SSC10-VII-6

Eliminating the Need for Payload-specific Coupled Loads Analysis

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ABSTRACT

Through a project recently completed for Operationally Responsive Space (ORS), we have demonstrated the feasibility of a more efficient structural verification process for small satellites. This new process eliminates the need for payload-specific coupled loads analysis (CLA) and simplifies structural testing while not increasing mission risk. The process entails

- Derivation of appropriate physical constraints for the satellite (launch-vehicle payload) or the satellite's payload, including mass, center of gravity, envelope, and natural frequencies.
- Up-front, rapid performance of multiple cycles of CLA for one or more launch vehicles and selected combinations of the payload's variable physical properties within the derived constraints. (We refer to this analysis as "variational CLAs.")
- Derivation of equivalent, single-axis load cases that are at least as severe as the max/min results of the variational CLAs, for design and sine-burst testing of the payload's primary structure.

This process can be applied to multiple launch vehicles and variable combinations of small satellites in rideshare missions to provide flexibility, enable rapid integration, and accommodate late manifest changes. The process also can be extended to provide a loads envelope for spacecraft equipment or to reduce risk for large spacecraft.

The benefits of this process are simplified structural verification and reduced programmatic risk during hardware development.

INTRODUCTION

Coupled Loads Analysis (CLA), the process of predicting low-frequency dynamic loads for a launch vehicle (LV) and its payload(s), is time consuming and expensive. CLA is the main part of a ***loads cycle*** (Fig. 1), which also includes math-model development, mathematical coupling of models, and loads assessment. Each unique combination of LV and payload(s) typically requires at least two full load cycles, one during design and one just prior to launch using test-correlated math models. Some programs do five or six load cycles.

Although this traditional approach is technically justified, it is not efficient, as each loads cycle can take between three and twelve months, depending on the size of the payload (spacecraft) and how many organizations are involved. Alternatively, it is feasible (at least for relatively small payloads) to address the technical problem more efficiently regarding cost and schedule: Perform many CLAs up-front for a particular weight class of payload, with different combinations of physical properties for the payload(s) such that the full set of CLAs envelops a defined set of payload constraints. The highest loads resulting from this ***variational CLA*** then become the design and test loads for the spacecraft structure.

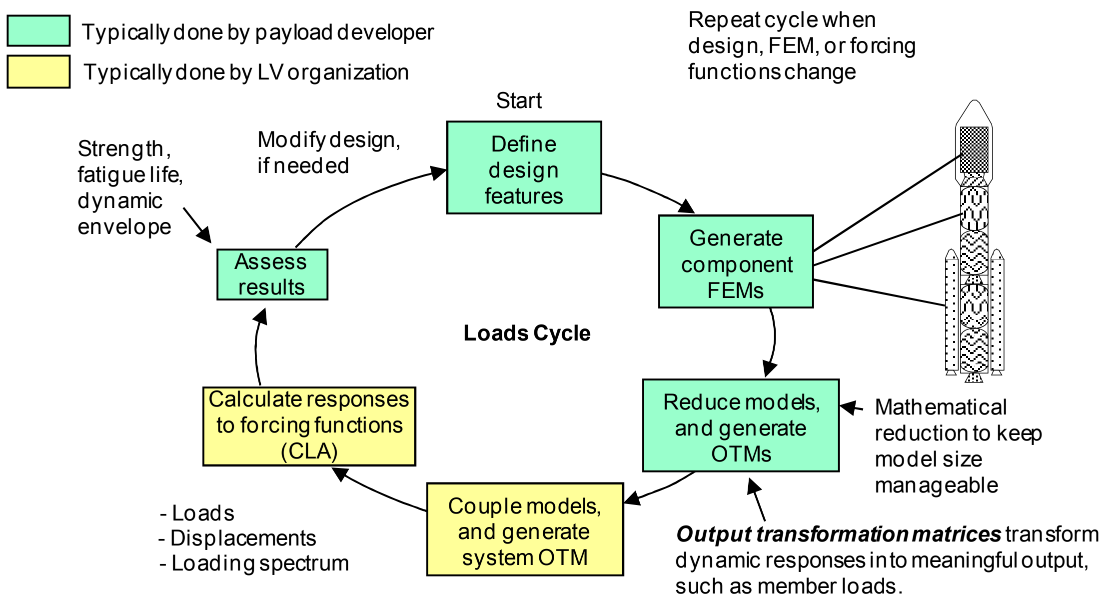

Figure 1: Loads Cycle.

