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ANALYSIS OF INTELSAT V FLIGHT DATA*

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Abstract

This paper summarizes results of an extensive evaluation of the INTELSAT V spacecraft flight data carried out by COMSAT Laboratories for INTELSAT. A structural loads data base for the INTELSAT V was assembled including actual flight measurements, coupled loads analysis predictions, and environmental test loads. The flight measurements incorporate both accelerometer and strain gauge signals transmitted during eight Atlas/Centaur and two Ariane launches of the INTELSAT V satellites. An evaluation of the loads data base placed primary emphasis on a comparison of coupled loads analysis predictions with statistically based flight loads.

The predictions of axial acceleration at the spacecraft/launch vehicle interface were found to be accurate. However, the lateral loads predicted by the coupled loads analysis were overly conservative. Several discrepancies between the structural analysis and the flight measurements have been revealed. The influence of the spacecraft's dynamic characteristics on interface motions can be readily observed in the data.

Introduction

The launch loads for a spacecraft are normally determined by a coupled launch vehicle/spacecraft dynamic analysis. Accurate prediction of launch loads is important to avoid structural failures during launch while simultaneously reducing overdesign and overtest. This prediction has been complicated by an increase in spacecraft mass, size and flexibility with resulting spacecraft/launch vehicle dynamic interaction.

The coupled loads analysis (CLA) is typically performed early in a spacecraft program. The mathematical models of the spacecraft and the launch vehicle are coupled together and load cases representing critical flight events are analyzed. A factor of safety is applied to the loads calculated from this analysis to determine the design loads. As the spacecraft program matures, the structural modeling is upgraded and the launch loads are updated. COMSAT's evaluation of the INTELSAT V flight data provides insight into the actual flight environment and comparison of this environment with the analysis.

One of the primary objectives of the launch data analysis for INTELSAT V is to evaluate a major issue in spacecraft structural design and testing. How well do the measured flight loads compare with the coupled loads analysis? Can fundamental structural dynamic behavior be observed in the flight data? This dynamic interaction has been used as the basis of a simpler method which has been developed to update launch loads.[1]

INTELSAT V Flight Data

INTELSAT spacecraft, beginning with the INTELSAT IV program, have been instrumented to measure launch loads. Each INTELSAT V satellite has a pair of lateral accelerometers and strain gages. The sensor deck of the antenna tower contains a pair of lateral response accelerometers. The spacecraft/launch vehicle adaptor has a pair of strain gage bridges to measure bending moment near the launch vehicle interface (Figure 1). In addition, the launch vehicles are instrumented near the interface with the spacecraft. General Dynamics has equipped the Atlas/Centaur with three accelerometers: longitudinal, yaw, and radial. Arianespace has equipped the Ariane with four accelerometers, one of which is a longitudinal accelerometer near the vehicle interface.

This effort encompassed a comparison of peak accelerations and bending moment predicted by the CLA with those actually measured in flight. Furthermore, the influence of the spacecraft's dynamic characteristics upon the interface motions was evaluated with a frequency domain analysis.

Analyzing the flight data gathered on the INTELSAT V generation satellite and comparing it with the coupled loads analysis permits determination of an analysis margin, defined as:

$$\text{analysis margin (AM)} = \frac{\text{coupled loads analysis predictions}}{\text{flight data measurements}}$$

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The actual margin of safety in terms of structural loads is the factor of safety multiplied by the analysis margin. Currently it is assumed that the analysis margin = 1. Determination of an analysis margin will define the actual margin of safety for structural loads, and show whether a factor of safety of 1.5 is overly conservative.

