique for satellite vibration measurements. With the August 1992 tests, vibration modes were excited by timed movements of the gravity-gradient boom to demonstrate open-loop vibration damping. Table 1 provides a capsule comparison between the two series of tests.

LACE (NORAD object number 20496) was launched on February 14, 1990 into a 540-km altitude circular orbit of 43 deg inclination. The spacecraft, shown in Fig. 1, was built for the Strategic Defense Initiative Organization (SDIO) by the Naval Research Laboratory. The primary mission was to evaluate atmospheric compensation techniques for ground-based lasers. The 1400-kg Earth-pointing LACE spacecraft has three deployable/retractable booms of maximum length 45.72 m (150 ft). The zenith-directed gravity-gradient boom is mounted on the top of the bus with a magnetic damper at its tip; the forward boom is deployed along the velocity vector; the balance boom is mounted and deployed counter to the velocity. The forward boom has an array of visible light retroreflectors at its tip for the primary experiment. Attitude stabilization to within about 1 deg libration amplitude is accomplished with the magnetic damper and by a constant speed momentum wheel installed in the bus to control roll and yaw motion. Table 2 gives the nominal structural parameters of LACE. The modal damping and stiffnesses shown in the table were developed and refined by the on-orbit measurements, as will be described in a later section. The LACE flight dynamics experiment includes germanium retroreflectors mounted on the tip of the lead retroreflector boom, the bottom of the satellite body, and the tip of the trailing boom as shown in Fig. 1. The Firepond laser radar targets the germanium reflectors with the CO_2 laser radar, as shown in Fig. 2. Two of the reflectors are illuminated simultaneously to provide differential Doppler measurements of the relative motion between the end of the boom and the spacecraft body. The beam width at the LACE altitude is about 5 m. The observations proceed with the satellite in the "terminator mode," with the sun 10–30 deg below the horizon; the site has a dark sky, but the satellite is still sun illuminated to allow tracking. The terminator mode window provides 7–8 days of possible targeting; the pattern repeats about every 8 weeks. During the window, the LACE satellite can be tracked and illuminated for one to two passes a day. LACE is acquired by the Millstone L-band tracking radar, also located at the Westford site, and by a pulsed continuous wave (CW) argon-ion laser targeted on the visible light retroarray at the tip of the lead boom. The argon-ion laser is multiplexed and

Received Aug. 23, 1993; revision received Aug. 12, 1994; accepted for publication Jan. 12, 1995.

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Table 1 Summary of tests

Test	January 1991	August 1992
Lead boom	24.4 m → 4.57 m	5.49 m (18 ft)
Trailing boom	45.72 m (150 ft)	45.72 m (150 ft)
Gravity-gradient boom	45.72 m (150 ft)	Retracted/deployed 15 cm; nominal, 45.72 m
Peak vibration velocity	15–20 mm/s	10 mm/s
Firepond detection	4-ms pulse	CW (1-s integral)
Receiver sensitivity	2 mm/s	0.5 mm/s

Table 2 LACE structural parameters

Parameter	Value
Mass of bus	1177.68 kg
Bus moment of inertia I_{XX}	1448.67 kg-m^2
Bus moment of inertia I_{YY}	1426.43 kg-m^2
Bus moment of inertia I_{ZZ}	1026.16 kg-m^2
Bus cross moment I_{XY}	3.61 kg-m^2
Bus cross moment I_{XZ}	19. 99 kg-m^2
Bus cross moment I_{YZ}	14.86 kg-m^2
Length (Z axis)	24.384 m (96 in.)
Width and breadth	1.3208 m (52 in.)
Length of boom cannister	1.2192 m (48 in.)
Mass of motor, cannister, gears	16.8 kg
Mass of boom	13.3 kg
Maximum deployed boom lengths (all 3)	45.72 m (150 ft)
Bending stiffness of booms	1.8632 × 10^4 N-m^2
Torsional stiffness	675 N-m^2
Deployment/retraction rate	6–9 cm/s (voltage dependent)
Cannister stiffness	0.9 × 10^4 − 1.6 × 10^4 N/m
Modal damping (assumed same for all modes)	2%

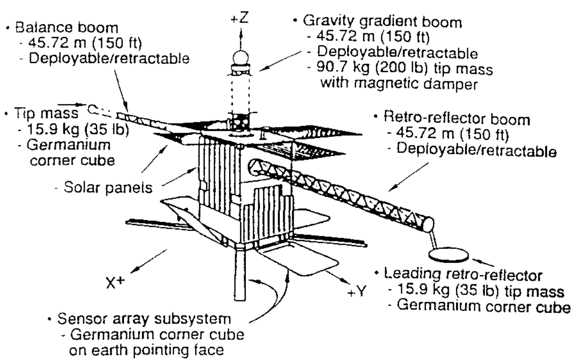

Fig. 1 LACE satellite showing placement of germanium retroreflectors.

boresighted with the CO_2 laser radar. The system also has the capability of passive tracking by reflected sunlight. Illumination times are limited to a maximum of about 2 min, since LACE is in low Earth orbit and therefore passes rapidly across the visible sky. Just prior to and during the illuminations, vibrations of the satellite are excited by boom movements.