Because small satellite structures are typically tested on a shaker, it is desirable to transform the loads envelope resulting from variational CLA into equivalent single-axis quasi-static loads, conducive to sine-burst testing. Doing so standardizes the structural test and thus eliminates engineering labor associated with designing a unique test.

With this approach, any payload meeting the constraints and passing the standardized structural test may be launched without dedicated CLA and without delivering finite element models (FEMs) to the LV organization, performing a modal survey test, and correlating FEMs with test results. Figure 2 summarizes the process of eliminating the need for payload-specific CLA.

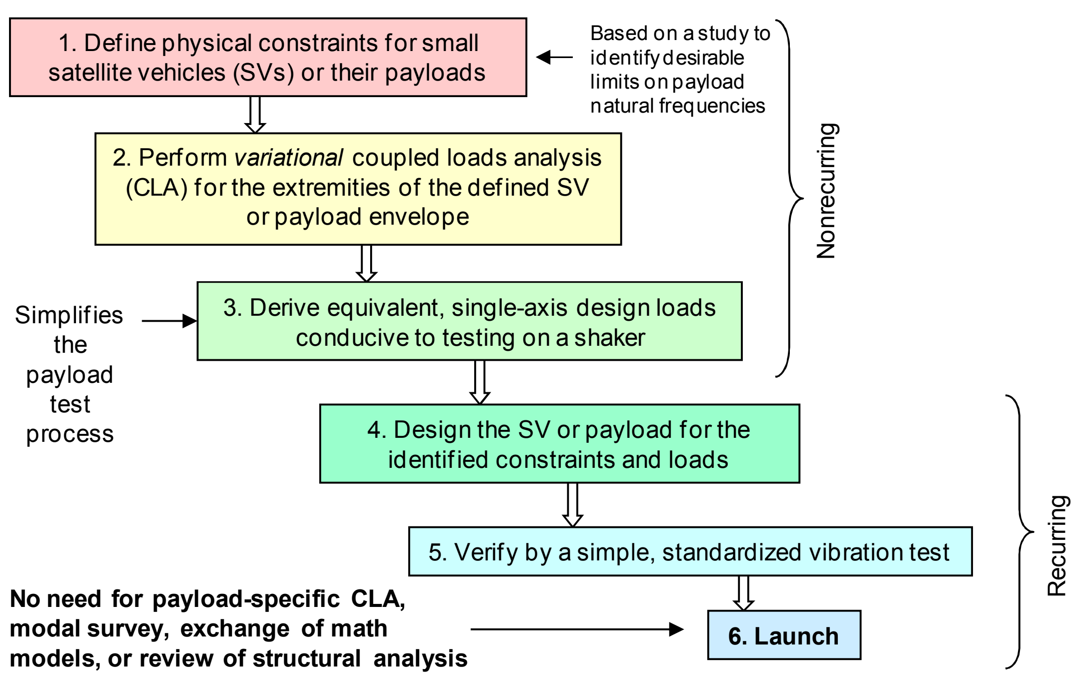

Figure 2: Process for Eliminating the Need for Payload-specific CLA.

There is no additional risk with this approach—and it can be argued that this approach actually reduces risk—but there is a weight penalty, as the payload must be designed to a loads envelope rather than to loads specific to that payload. The weight impact can be reduced by intelligently defining the payload's physical constraints based on knowledge of the LV's characteristics and forcing functions, in order to avoid high loads. Effective use of vibration isolation significantly reduces the loads envelope as well.

ORS PROJECT

We recently completed a study for Operationally Responsive Space (ORS) to demonstrate feasibility of the above process. The configuration studied was a non-variable spacecraft (S/C) bus with a variable payload (Fig. 3), which together form a satellite vehicle (SV) to be launched on a Minotaur I. Variational CLA was performed with and without a simple vibration isolation system to determine the benefits of such a system.

