Microdynamic Behavior of a Joint-Dominated Structure On-Orbit

Marie B. Levine, Ph.D.
Interferometry Technology Program,
Jet Propulsion Laboratory
4800 Oak Grove Drive, M.S. 157-316
Pasadena, CA 91109, USA
tel: (818)354-9196 / fax: (818)393-1156
e-mail: marie.levine@jpl.nasa.gov

Abstract

The Interferometry Program EXperiments (IPEX) I and II are the first free-flying space experiments specifically designed to characterize the sub-micron ***dynamic*** behavior of large flexible structures subjected to on-orbit thermal and mechanical disturbances. These technology demonstration flight experiments are precursors to the 10-meter baseline Space Interferometry Mission (SIM) scheduled to launch in 2005, and will address the mission's nanometer-level structural stability requirements. Stringent microdynamic stability is also a key element for the success of the other optical space missions within the NASA ORIGINS program [1].

Of particular concern is the existence of transient impulses when space structures undergo rapid thermal variations, such as sun-to-shade transitions, or of other instabilities which can occur due to internal strain energy release mechanisms within joints or materials. This information is needed to characterize down to the nanometer level uncontrollable high-frequency vibrational disturbances and to validate structural designs and modeling approaches for optical performance prediction. Motivated by the joint instabilities observed during the Hubble Space Telescope mission, and the nanometer stability requirements of future optical platforms, recent ground test efforts have begun to investigate the microdynamic behavior of mechanisms in a 1-g environment [2, 3, 4]. Although the ground programs have been successful in identifying microdynamic behavior in certain hinges, joints and materials, there are concerns that gravity may obscure other classes of microdynamic instabilities.

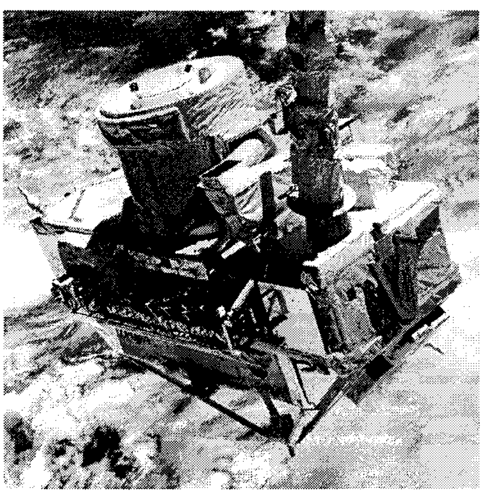

Figure 0. IPEX-II boom on Astro-Spas, prior to release from STS-85.

IPEX-II, performed aboard the German Daimler-Benz ASTRO-SPAS during the Space Shuttle STS-85 mission in August 1997, monitored the microdynamic behavior of a 9-bay, 2.5m, extrudable AEC-ABLE mast, typical of an architecture envisioned for SIM (Fig.1). This type of boom relies on steel cables to apply approximately 250-lbs of pre-load to the ball joints between each bay. There are 36 joints in all, plus various connections between the 6 base support struts, which form a kinematic mount to the Astro-Spas frame. The primary objective of the experiment was to determine whether transient snapping could occur even when joints were heavily pre-loaded, and to assess the microdynamic stability of the structure with respect to the SIM instrument requirements.

The instrumentation included 24 micro-g accelerometers, 24 collocated temperature sensors, 8 load cells, and 2 electro-magnetic shakers. The shakers were used to perform a series of burst- random and step-sine modal tests to determine the boom's dynamic and physical properties on-orbit. The custom-built 16-bit A/D electronics provided a 1000 Hz sampling frequency, with a measurement noise floor of about 1g RMS per 1Hz band up to 500Hz (Fig. 2.b.), and thus was sensitive enough to measure disturbances in the range of interest for precision opto-mechanical structures. Experiments were performed over 45 hours of free flight, and over 10 gigabytes of data was collected. All instrumentation performed as planned. This was an accomplishment in itself since the whole mission was performed in 8 months, from start to complete integration on the Astro-Spas, including Shuttle and Astro-Spas flight safety approvals.