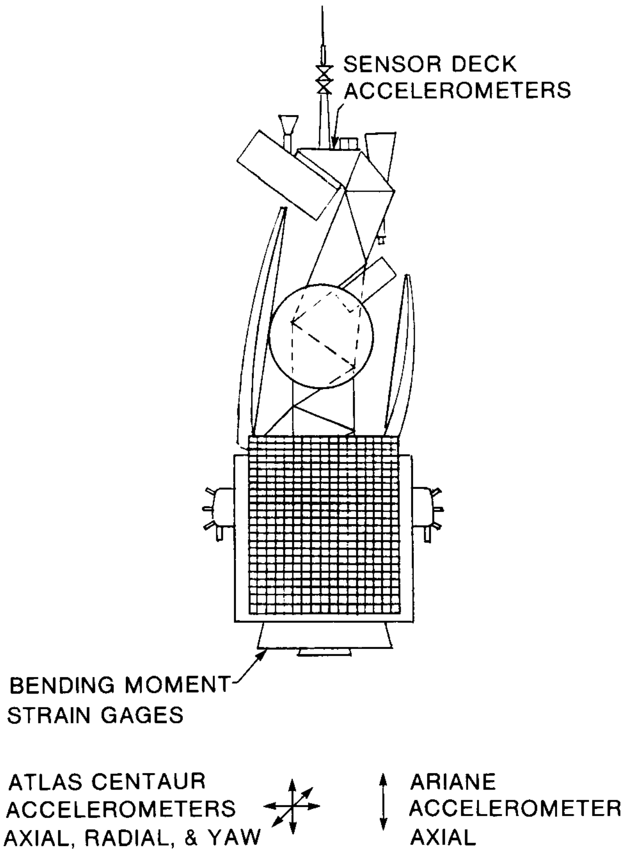


Figure 1. INTELSAT V Instrumentation Location

The analysis of INTELSAT V flight data was accomplished in two phases. The first phase of the project consisted of the decision to instrument flight spacecraft and the subsequent data collection for 10 consecutive flights over 6 years. A data base was assembled summarizing the INTELSAT V launch related loads. This data base consisted of the following data:

a. the measured flight data from the first 10 INTELSAT V launches;
b. the results from the coupled loads analysis for the Atlas/Centaur, Ariane, and STS launch vehicles; and
c. the spacecraft environmental test loads.

Actual flight measurements were recorded for eight Atlas/Centaur launches and two Ariane launches.

The second phase was the evaluation of the launch loads data base. The launch loads data were analyzed to compare the flight loads with both the CLA predictions and the environmental test loads. As part of the evaluation, various methods were used to determine how the spacecraft dynamic characteristics influence interface motions.

Comparison of Flight Data With Analytical Predictions

Peak values were used to compare the flight data with the CLA predictions. Maximum non-time-correlated peak accelerations and bending moments were obtained from the CLA for comparison with upper tolerance limits (UTLs) derived by statistical techniques from the Atlas/Centaur measured flight data. Since the flight loads data base included only two Ariane launches, the upper tolerance limit would be unrealistic; therefore, the peak flight measurement without statistical accuracy was compared with the CLA results. The environmental test loads included both qualification and acceptance testing levels. The comparison has been summarized in Figure 2. Table 1 summarizes the peak acceleration and peak bending moment for several flight events.

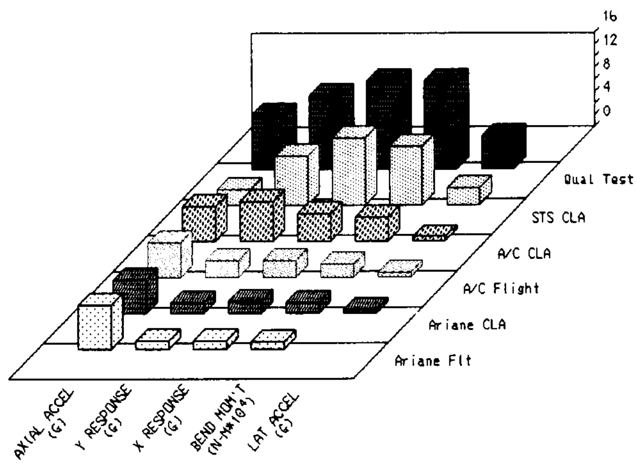


Figure 2. Peak Acceleration Comparison

Atlas/Centaur Comparison

The flight data UTL values derived from the Atlas/Centaur launches were compared with the coupled loads analysis (CLA) peak values. The upper tolerance limit was derived for 3σ, 50-percent confidence from Reference 2. This UTL definition was chosen because it provided a means of bounding the upper extreme with a limited amount of samples. The CLA predictions varied from accurate to conservative relative to the Atlas/Centaur flight data. The maximum axial acceleration at the base of the spacecraft was predicted very accurately, with an analysis margin of approximately unity. The CLA results, however, predicted loads that exceeded the flight data UTL and the analysis margin was >2 for lateral acceleration at the base of the spacecraft, response acceleration of the sensor deck, and bending moment at the separation plane.