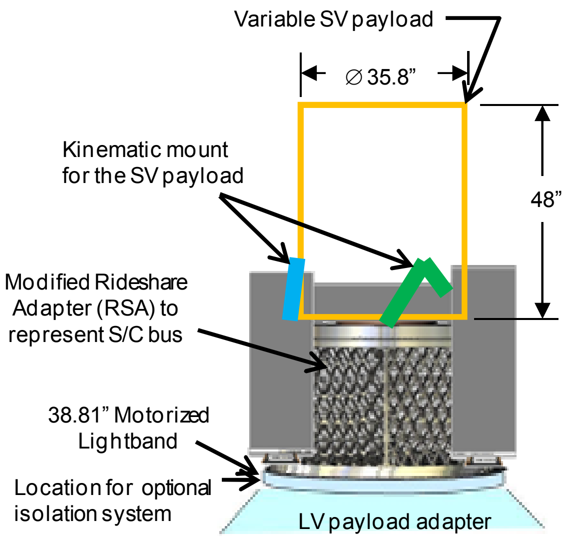

Figure 3: Configuration Studied.

We configured the Falcon 1 Rideshare Adapter developed by Design Net Engineering to represent a spacecraft bus, with all the typical equipment such as solar panels, propulsion system, battery, antennas, and electronics. Total weight of the bus, as used in the study, is 521 lb (236 kg mass). This bus configuration meets the preliminary bus constraints established by the Integrated Systems Engineering Team (ISET). With the SV payload also satisfying the preliminary ISET constraints, the resulting SV should be representative of typical ORS payloads.

The range of SV payload mass properties used in this study are as follows:

- Weight: 220 to 385 lb (100 to 175 kg mass)
- Center of gravity (CG) height, as measured from the mounting surface on the top of the bus: 10.0 to 19.1 inch for payloads at maximum mass and 10.0 to 33.0 inch for payloads at minimum mass (Note: In this study, the struts making up the kinematic mount were considered part of the payload.)
- Lateral CG offset from LV center: 1.0 inch
- Mass moments of inertia: selected to be consistent with envelope and CG

We developed finite element models (FEMs) of the bus and Planetary Systems Corporation's Motorized Lightband (MLB), and assembled them along with a rigid representation of the payload on a 3-point (kinematic) interface. Figure 4 shows the FEM's representation of the fundamental lateral mode of vibration for the stack, with the SV payload set at maximum mass properties. The 45.7-Hz natural frequency for this mode is based on a rigid SV payload. Introducing a spring to set the SV payload at a particular natural frequency in the lateral direction causes the natural frequency of the stack to drop below 45.7 Hz. The fundamental axial mode (not shown) has a predicted natural frequency of 52.4 Hz when the SV payload is rigid and set at maximum mass.

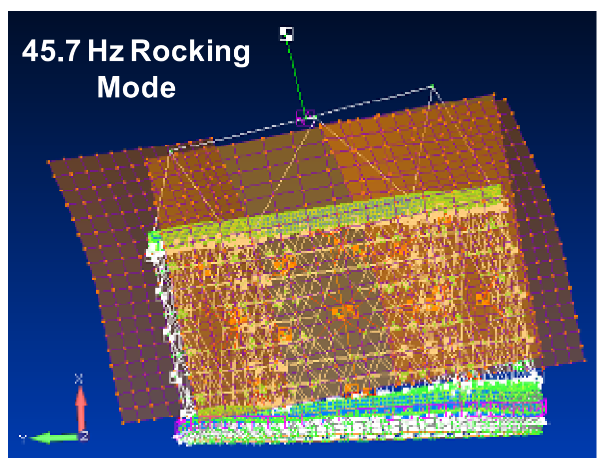

Figure 4: Fundamental Lateral Mode of the SV with Rigid Payload at Maximum Mass Properties.