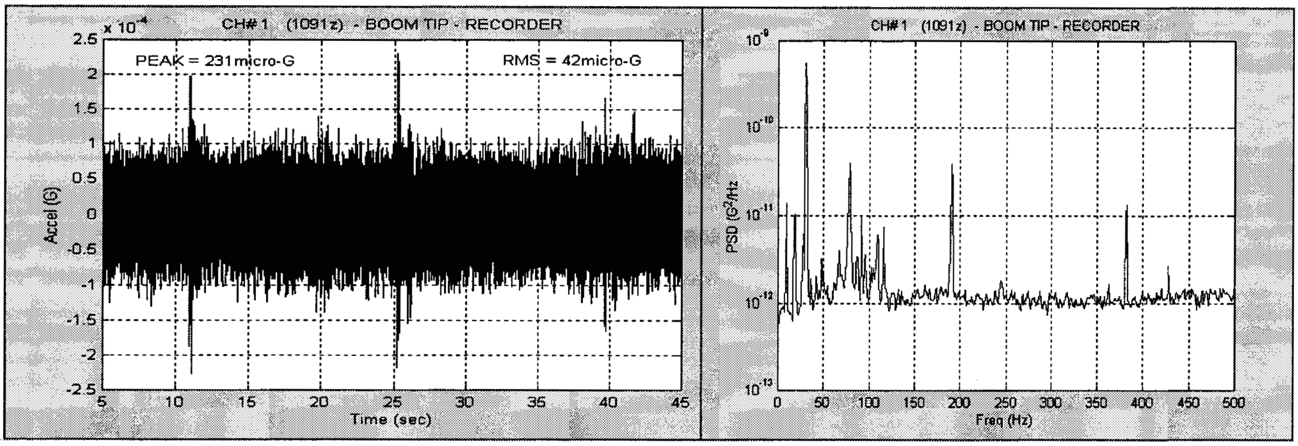

Figure 2. Acceleration time history (a) and PSD (b) measured along a transverse direction at the tip of the boom, for a 45-sec segment during the quiet period prior to shade-to-sun transition.

The paper will discuss in detail the objectives of the flight experiment, the mission scenario, the description of the mechanical properties and configuration of the experiment, the presentation of the analyses of the flight results, as well as comparisons to pre-flight tests performed on the boom. In particular the paper will focus on a "quiet" segment where the spacecrafts thrusters, gyros and payloads were inhibited during a shade to sun transition. During this period the only known active mechanical disturbance is the reel-to-reel tape recorder which produces periodic impulses at 15-second intervals (Fig. 2).

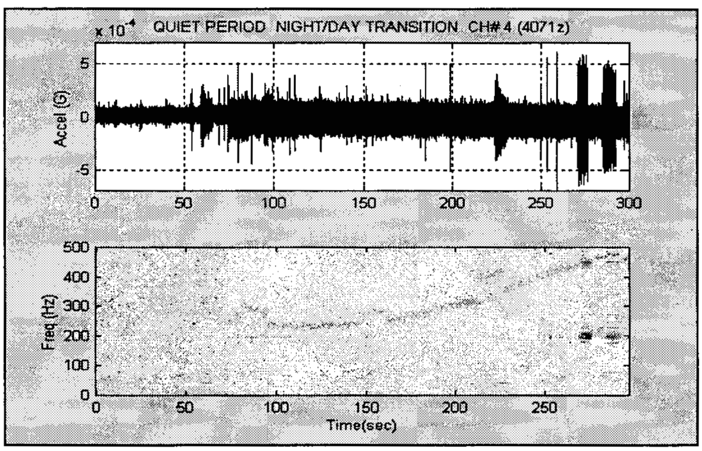

Figure 3. IPEX-II transverse boom response near tip during on-orbit "quiet" period. Night/day transition occurred at 30 seconds. Forced thruster pulsing sequence after 270 sec.

Contrary to common engineering judgement, the heavily pre-loaded boom did exhibit a multitude of transient snaps. Major snaps are observed immediately after the abrupt temperature change from -50deg C to 0degC, approximately 30seconds into the record (Fig. 3). Two major types of event stand out, an impulse with a single 42Hz mode decay at about 55 and 225 seconds, and persistent crackling starting at 74 seconds which continues through the duration of this segment. The crackling disappears 10 minutes later, when the next experiment was recorded. Furthermore, spectrograms show that the predominant frequency of the crackling is increasing with time. The paper will discuss possible sources for this puzzling behavior.