In the January 1991 tests, the lead boom (which also contains one of the germanium retroreflectors) was retracted from a length of 24.4 m (80 ft) to a length of 4.572 m (15 ft). The trailing boom and gravity-gradient booms were fixed at 45.72 m (150 ft). Simultaneous reflections from the reflectors at the tip of the lead boom and on the bottom of the LACE bus enabled measurements of the relative velocity between those two points. The maximum relative velocity was observed to be about 20 mm/s immediately after the retraction was completed. Previous papers[4–6] have presented power spectral density (PSD) frequencies of the forced oscillations during the boom movements and analyses of the free–damped system vibrations observed after the retraction stopped. The free–damped vibrations were analyzed by the eigensystem realization algorithm[7] (ERA) and the minimum model error[8] (MME) methods; the values of the identified modal frequencies and damping factors were compared with predicted modal frequencies, with ground tests, and

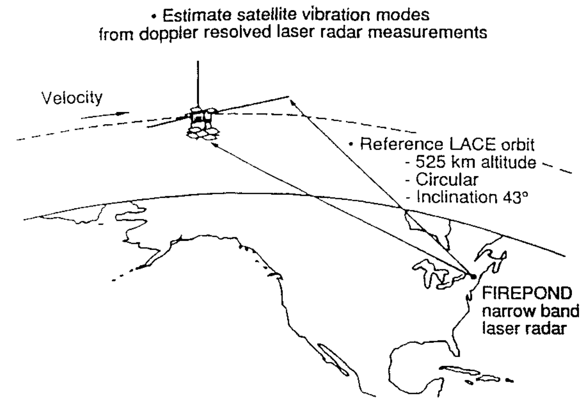

Fig. 2 LACE dynamics showing targeting from Firepond.

with previous on-orbit measurements. The results demonstrated the importance of in situ verification of initial finite element modeling; a mode not previously predicted was observed, and the identified frequencies were shifted somewhat from predicted values. This first test also showed that the Firepond system, as it was then configured, could measure LACE boom tip vibration amplitudes as low as 2 mm/s. Significant improvements, to be discussed in the next section, were made for the 1992 tests.

Description of Firepond Laser Radar System

The Firepond laser Doppler system observes boom vibrations by observing the variation in time of the relative velocity between the body and lead boom retroreflectors, projected onto the radar line of sight (LOS). The measurements require simultaneous illumination of the two retroreflectors by the transmitted radar beam. Since the (near) diffraction limited full width at half-maximum (FWHM) of the transmitted beam is about 10 μrad, the projected separation of the retroreflectors is limited to a maximum of approximately 5 m at the 500-km altitude of LACE. The original system, used in the 1991 tests, operated at 600 W with a pulse duration τ of 3.4 ms and a pulse repetition frequency of 62.5 Hz. The Doppler resolution was about 294 Hz (resolution is $\approx 1/\tau$), giving a nominal velocity resolution of approximately 1.8 mm/s, according to the Doppler shift equation

$$\frac{\Delta f}{f} = 2\frac{\Delta v}{c} \Rightarrow \Delta v = \tfrac{1}{2}\lambda \Delta f = \frac{10.6}{2} \times 10^{-6} \times 294\,\text{m/s}$$

$$= 1.8 \times 10^{-3}\,\text{m/s}$$

With this system, data processing at the Firepond site consisted of digitizing the 3.4 ms of inphase (I) and quadrature (Q) data at a 1.2-MHz rate, resulting in 4080 complex IQ samples for each pulse. The IQ envelope has an oscillatory behavior due to coherent interference between the two retroreflectors (i.e., speckle). This speckle or autodyne pattern contains Doppler information regarding the relative velocity of the retroreflectors. The speckle pattern was analyzed by taking a discrete Fourier transform of the modulus of IQ to obtain the PSD of the pulse. The PSD was then filtered for noise and only the maximum Doppler shift between 4.5 and 19.5 kHz was kept. A single value of the Doppler shift frequency Δf was thereby obtained from each return pulse.

To detect the weaker vibrations excited by the gravity-gradient boom maneuvers (maximum relative velocity of about 10 mm/s), the Firepond laser radar was improved considerably between the 1991 tests and the 1992 tests by the installation of a CW system. The novel modifications implemented by the CW system[9] improved the nominal velocity resolution to approximately 0.5 mm/s by allowing a 10-ms integration time window, compared with the 3.4-ms time window of the 1991 tests. This 10-ms integration time provided a differential Doppler frequency resolution of about 100 Hz (as compared with the 294 Hz of the original pulsed system.) The modifications included a unique method to spatially multiplex the transmit-and-receive beams angles. In addition, autodyne receivers were used to relax laser coherence and frequency-tracking requirements and to simplify both real-time and postmission data processing. The re-