Five flight events were included in the variational CLA for Minotaur I, with math models and forcing functions provided by Orbital Sciences Corporation:

- Pre-ignition (2 load cases)
- Liftoff (2 cases)
- Transonic (7 cases)

- Supersonic (8 cases)
- 2nd-stage Ignition (10 cases)

This makes five different configurations for the coupled math models and 29 total load cases for a full CLA.

To select appropriate constraints on natural frequencies for the payload, we performed a "pseudo-payload" CLA. We used the SV FEM shown in Fig. 4 but with the payload weight set at 309 lb (140 kg mass). To this model, we added a set of 0.5-lb translational oscillators with frequency varying from 1 to 85 Hz, in 1-Hz increments, in each axis. We then ran a full CLA, calculating response accelerations for the oscillators. Finally, we plotted the peak acceleration vs. frequency, one plot for each axis. Figure 5 shows the resulting spectra of lateral response accelerations for all flight events. The peaks in these plots indicate natural frequencies to avoid in order to prevent high payload accelerations during launch.

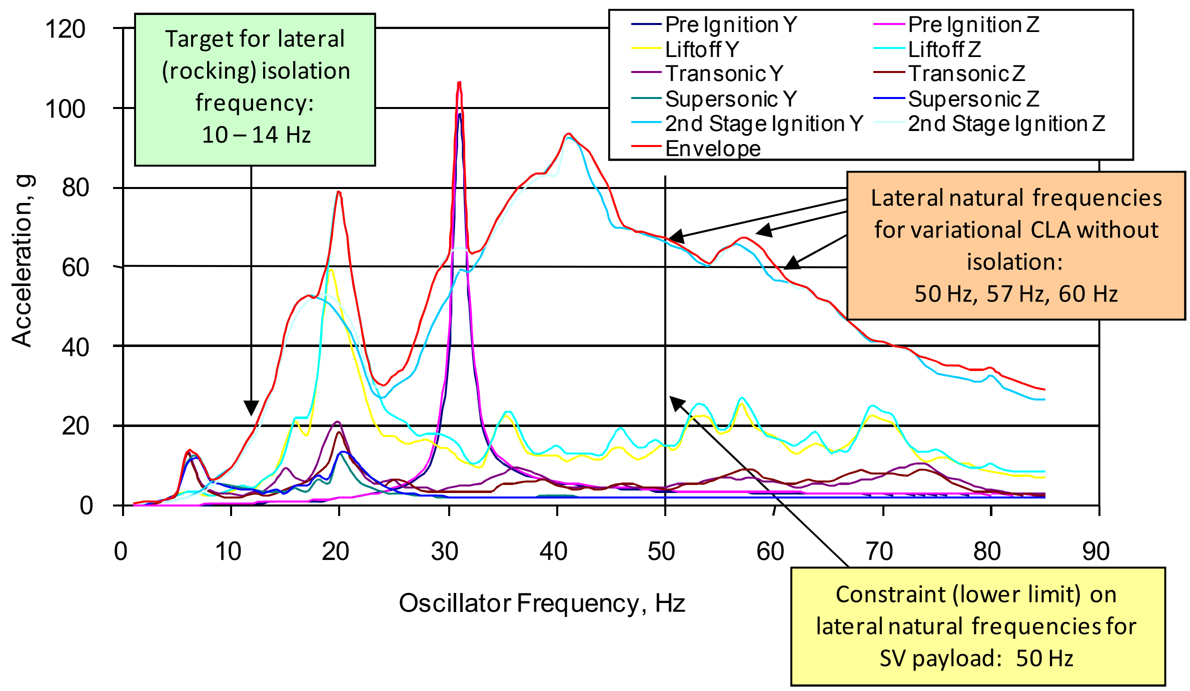

Figure 5: Results of Pseudo-payload CLA without Isolation—Maximum Lateral Acceleration of Oscillators vs. Frequency.

Based on the results of the pseudo-payload CLA, we identified the following constraints on payload natural frequencies:

- Axial frequency ≥ 60 Hz
- Lateral frequency ≥ 50 Hz

We selected several axial and lateral payload natural frequencies to run in the variational CLA, from the lower limit up to the 80-Hz truncation frequency used in Minotaur I CLA.

