Ground-based laser radar measurements of satellite vibrations

K. I. Schultz and S. Fisher

Vibration signatures from the low-power atmospheric compensation (LACE) satellite are obtained by using the MIT Lincoln Laboratory Firepond coherent CO_2 laser radar facility located in Westford, Mass. The LACE satellite is equipped with IR germanium retroreflectors on deployable/retractable booms to enhance ground-based IR laser radar measurements of on-orbit boom vibrations. Analysis of pulsed cw laser radar measurements of the satellite during and subsequent to boom retraction indicates the presence of a complex time-varying model structure. The observed vibration spectra include vibration modes not previously predicted. These data represent the first observations of satellite vibration modes from a ground-based laser radar.

Key words: Laser radar, ladar, infrared ladar, Doppler vibration signatures, ladar satellite signatures.

1. Introduction

Control–structure interaction technology issues are critical to the understanding and development of stable space-based platforms. While sophisticated mechanical simulation programs for evaluating in-space dynamics exist, *in situ* measurements of satellite vibration are rare; to date, there has been only one previous experiment dedicated to collecting on-orbit vibration data.[1] The experiment, the solar array flight experiment, used on-board sensors to measure boom vibrations during an 18-h period. While this experiment provided considerable data, a larger database is required for developing and validating structural dynamics models.

The success of the low-power atmospheric compensation (LACE) satellite vibration experiment suggests the feasibility of using a remote laser radar (which is abbreviated as ladar) system to acquire high-resolution vibration data at a relatively modest add-on cost to an existing space experiment. The primary mission of the LACE satellite [North American Air Defense System (NORAD) object #20496], which is shown in Fig. 1, was the evaluation of atmospheric compensation techniques. The LACE satellite, which was launched on February 14, 1990, into a 540-km altitude circular orbit of 43° inclination, consists of a massive body and three deployable/retractable booms with a maximum length equal to 45.7 m (150 ft). Constant-rate boom deployment/retraction maneuvers are remotely controlled through a ground-based telemetry link.

In order to facilitate ground-based coherent IR ladar measurements, 3.8-cm IR Ge retroreflectors were mounted on the lead boom, body, and trailing boom, as shown. The addition of these retroreflectors was the only modification to the existing structure. The Doppler resolution of the pulsed cw ladar was sufficient to measure the relative velocity between retroreflectors located on the lead boom and the (relatively massive) satellite body. By observing the relative retroreflector velocity over time, we estimate boom-tip vibration modes from the ladar returns. These measurements represent the first observations of satellite vibration modes from a ground-based ladar.

2. Description of Firepond CO_2 Doppler Laser Radar

The coherent pulsed cw IR ladar used to collect satellite vibration data, which is depicted in Fig. 2, is based on a master oscillator power amplifier (MOPA) configuration operating on the $P_I(20)$ line of $^{12}C^{16}O_2$ ($\lambda = 10.59$ μm) (see Ref. 2). The master oscillator (MO) and the 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.[3] The MO output passes through an InSb isolator to the first tube of a linear discharge axial flow 1-kW power amplifier (PA). The amplified output is

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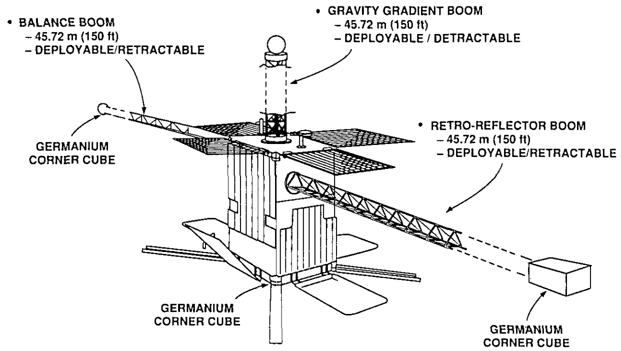

Fig. 1. Simplified representation of the LACE satellite.