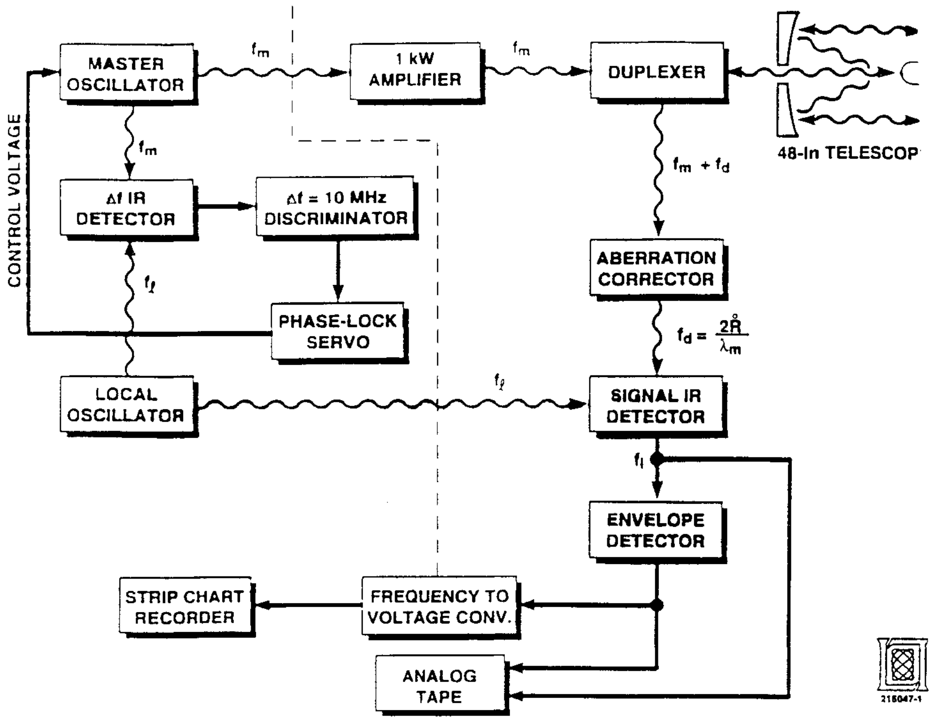

Fig. 3 Block diagram of the CW IR laser radar.

sultant vibration signatures were observed in real time by feeding the output of an autodyne receiver to a frequency-to-voltage converter whose output was then displayed with a chart recorder. The raw speckle (autodyne) data were also recorded on analog tape and subsequently digitized for postprocessing.

A block diagram of the infrared (IR) laser radar is provided in Fig. 3. The coherent narrow-band IR laser radar used to collect satellite vibration data is based on a master oscillator power amplifier (MOPA) configuration operating on the $P_I(20)$ line of $^{12}C^{16}O_2(\lambda = 10.59\,\mu m)$.[10] The master oscillator (MO) and local oscillator (LO) are a pair of frequency offset locked ($\Delta f = 10$ MHz) CO_2 lasers operating CW. The mutual long-term stability of the laser pair has been measured to be better than 1 Hz.[11] The MO output passes through an InSb isolator to the first tube of a linear discharge axial flow 1-kW-power amplifier. In the CW operating configuration used in the latest set of tests, the resultant output converges to a focus where it passes through a small aperture in the transmit/receive duplexing mirror. The transmit beam then passes to a 1.2-m (48-in.) Cassegrain telescope fitted with a high-speed secondary mirror for precision angular tracking. The nominal CW transmit power was 600 W. The received signal is collected by the 1.2-m aperture where it is directed toward the duplexing mirror located at the telescope focal point. After the satellite elevation exceeds approximately 45 deg, the satellite's apparent motion in the sky generates a measurable difference in angle between the transmitted and received beams. The difference in angle is sufficient to move the received beam away from the small transmit aperture and onto the duplexing mirror surface where it is directed toward the receive optics. The received signal, which contains both the translational and vibration-induced frequency shifts, is then mixed with the 10-MHz offset LO onto a wideband HgTe detector. Finally, the resultant signal is amplified and envelope detected to extract the speckle signature. This offset detection arrangement can be interpreted as a matched filter that rejects background radiation near the operating wavelength of 10.6 μm. The time-varying envelope signature is simply the speckle pattern induced by the relative motion between the illuminated IR retroreflectors. The technique improves the velocity resolution measurement capability of the Firepond system by increasing the measurement coherence time, even though phase information is lost by this procedure. The potential increase in the coherent integration time using the autodyne technique is achieved because 1) the time delay of relevance is defined by the distance between the retroreflectors, not the round-trip distance between the radar and target, and 2) all mixing signals traverse the same optical path. Furthermore, the speckle method obviates the need to track the gross body Doppler frequency and simplifies signal processing.

A passive 24-in. visible light tracker was used to acquire the target in angle as the target was observed during the terminator passes. Once acquired, a more accurate angular track was obtained with a quad monopulse track using the sun-illuminated visible returns from LACE collected by the 1.2-m telescope.