The pseudo-payload CLA also allowed intelligent selection of target isolation frequencies, i.e., lateral and axial natural frequencies to aim for when the SV-MLB assembly is mounted on a vibration isolation system:

- Axial: 10 to 40 Hz
- Lateral: 10 to 14 Hz

We used these target frequencies to identify the needed stiffness characteristics for a hypothetical isolation system. To ensure the isolation system is practical, we based the design on an array of off-the-shelf wire-rope isolators.

The variational CLAs were performed with Applied Structural Dynamics' proprietary software, ASD/CLAS. This software uses an innovative multi-body approach, which is conducive to rapid iterations with varying payload properties. The full variational CLA without isolation consisted of 90 separate CLAs, each performed with a different combination of payload mass properties and natural frequencies. Based on the results of the variational CLAs without isolation, we down-selected to 30 combinations for the variational CLAs with isolation.

Each CLA computed key response parameters, such as total force and moment at the payload-bus interface (base of the mounting struts), loads at the 3-point interface, and force in each of the six mounting struts. We referred to these parameters as "target parameters." ASD/CLAS generated tables of maximum and minimum values for each of these parameters and identified the combinations of variables leading to the max/min values.

The next step was to derive equivalent single-axis accelerations. The objective was to find three single-axis uniform accelerations—one in X, one in Y, and one in Z—that, if duplicated one at a time in sine-burst tests, would load each of the target parameters to the loads envelope from variational CLA. Table 1 shows the resulting single-axis load cases compared with actual max/min payload CG accelerations resulting from the variational CLA. As expected, the single-axis accelerations are considerably higher than the actual calculated accelerations because they were derived to load the structure as severely as the launch loads envelope, which includes the effects of multiple axes of acceleration (including angular acceleration) acting simultaneously.

Table 1: Results of Variational CLA and Derived Equivalent Single-axis Load Cases.

Configuration	Payload CG Accelerations (g), absolute maxima			Equivalent Single-axis Loads (g)	
	X	Y	Z	X	Y & Z
No isolation	12.9	10.9	11.9	13.3	22.9
Isolation	5.3	4.9	4.7	12.6	10.7

These loads are higher than we had hoped to see, especially in the lateral (Y and Z) directions. Clearly, isolation helps, but even then the loads are not benign. The basic approach is expected to generate design loads that are not optimum for any one design (the price of a robust-design philosophy and a simplified verification process), but we believe the high loads in this case are also a product of the configuration studied. With a kinematically mounted SV payload having a CG in plane with the three-point interface (one of the configurations included in the analysis), angular acceleration resulting from CLA causes a moment at that plane, whereas quasi-static acceleration does not. For such a configuration, the single-axis accelerations must be quite high to achieve all the target loads within the structure.

The final step was a partial validation of the process. We generated a configuration and a FEM of a hypothetical telescope assembly that meets the payload's physical constraints defined in this study. We set the weight at 385 lb, the axial CG at 19.3 inches above the bus top surface, and the lateral CG at 1.0 inch from the LV centerline. We tuned the FEM so its fundamental lateral (rocking) frequency is 50.3 Hz, with amplified motion of the secondary mirror, and its fundamental axial frequency is 61.8 Hz, again with amplified motion of the secondary mirror. We then mathematically reduced this model, coupled it with the bus and LV models, and performed full CLAs, with and without vibration isolation, computing loads for all the target parameters. Figure 6 shows the hypothetical payload (HPL).

We also subjected the HPL FEM to the derived equivalent single-axis load cases shown in Table 1. Table 2 shows absolute maximum loads for target parameters from the single-axis load cases (design loads) compared with absolute maxima from the CLA, without isolation. As can be seen, the design loads envelop the CLA results, as shown by all ratios being above 1.0, confirming that there is no need for a CLA for this payload if it is designed and tested to the single-axis load cases. Note, however, that the design loads are more severe than would be necessary if the payload-specific CLA is performed. Similar results and the same conclusions apply to the configuration including isolation.