chopped to form 3.2-ms pulses at a pulse repetition frequency (PRF) of 62.5 Hz. The resultant output converges to a focus at the receiver duplexer and then passes to a 1.2-m (48 in.) Cassegrain telescope fitted with a high-speed secondary mirror for precision angular tracking. The full width at half-maximum (FWHM) of the (near-) diffraction-limited transmit beam is approximately 10 μrad, which results in a nominal 5-m FWHM footprint at a range of 500 km. The nominal peak transmit power is 600 W. The received signal, which contains both gross target Doppler shifts and vibration-induced frequency shifts is mixed with the 10-MHz offset LO. The heterodyne-detected signal is then converted to a fixed IF frequency by mixing the return with an estimate of the body Doppler frequency. This estimate may be obtained from a predicted satellite orbital track file, from a real-time estimate derived from the Doppler return signal, or from a real-time frequency estimate obtained from the Millstone L-band tracking radar. After further mixing to generate a baseband signal, the complex in-phase and quadrature (IQ) signal is digitized by using a 1.2-MHz analog-to-digital (A/D) converter and stored for subsequent processing. The 1.2-MHz A/D converter, which digitizes a 3.4-ms segment of the received signal, is triggered based on the predicted round-trip transit time.

The stability of the entire ladar system, including round-trip atmospheric propagation effects, has been obtained by estimating the frequency spread associated with a single retroreflector located on the GEOS III satellite (NORAD object #7734).[3] The results

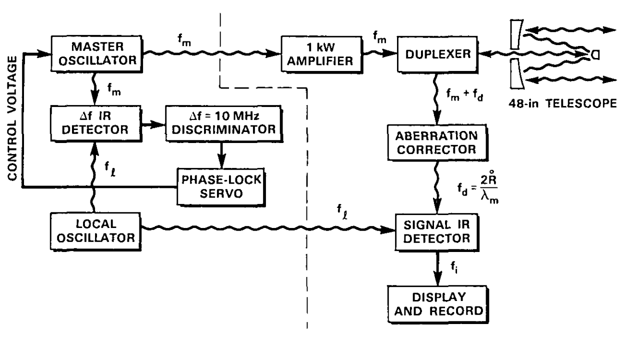

Fig. 2. Simplified block diagram of the pulsed cw CO_2 ladar facility.

suggest a short-term stability of better than 1.5×10^{-13} for a 7-ms round-trip duration. Doppler resolution is, however, limited by the 3.2-ms pulse duration; the radar achieves a Doppler frequency resolution of approximately 300 Hz, which corresponds to a velocity resolution of 1.6 mm/s at $\lambda = 10.59$ μm. A nominal resolution of 2.4 mm/s is obtained when the pulse is Hamming weighted before Fourier transformation.

Satellite tracking was accomplished with the aid of two additional radar systems: a pulsed cw Ar^+ laser multiplexed and boresighted with the CO_2 beam and the Millstone L-band tracking radar. The pulsed Ar^+ laser, operating at a PRF of 62.5 Hz, was used in conjunction with a quad monopulse photomultiplier-tube detector array to obtain a precise angular track on a visible retroreflector array located on the forward boom of the LACE satellite. The Millstone L-band radar supplied real-time target state vector information for target acquisition and tracking. In particular, target frequency information for range rate (Doppler) was used to help acquire and track the LACE satellite. A passive 60.96-cm (24-in.) visible tracker was used to acquire the target in angle; the target was observed during terminator passes, i.e., the sun-illuminated satellite was observed against a dark night sky.

3. Experimental Methods

A series of experiments were conducted to measure the forced vibrations present during boom retraction and the free-damped vibrations present subsequent to boom retraction. Observations were obtained within a (minimum FWHM) 5-m footprint that included both the lead-boom and the body retroreflectors; the trailing-boom retroreflector was fully extended to preclude observation. [The projection of the extended boom onto the cross-range area defined by the ladar line of sight (LOS) must lie within the ladar footprint. This, in conjunction with the geometry of the satellite trajectory with respect to the radar LOS, resulted in measurements with the boom extended beyond 5 m.] Observation windows for each pass were predetermined by NORAD. Before the onset of the allowed window, the boom, which was initially set at 24.4 m (80 ft), was retracted to 4.6 m (15 ft). The retraction was timed so that the boom stopped within the allowed observation window.