Description of August 1992 Tests: Open-Loop Control

To perform open-loop control, the gravity-gradient boom was used as an actuator, with the lead boom fixed at 5.486 m (18 ft) and trailing boom fixed at 45.72 m (150 ft). Figure 4 illustrates the square-wave impulses given by a single 0.15-m (6-in.) bay retraction and deployment of the gravity-gradient boom. Each retraction and/or deployment effectively gives two 0.5-s duration forces of equal magnitude and opposite direction to the satellite body and hence the lead boom. Timing of repeated retractions/deployments can excite or damp vibrations depending on the phasing of the maneuvers. The maximum amplitude of the vibration velocity excited by this method is about 10 mm/s; the acceleration of the boom retraction/deployment rate from rest to its maximum is 0.076 m/s and the ratio of the gravity-gradient tip mass to the mass of the LACE satellite is 0.075. Computer simulations were performed as an aid to determine an appropriate sequence of deployment/retraction maneuvers that would both excite and then damp boom vibration modes. The sequences were preprogrammed 24 h ahead of the test and uplinked to LACE. During the pass observations at the Firepond site, a voice command is given to the ground control site from Firepond to initiate the boom maneuver sequence after target acquisition and track initiation.

The open-loop control tests were conducted with LACE during a 7-day terminator mode window in August 1992. Table 3 gives the details of the commanded boom deployments/retractions for days 239 and 242. As the data windows for days 239 and 242 were significantly longer than for other days, only the analyses of those observations are presented. The degree to which the actual forcing functions matched the idealized forcing functions presented in Table 3 is unknown, as the boom status was monitored by sampled values of motor current at 0.25-s intervals; the precise relationship between the motor current and boom movement was unavailable.

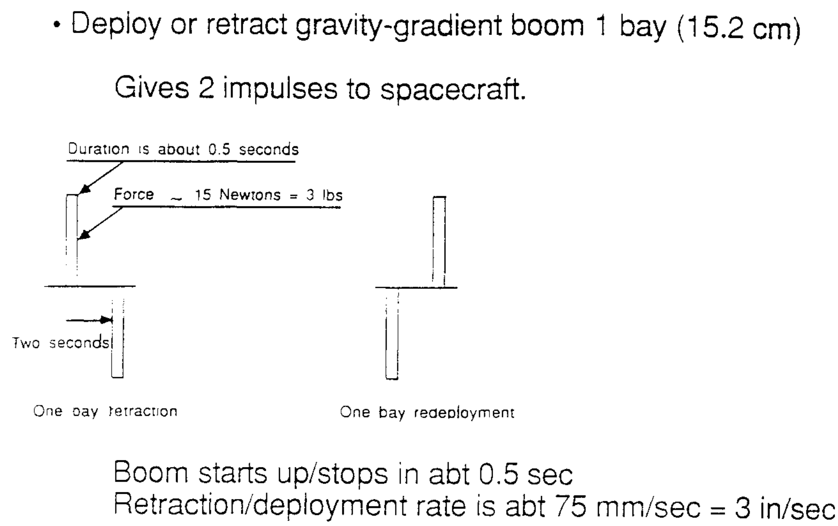

Fig. 4 Impulse pattern from gravity-gradient boom retractions and deployments.

Table 3 Boom maneuver summary

Day	Illumination window[a]	Data window[a]	Boom sequence Time[a]	Maneuver[b]
239[c]	6244–6589	6360–6410	6369 (−20)[d]	Retract
			6389 (0)	Deploy
			6409 (20)	Retract
			6429 (40)	Deploy
24[c]	1265–1850	1420–1485	1427 (−28)[d]	Retract
			1447 (−8)	Retract
			1455 (0)	Deploy
			1466 (11)	Deploy

[a]Greenwich Mean Time, seconds after midnight.
[b]Deploy or retract gravity-gradient boom 1 bay (15.2 cm).
[c]Lead boom at 5.486 M, balance boom at 45.72 m.
[d]Numbers in parentheses are times relative to key maneuver.

Uncertainties in motor response could be 1/2 s or more. Each retraction or deployment was programmed for one bay, or about 15.24 cm (6 in.). With the test on day 239, the boom was commanded to retract and deploy at 20-s intervals. The goal was to excite vibrations large enough to be observable by the Firepond system. An early analysis of the data showed that two modes were observable: 0.13 and 0.31 Hz. Therefore, an effort was made to demonstrate open-loop damping on day 242. (Other factors precluded tests on days 240 and 241.) For this demonstration, a deployment/retraction pattern, shown in Table 3, and known as the Taylor squelch (developed and aptly named by co-author Lawrence W. Taylor Jr.), was employed to first excite the 0.31-Hz vibrations and then to damp them. From the table, it can be seen that a delay of 11 s was commanded for the last deployment. It was this last deployment that was expected to damp the 0.31-Hz vibrations.

Detected Modes and Observed Boom Tip Motion

The decoded autodyne frequency spectra are processed with a 10-ms temporal window. The residual vibration data are obtained by median and low-pass filtering and by averaging out the rigid-body rotation relative to the radar LOS. The relative velocities obtained for days 239 and 242 are shown in Fig. 5, together with a Fourier frequency analysis of the data. Also indicated are the boom movements at −20, 0, and 20 s for day 239 and −8, 0, and 11 s for day 242. The zero time has been referenced to a boom deployment: 6389 s after midnight on day 239 and 1455 s after midnight on day 242. (See Table 3 for boom maneuver timing.) Figure 6 shows the relative velocity data with the boom deployments/retractions superimposed. The data clearly show excitation of vibrations with the boom maneuvers, especially around the $t = 6389$ s deployment on day 239 and the $t = 1455$ s deployment on day 242. The peak vibration amplitude is about 10 mm/s, with the bulk of the vibrations at 5 mm/s or less. Later in this paper we discuss the effectiveness of the damping strategy for the tests of day 242.