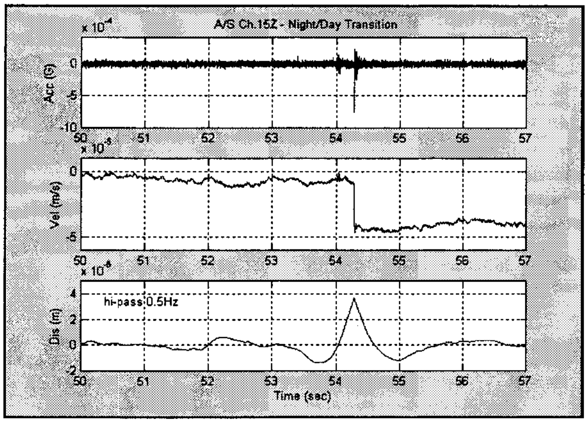

Figure 4. Transient impulse at the base of the boom with sudden 50μm/sec jump.

Some events are impulses with large instantaneous velocity jumps. One such occurrence is shown in Fig. 4. Synchronization of this particular event indicates that the snap originated near the base of the boom, and propagated along the boom with a rate consistent with the first axial mode of the boom at 95Hz. This particular event was double integrated in the time domain. Low frequency errors in the displacement due to unknown initial conditions and mean were removed with a high-pass filter at 0.5Hz. The signal displays a quasi-instantaneous velocity of about 50μm/sec, with a corresponding peak-to-peak displacement of about 5μm.

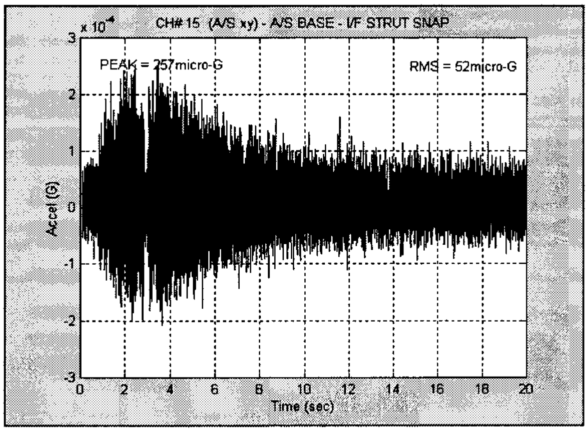

Figure 5. Transient snap and decay at interface strut *prior* to nigh/day

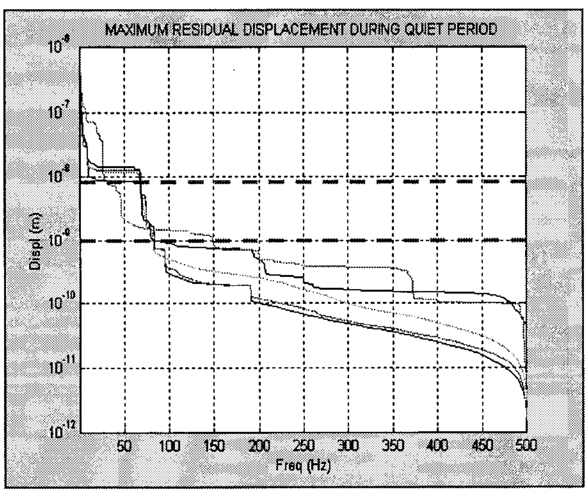

Figure 6. Maximum residual displacement for the IPEX II boom during the quiet period.

Although most snaps occurred immediately following the abrupt thermal change, some could also be observed prior to the event, as shown in Fig. 5. Snaps are a reflection of a local strain energy release in the system due to a change of internal load distribution. Applying heat to a structure is only one mechanism by which the internal force is redistributed within a structure. Other ways include moving large masses (e.g., optical delay lines), or reorientation with respect to the gravity field (e.g., spacecraft slewing). Furthermore, as for earthquakes, the strain energy release can occur over a long period of time after the initial change in load distribution, and the instability can be triggered by some other disturbance (e.g., thruster pulsing).