Boom-vibration measurements were obtained on January 7, 8, and 10, 1991. The data consisted of 3.4-ms of digitized IQ data received at a nominal 62.5-Hz rate during temporal observation windows of approximately 100 s. The quantity of interest, that is, the quasi-instantaneous velocity between the illuminated retroreflectors, is encoded in both the amplitude and frequency of the IQ data. In particular, the time-varying signal amplitude or envelope is a result of the coherent interference between two flood-illuminated retroreflectors. In this case, the amplitude modulation frequency is proportional to the relative velocity component between the two retroreflectors projected onto the ladar LOS. Alternatively, the net Doppler shift of each retroreflector (which corresponds to the Doppler shift induced by the net projected retroreflector velocity relative to the site LO) is imparted to the reflected signal. The amplitude and frequency encoding of the desired information has an impact on both the signal processing and the possible receiver architecture. The analysis presented here is based on frequency-encoded velocity information; the power spectra of the complex IQ time data is computed for each 3.4-ms digitized pulse (i.e., the magnitude squared of the complex 4080-point fast Fourier transform is computed for each received pulse). Each power spectrum contains two peak returns with associated difference frequency Δf, which is given by the following expression:

$$\Delta f = \frac{2v_r}{\lambda}, \tag{1}$$

where v_r and λ correspond to the relative velocity along the ladar LOS and laser wavelength, respectively. The desired boom vibration is obtained through a spectral analysis of the time evolution of the difference velocity between the two retroreflectors.

The relevant component of boom-tip motion is due to complex three-dimensional time-varying vibration modes. What the ladar ultimately measures, however, is the one-dimensional projection of the net boom-tip velocity relative to the satellite body onto the ladar LOS. This relative velocity between the boom tip and satellite body consists, in general, of three components: the desired vibration-induced velocity, the retraction/deployment velocity, and the velocity that is induced by rigid body motion between the lead boom tip and satellite body. Using detailed information regarding the satellite trajectory, we can compute the satellite orientation with respect to the ladar LOS and, with knowledge of the boom deployment/retraction rates, we may infer the vibration-induced component. This compensated vibration mode data collected from a given satellite pass represents mode data projected onto the ladar LOS. Theoretically the three-dimensional modal structure may be derived by applying reconstruction from projection techniques to a set of projection data obtained at multiple aspect angles. The practical implementation of this, which depends on both a large viewing angle and the repeatability of a given experiment, is not addressed here.

The following steps, based on the above considerations were used to obtain the projected boom-tip velocity as a function of time:

(1) Compute the power spectrum of each pulse.

(2) For each spectrum, detect two peak returns associated with the lead-boom and the body retroreflectors.

(3) Estimate the difference frequency (relative velocity) between retroreflector returns.

(4) Compensate for the boom-retraction rate and changing satellite aspect angle effects.

With the compensated boom-tip velocity computed in accordance with the above steps, modal frequency analysis proceeds as follows. For data collected during the boom retraction maneuver, a simple time-frequency analysis based on a short-time Fourier-transform technique is employed. In this case, the power spectrum of a moving Hamming window of a temporal duration equal to 24 s (corresponding to 1500 samples at the 62.5-Hz PRF) is computed at 0.1-s intervals. The effective frequency resolution ($\sim$0.06 Hz) and time resolution ($\sim$17 s) were selected on the basis of a qualitative analysis of the data; more sophisticated time-frequency analysis techniques are not discussed here.

The free-damped system vibration analysis proceeded along a somewhat path; as a detailed mechanical-dynamic model of the boom arm in free vibration exists, observations subsequent to boom retraction were analyzed by using two system identification techniques: an eigensystem realization algorithm[4] and a minimum model error- (MME-) based approach.[5] These techniques employ *a priori* information to achieve improved resolution with respect to conventional Fourier spectral analyses. As the results of both these analysis techniques were similar, only the MME results are reported here.