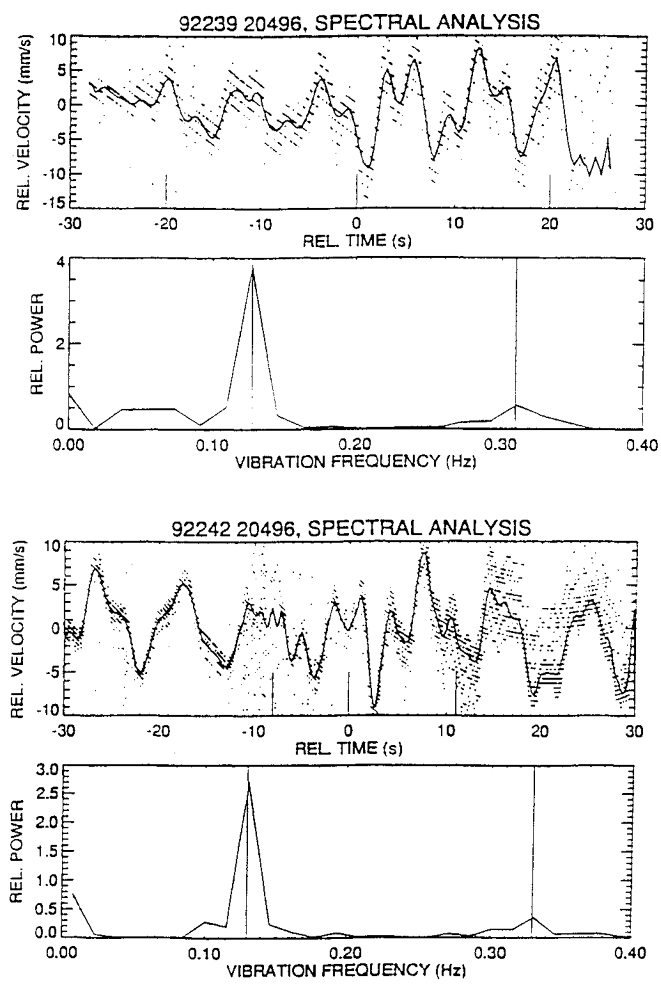

Fig. 5 Observed velocity vibration data and Fourier analysis, days 239 and 242.

The Fourier transforms were performed with a moving 5.25-s Hamming window, taken at 0.5-s intervals. The results are shown in Table 4; on day 239 the detected frequencies were 0.13 and 0.31 Hz, whereas on day 242 the detected frequencies were 0.13 and 0.33 Hz. The vibration frequency resolution for both days 239 and 242 is approximately 0.02 Hz. The difference between the frequencies of the second observed mode is within the error of the

Table 4 Modes detected: day 239

Mode	Fourier transform frequency (Hz)	ERA Frequency (Hz)	ERA ζ,%
4	$0.13 \pm .02$	0.122	1.35
7	$0.31 \pm .02$	0.31	0.62
10	——	0.49–0.52	5.0

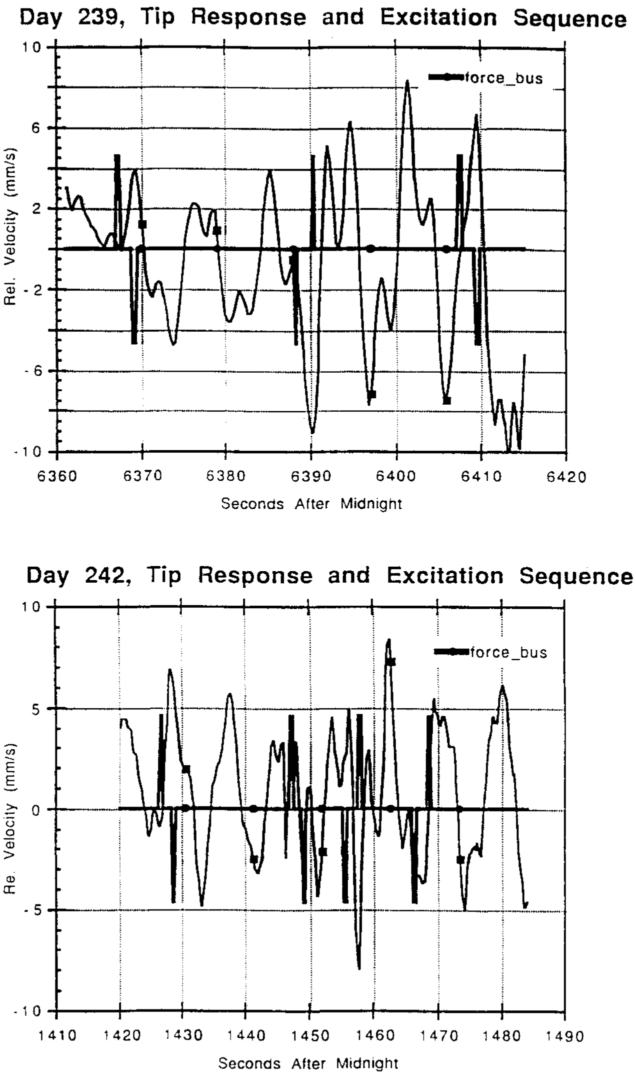

Fig. 6 Overlay of boom retractions deployments on observed data, days 239 and 242.