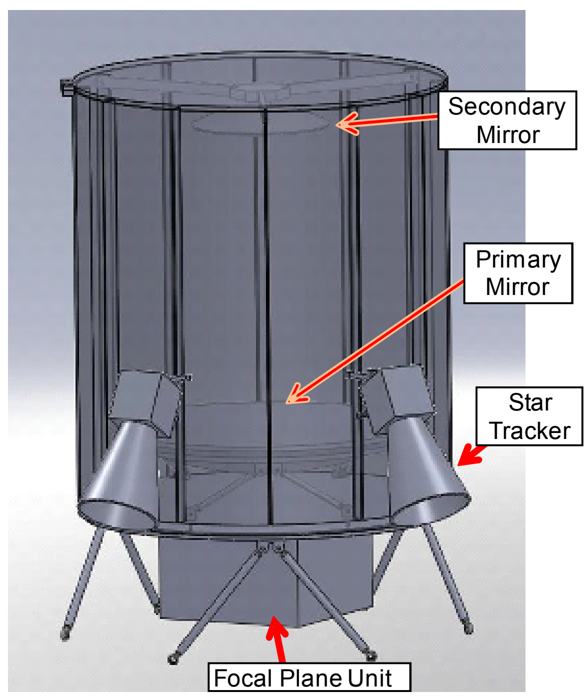

Figure 6: Hypothetical Payload (HPL).

Table 2: Comparison of HPL Design Loads with Payload-specific CLA Results (Absolute Maxima) Without Isolation. Units: lb, in.

Parameter	CLA	Design	Ratio
Mounting-strut force	2307	5088	2.21
3-pt interface axial (X) force	2400	3259	1.36
3-pt I/F lateral (tangential) force	1795	6056	3.37
HPL-to-Bus I/F loads:			
ΣF_x	1918	5132	2.68
ΣF_y	2821	8837	3.13
ΣF_z	3064	8837	2.88
ΣM_y	88391	170500	1.93
ΣM_z	82666	170500	2.06

CONCLUSIONS AND APPLICATIONS

The conclusion reached from the ORS project is that it is feasible to eliminate the need for recurring coupled loads analyses without incurring additional mission risk. To do so, up-front variational CLA must be performed to encompass the range of variables within defined constraints, whether for an SV payload, as demonstrated in this study, a small satellite riding as the sole LV payload, or a combination of small satellites riding as secondary payloads. The payload must be designed and tested to a bounding set of load cases that are applicable to the entire class of payload and are thus not optimal for any one. For this reason, the demonstrated approach becomes less practical as payload size increases because weight typically becomes more critical with increasing payload size and complexity.

Vibration isolation significantly reduces the resulting design loads and thus makes the process we have demonstrated more practical. Use of isolation may enable the process to be extended successfully to larger payloads.

We recognized during the study that, although the process was sound for the payload's primary structure, we did not address local component modes or panel modes. We recommend that, for any follow-on project such as this, the process be extended to include variations that would enable development of mass-acceleration curves for design of SV components.

Potential applications and extensions of this process include the following:

- Eliminating the need for recurring CLAs for LV payloads of a certain weight class (probably less than 1000 lb to be practical) and for one or more selected LVs.
- Eliminating the need for recurring CLAs for various manifest configurations of secondary payloads on rideshare missions. (With this goal in mind, variational CLAs would account for uncertainties in number, mass, and natural frequencies for the secondary payloads.)
- Reduce the number of needed loads cycles for large payloads and reduce program risk by performing variational CLAs to account for uncertain modes of vibration. (Here it is assumed that there are too many variables for variational CLAs to provide the necessary confidence for eliminating payload-specific CLAs. Instead, variational CLAs would be used to establish appropriate loads uncertainty factors for various zones within the payload, thus allowing a more weight-efficient design and reducing the likelihood of loads increasing in the verification CLA.)

Acknowledgments

We wish to thank ORS for having enough confidence in us to fund this project; Orbital Sciences Corporation for providing math models, forcing functions, and technical support; and Steve Buckley of ORS and Reggie Alexander of NASA Marshall Space Flight Center for their leadership and support throughout the project.