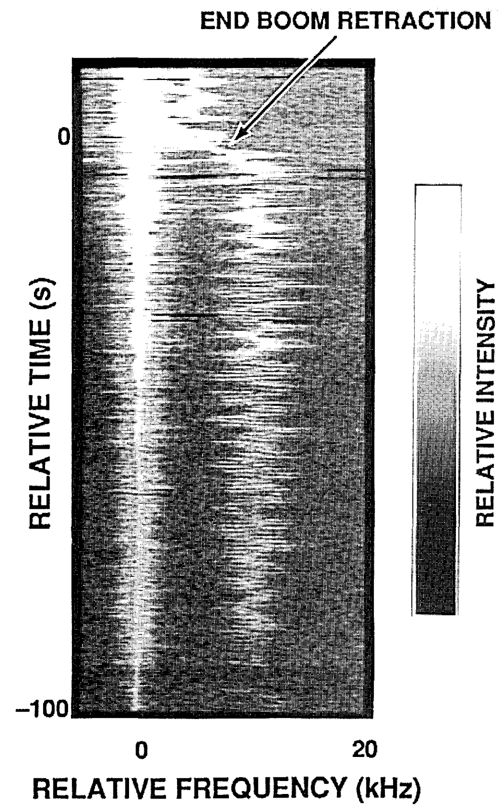

Fig. 3. DTI representation of data acquired on 8 January 1991. The data have been aligned to the peak return. Vibration effects are clearly evident. The step in the oscillatory trajectory coincides with the termination of boom retraction.