measurements. There is a possibility that the boom length was not the same on day 242 as on day 239. The lead boom had been extended its full length of 45.72 m and then retracted to 5.486 m during the time between the two measurements. However, a difference of length of even two bays, or 0.305 m, would only shift the frequency by 0.005 Hz. The detected modes correspond to modes 4 and 7 of the finite element model (FEM) to be discussed in the next section. From the FEM model, modes 4, 7, and 10 are the most observable modes. They include a significant pitch amplitude at the tip of the lead boom and have the highest model costs.[12] An ERA was done on the day 239 data for the free decay periods between −20 s and 0 and between 0 and 20 s relative time. Other data segments were too short or too noisy for ERA analysis. The ERA also detected mode 10 with the frequencies and damping given in Table 4. The identified frequencies of 0.122 and 0.314 Hz for modes 4 and 7 agree with the frequencies obtained from the Fourier transforms, within the errors of the Fourier transform frequency resolution.

Table 5 FEM modifications: modal frequencies and stiffnesses[a]

Mode	1990 Model[b] frequency, Hz	1991 Model[c] frequency, Hz	1992 Model[d] frequency, Hz
1	0.019	0.019	0.02
2	0.108	0.107	0.113
3	0.112	0.111	0.120
4	0.122	0.121	0.128
5	0.258	0.258	0.269
6	0.296	0.290	0.297
7	0.315	0.308	0.310
8	0.320	0.319	0.345
9	0.641	0.529	0.509
10	0.678	0.584	0.544
EI	1.55×10^4 N-m^2	1.55×10^4 N-m^2	1.82×10^4 N-m^2
GJ	575 N-m^2	575 N-m^2	674 N-m^2
Cannister	1.70×10^4 N/m	1.70×10^4 N/m	0.90×10^4 N/m

[a]Lead boom at 5.486 M, others at 45.72 m.
[b]Model based on static ground tests.
[c]Model modified based on ERA of 1991 tests.
[d]Model modified based on 1992 tests.

Finite Element Modeling and Updates

During the course of the experiments and analyses, a sequence of three NASTRAN FEMs were developed:

1) Prior to the LACE launch, an FEM model of the system was generated, referred to herein as the 1990 model. In this model, the booms were modeled as simple beams, with the LACE body treated as rigid. The LACE size, weight, and inertias were provided by the Naval Research Laboratory spacecraft engineering group that built the spacecraft.[13] In addition, static ground tests conducted by the boom manufacturer[14] measured the bending and torsion stiffness of the booms and the boom–cannister interface stiffness.

2) Subsequent to the 1991 observations and following an ERA analysis of flight data, the FEM model was modified to more accurately reflect the design of the flexible mount holding the reflector plate on the tip of the lead boom.[12] The ERA analysis also gave a measure of modal damping ratios. A value of 2% damping, uniform for all modes, was incorporated into this 1991 model.

3) Finally, the current 1992 model was developed by modifying the bending stiffness and torsional stiffness of the booms and the boom–cannister interface stiffness to match the open-loop excitation and control responses observed in the 1992 tests. All three booms were assumed to have identical stiffnesses as in the 1990 and 1991 models.

Table 5 shows a comparison of modal frequencies thereby obtained for the three FEM models, together with a listing of the changes in the structural parameters. A modal model, set up to match the observed 1992 open-loop excitations, gives 0.126 Hz for mode 4 and 0.309 Hz for mode 7.

Discussion of 1992 Model

The boom bending stiffness that best matched the 1992 data was 1.82×10^4 N-m^2, a value of about 13% higher than the maximum static ground-based measurement for static bending stiffness; the static tests measured a range of bending stiffnesses from 1.25×10^4 to 1.6×10^4 N-m^2. Other changes in the 1992 model included an increase of torsional stiffness from 575 to 675 N-m^2 and a decrease in the boom–cannister interface stiffness from 1.6×10^4 to 0.9×10^4 N/m. The total of all of the changes in the system parameters produce an increase of 6% for the frequency of mode 4 (0.121 Hz in the 1991 model and 0.128 Hz in the 1992 model) and 0.6% in the frequency of mode 7 (0.308 Hz in the 1991 model and 0.310 Hz in the 1992 model). The differences between the 1991 and 1992 models could be caused by several factors. First of all, the 1991 tests provided only two time series samples; one of length 45 s and one of length 28 s. The frequency resolution obtainable from the measurements would be of the order of 0.02 Hz, an amount greater than the observed differences. It is also possible that temperature differences, produced by seasonal and orbital sun angle changes, might change the stiffness of the boom fiberglass longerons. Other factors include possible boom stiffness changes caused by the 60 or