Nonetheless, it is also shown that the SIM broadband stability requirements have been met. The residual motion plot in Fig. 6 measures the RMS displacement up to 500Hz obtained by applying a controller with a specified closed-loop bandwidth frequency. For the IPEX-II on-orbit data the open-loop motion above 100 Hz is less than 10nm RMS, and above 200 Hz, the open-loop residual motion is less than 1nm. It should be noted that RMS requirements, while being appropriate for steady-state disturbances such as reaction wheels and gyros, do not accurately evaluate the effect of transients such as those observed in Fig. 5.

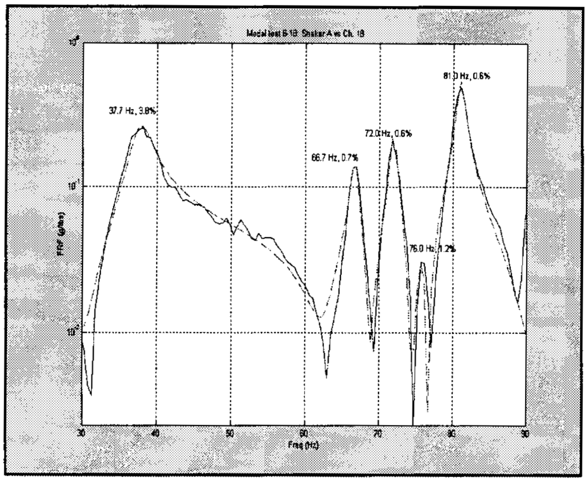

Figure 7. Modal identification of the IPEX-II on-orbit burst random tests.

Other experiment segments will also be presented, including thruster pulsing at specific rates for disturbance propagation analyses and multi-shaker on-orbit modal tests for identification of on-orbit structural properties (Fig. 7). Preliminary analysis shows that the damping of the first torsional mode at 38Hz increased from approximately 1% from pre-flight ground estimates, to almost 4% on-orbit. This trend is consistent with the MODE experiments performed inside the Shuttle [5].The cause of the large damping increase is still being investigated, and ground tests will be performed to assess the effect of cables. Nonetheless, such high damping values could have favorable impact on achieving on-orbit stability requirements to steady-state disturbances, such as reaction wheels.

The IPEX-II flight experiment has provided extremely valuable insight as to the microdynamic stability of large flexible structures in space. This unique data, which contains a wealth of information, will serve to further advance the field of structural dynamics for years to come. Results of the flight experiments are currently being augmented by a series of ground and flight experiments [6] which will enhance our understanding of structures and mechanisms at the microdynamic regime, and which will lead to improved design approaches and modelling techniques for high precision opto-mechanical flight systems.

REFERENCES

[1]. Naderi, F. "NASA's ORIGINS Program", *Proc. SPIE Astronomical Telescopes and Instrumentation Conference*, March 1998, Kona, Hawaii, SPIE 3350-125.

[2]. Warren, P.A., and Peterson, L.D., "Experimental Characterization of the Non-linear Post-Deployment Micro-Mechanics of Precision Deployable Space Structures", *Proc. Of the 37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Salt Lake City, UT, April 15-17, 1996.

[3]. Hachkowski, M.R. and Peterson, L.D. "Reduction of Hysteresis in the Load-Displacement Response of Precision Deployment Mechanisms Through Load-Path Management" Doctoral Dissertation. Report No. CU-CAS-98-07. May 1998.

[4]. Hinkle, J.D. and Peterson, L.D. "Frictional Microslip Due to Roughness in Metallic Interfaces at the Nanometer Scale" Doctoral Dissertation. Report No. CU-CAS-98-12. July 1998.

[5]. Crawley, E.F., Van Schoor, M.C., and Bokhour, E.B., "The Middeck 0-Gravity Dynamics Experiment – Summary Report", Report NASA-CR-45000, 1993.

[6]. Peterson, L.D., Lake, M.S., and de Luis, J., "Micron Accuracy Deployment Experiments (MADE): A Space Station Facility for Validating Precision Deployment and Active Control", *Proceedings of the Next Generation Space Telescope Technology Challenge Workshop*, Oxnard CA, June 5, 1998.