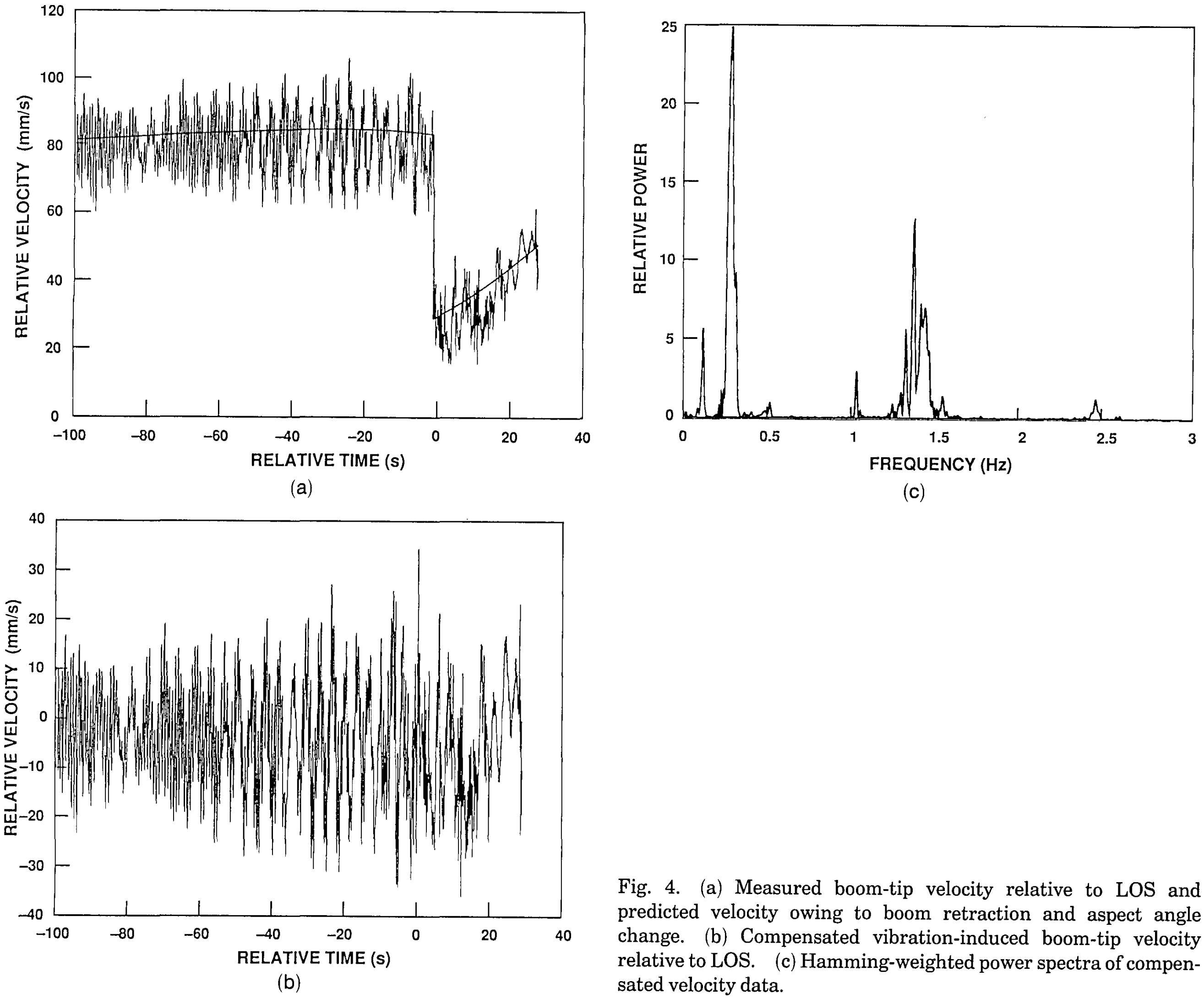

Fig. 4. (a) Measured boom-tip velocity relative to LOS and predicted velocity owing to boom retraction and aspect angle change. (b) Compensated vibration-induced boom-tip velocity relative to LOS. (c) Hamming-weighted power spectra of compensated velocity data.

4. Results and Discussion

Data were collected during terminator passes on January 7, 8, and 10 (days 7, 8, and 10) of 1991. Only data from days 8 and 10 are presented here. Measurments acquired during day 8 contain approximately 100 s of data taken during the boom retraction with another 35 s of post-boom-retraction data. These data are used to obtain a time-frequency analysis during the boom deployment period and a modal analysis for data subsequent to the retraction. Day 10 contain ~20 s of data taken during boom retraction and 60 s of data subsequent to boom retraction. We note here that the receiver generates artifacts near the zero-Doppler (or turn-around) point in the trajectory, which, in the case of day 10, occurred just before boom stopping. As a result, data from day 10 have been analyzed for the presence of free vibration modes only. (While day 7 data are not presented here, the results are completely consistent with data collected on day 8.)

A. Vibrations during Boom Retraction

The power spectra data associated with day 8 are shown in a Doppler-time-intensity (DTI) format in Fig. 3. Here the power spectrum from each 3.4 ms of digitized data is aligned and displayed along the vertical time axis. The horizontal axis corresponds to Doppler frequency (or velocity). The relative motion between the two retroreflectors manifests itself as an oscillatory curve in the DTI. For example, the end of the boom retraction is indicated by the step in the curve, and the presence of high-frequency vibration modes are apparent during the retraction.

The result of peak detection and subsequent temporal filtering yields the data shown in Fig. 4(a). (Median and low-pass filtering were employed.) Here the projected or apparent relative velocity between the boom tip and satellite body is plotted against time relative to the termination of the boom-retraction maneuver. (In this case, 0-s relative time corresponds to 81,600 s after midnight.) The com-

Table 1. Predicted and Measured Modal Frequencies

Predictions (Hz)	MME Results (Hz) 8 January 1991	MME Results (Hz) 10 January 1991
0.0191	—	0.0210 ± 0.0020
0.1298	0.1226 ± 0.0005	0.1245 ± 0.0011
0.3238	0.3248 ± 0.0006	0.3320 ± 0.0008
—	0.5201 ± 0.0030	0.5120 ± 0.0064

Table 2. Measured Modal Damping

Observed Modal Frequency (Hz)	MME Results (%) 8 January 1991	MME Results (%) 10 January 1991
0.02	—	1.39 ± 2.26
0.1	−0.35 ± 0.35	2.10 ± 0.30
0.3	1.11 ± 0.05	2.00 ± 0.30
0.5	4.59 ± 0.26	10.80 ± 1.02

bined rigid body and boom-retraction velocities are superposed onto the measured values. The residual vibration-induced boom-tip velocity shown in Fig. 4(b) is obtained after subtracting the nonvibrating velocity component and scaling the result to compensate for aspect angle variations during the observation window. A preliminary frequency analysis of the time series data is performed by Hamming weighting the data over the entire temporal window and computing the power spectrum. (The nominal resolution of the resultant spectrum is 0.01 Hz.) The result, presented in Fig. 4(c), indicates the presence of multiple vibration frequencies. Values of observed vibration frequencies are listed as follows: 0.12, 0.28, 0.51, 1.03, 1.25, 1.29, 1.31, 1.37, 1.41, 1.45, 1.55, and 2.46 Hz. The accuracy of these measurements has not been determined because of the limited number of observations.