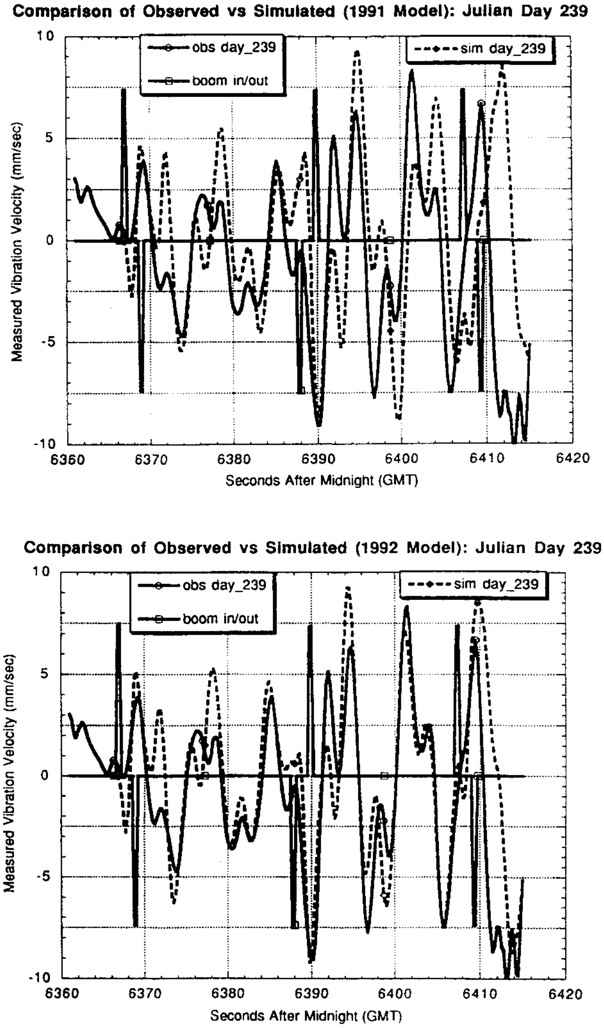

Fig. 7 Comparison of observed velocity vibration amplitudes vs simulated days 239 and 242.

so boom deployments and retractions commanded in the 18 months between the two test series. To test this hypothesis, it was planned to repeat the January 1991 test procedures to observe LACE vibration responses to similar excitations. However, resources did not permit such tests.

Figure 7 compares the 1991 model with the 1992 model by means of simulations of the day 239 data. In the figure, the day 239 observations of the vibration velocity amplitudes are superimposed on simulated system responses for the two models. The 1992 model matches the relative vibration amplitudes quite well until the last few seconds of the observation period. The figure displays the sensitivity of system open-loop responses to the parameter changes between the two models.

Open-Loop Damping

Figure 8 shows evidence for the effectiveness of the open-loop control strategy, i.e., for modal vibration damping generated by the final deployment movement of day 242 at $t = 11$ s. (Day 239 had a retraction at $t = 20$ s.) The figure shows a reduced interference distribution (RID)[15] plot of the power in the 0.31-Hz mode as a function of time for days 239 and 242. In the figure, the relative time is the same as with Fig. 5. The figure shows an oscillation frequency in the power of about 0.2 Hz, not far from the difference frequency between the two principal modes (0.31 and 0.128 Hz). This fluctuation pattern appears to be an artifact of the nonlinearities of the RID transform. Tests on RID transforms of a composite sinusoid, $\sin(2\pi \times 0.13t + \sin(2\pi \times 0.128t)$, show a similar oscillation structure. For day 239, the figure shows an increase in modal power with the deployment at $t = 0$, then a free decay at about a 2% damping rate. The retraction at $t = 20$ s re-excites the mode slightly. For day 242, the figure shows a similar excitation at $t = 0$, but it also shows an attenuated power relative to day 239 subsequent to the deployment at $t = 11$ s. It is therefore quite possible that the control actuation did damp the 0.31-Hz mode. However, it would be necessary to replicate the experiment several times to convincingly demonstrate open-loop damping with this procedure.

Figure 9 shows output obtained from FEM simulations of the day 239 and day 242 excitations and responses. The simulation provides the 0.31-Hz modal response. The figure is a normalized plot of the envelope of the peaks of the 0.31-Hz modal amplitude squared vs

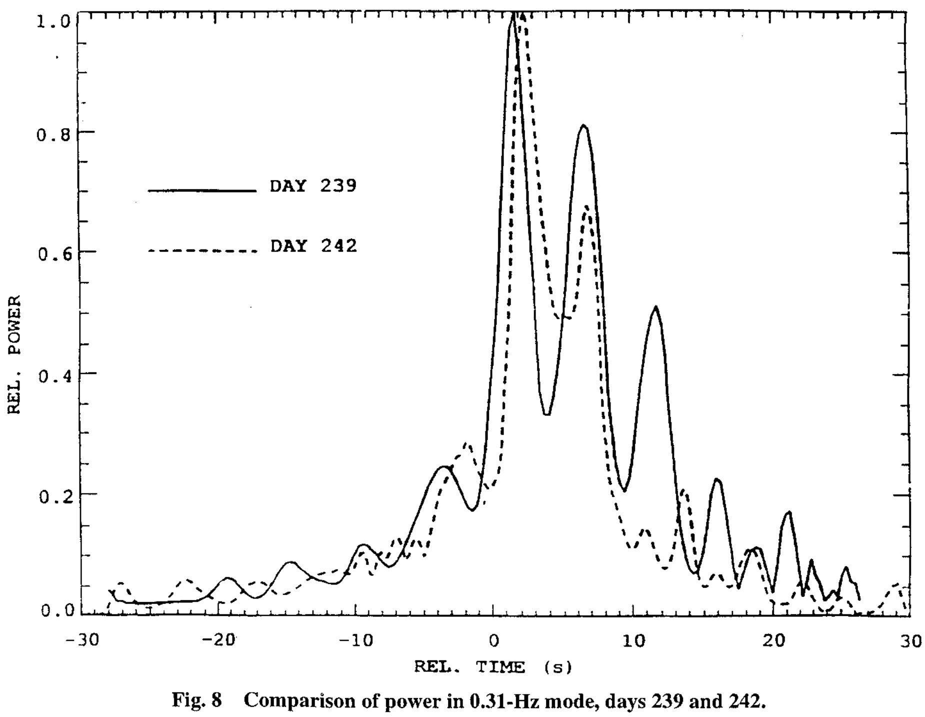

Fig. 8 Comparison of power in 0.31-Hz mode, days 239 and 242.

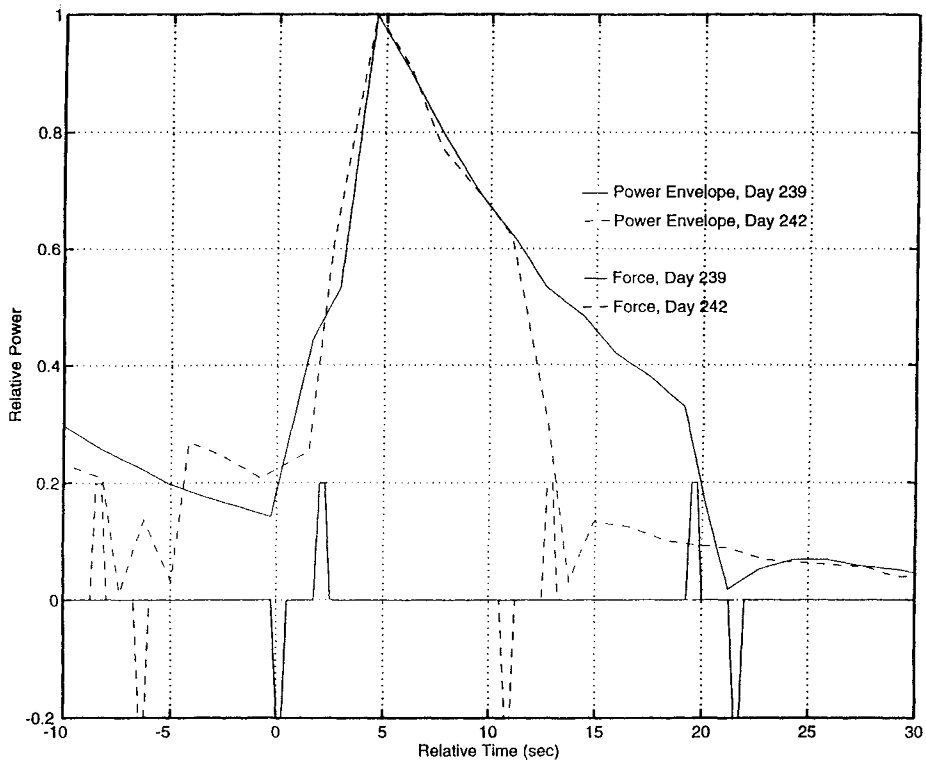

Fig. 9 Simulated comparison of power in 0.31-Hz mode, days 239 and 242.

time. The zero times for days 239 and 242 are the same as in Fig. 8. With the simulation, the control actuation at $t = 11$ s attenuates the power in the 0.31-Hz mode at a rate close to the observed rate.

Conclusion

The LACE satellite dynamics has demonstrated the feasibility of remote sensing as a relatively low cost technique for health monitoring and vibration measurements of orbiting structures. The only space hardware required are germanium corner reflectors, which cost about $5000 each. Therefore, an array of the reflectors on board a large structure could give structural information at relatively low cost and allow for a periodic assessment of structural health at intervals accessible by available terminator mode windows.

The experiment has allowed for considerable improvement in the structural model. The Firepond laser radar has demonstrated a capability of measurements of vibration amplitudes as low as 0.5 mm/s. The velocity resolution capability of the CW autodyne laser radar was estimated to be of the order of 0.01 mm/s.

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