The spectral peak at 1.03 Hz is close to the expected driving frequency of the boom-retraction mechanism. The 0.12-Hz mode is close to the predicted free-damped vibration mode of 0.13 Hz (see Table 1). The 0.28-Hz mode is relatively close to the predicted 0.32-Hz value. The slight bias between the observed and predicted values may be attributed, in part, to the fact that this mode appears to increase in frequency as the boom is retracted, a result suggested by the time-frequency analysis described below. The remaining modes have not been well modeled, and represent a new observation regarding on-orbit boom-vibration dynamics.

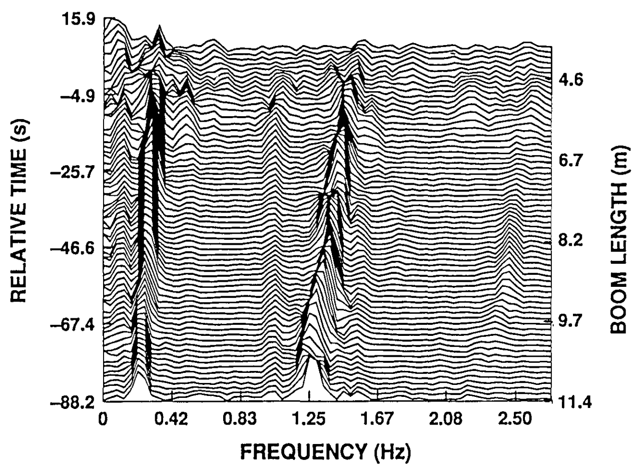

Fig. 5. Time-frequency analysis of vibration data obtained from the LACE satellite on 8 January 1991.

The time-frequency analysis of the data from day 8 is presented in Fig. 5. The data represented in this way clearly indicate that modes in the 0.28-Hz regime and in the higher 1.25-Hz–2.46-Hz regime increase in frequency as the boom retracts. Figure 5 also indicates the relative stability of the 1.03-Hz mode, a result that is consistent with the behavior of a constant drive mechanism.

B. Vibrations subsequent to Boom Retraction

The MME system identification algorithm was used to estimate vibration modes during the post-boom-retraction phase of data collected on January 8, 1991, and January 10, 1991. (The MME technique was employed as it provides improved resolution with respect to conventional Fourier spectral analyses.[5]) Statistically independent realizations of the observed process were obtained by taking advantage of the oversampled nature of the data. Results for measured modal frequencies and damping factors are given in Tables 1 and 2, respectively.

The results indicate reasonable agreement between measured and predicted modal frequencies. Measurements indicate, however, the presence of an additional mode at ~ 0.5 Hz, which was not predicted. This additional mode may be due to incomplete modeling or nonlinear dynamics. The small yet statistically significant bias between results from days 8 and 10 may be the result of a difference in boom orientation relative to the ladar LOS, a fundamental limitation on the repeatability of the experiment, nonlinear boom dynamics, or slight biases introduced by the compensation algorithm. The difference between damping factors measured on days 8 and 10 is relatively large. The source of these biases may be caused by the factors mentioned above. It should be noted, however, that mode amplitudes are more sensitive to the satellite orientation than are the modal frequencies, and are consequently more sensitive to bias errors introduced by the velocity compensation algorithm.

5. Summary

The LACE satellite vibration experiments have demonstrated the feasibility of measuring satellite vibrations from a ground-based coherent IR ladar with minimal impact on both the satellite construction and the on-orbit performance. Analysis of the ladar data indicates the presence of complex vibration modes during boom retraction. These data may prove useful in the development and validation of the next-generation modeling programs that are capable of accommodating a continuous excitation source. While the observed free-damped system vibrations were found to agree well with predictions, measurements indicate the presence of an additional vibration mode not previously predicted.

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