Table 1. INTELSAT V Flight Loads Peak Acceleration Upper Tolerance Limit (g)

Description	Event	Average	Standard Deviation	UTL*	Peak	CLA
Centaur axial acceleration	BECO	5.4	0.20	6.0	5.7	6.0
	BPJ	1.4	0.07	1.6	1.5	1.8
	MECO	3.7	0.27	4.6	4.1	4.1
	Max αQ	2.9	0.13	3.3	3.0	2.2
Ariane axial acceleration	LO	6.8	1.2	12.2	7.6	n/a
	FSCO	4.6	0.57	7.2	5.0	5.4
	SSCO	5.1	0.57	7.7	5.5	5.8
	Max αQ	4.0	0.50	6.2	4.3	2.7
Centaur yaw x-axis lateral acceleration	LO	0.41	0.08	0.67	0.59	n/a
	BECO	0.11	0.02	0.16	0.14	0.56
	BPJ	0.21	0.02	0.29	0.25	0.42
	MECO	0.33	0.07	0.56	0.43	0.30
	Max αQ	0.26	0.03	0.34	0.32	0.44
	IPJ	0.54	0.07	0.75	0.65	n/a
	JF	6.50	0.06	0.69	0.59	n/a
Centaur radial y-axis lateral acceleration	LO	0.26	0.04	0.39	0.34	n/a
	BECO	0.22	0.05	0.39	0.31	0.75
	BPJ	0.18	0.04	0.32	0.25	0.53
	MECO	0.26	0.09	0.57	0.35	0.33
	Max αQ	0.27	0.06	0.46	0.41	0.44
	JF	0.46	0.05	0.62	0.55	n/a
Spacecraft x-axis response acceleration	A/C LO	1.7	0.36	2.9	2.2	n/a
	BECO	0.63	0.09	0.93	0.72	4.8
	BPJ	1.1	0.10	1.4	1.2	3.8
	MECO	1.2	0.31	2.3	1.6	1.6
	A/C Max αQ	0.81	0.24	1.6	1.2	3.5
	IPJ	1.24	0.12	1.6	1.2	n/a
	JF	0.91	0.36	2.1	1.4	n/a
	Ariane LO	1.0	0.41	2.8	1.3	n/a
	FSCO	0.91	0.01	1.0	1.0	
	SSCO	1.2	0.21	2.1	1.3	2.0
	Ariane Max αQ	1.45	0.07	1.8	1.5	1.8
Spacecraft y-axis response acceleration (G)	A/C LO	1.2	0.14	1.7	1.4	n/a
	BECO	1.4	0.43	2.8	2.0	6.7
	BPJ	1.2	0.26	2.0	1.7	5.1
	MECO	1.2	0.32	2.2	1.6	1.8
	A/C Max αQ	0.7	0.09	1.0	0.85	3.9
	JF	0.9	0.07	1.1	1.0	n/a
	Ariane LO	1.05	0.05	1.28	1.1	
	FSCO	1.1	0.07	1.4	1.2	
	SSCO	0.98	0.31	2.4	1.2	
	Ariane Max αQ	1.4	0.0	1.4	1.4	1.9
Spacecraft bending mount (KNM)	A/C LO	10.0	2.0	16.0	13.0	n/a
	BECO	11.0	3.7	23.0	18.0	41.0
	BPJ	10.0	1.0	14.0	12.0	38.0
	Ariane LO	7.5	6.7	10.6	8.0	n/a
	FSCO	10.0	3.4	25.1	13.0	4.2
	SSCO	10.0	1.4	15.8	11.0	2.2
	Ariane Max αQ	9.0	0.5	11.4	10.0	18.0

n/a: not analyzed, this load case was not analyzed in the coupled loads analysis.

When individual load cases from the Atlas/Centaur CLA are compared to actual flight events, certain discrepancies are revealed. The CLA results predict booster engine cutoff (BECO) to be the worst-case event for all five of the load cases considered in this investigation. The flight data reveal that BECO is the most severe event for only three of the five loads. Events not considered in the CLA--liftoff (LO), insulation panel jettison (IPJ), and nose fairing jettison (JF)--were found to be the dominant lateral load conditions. In all cases, the flight UTLs were equal to or less than the BECO accelerations predicted by the CLA.

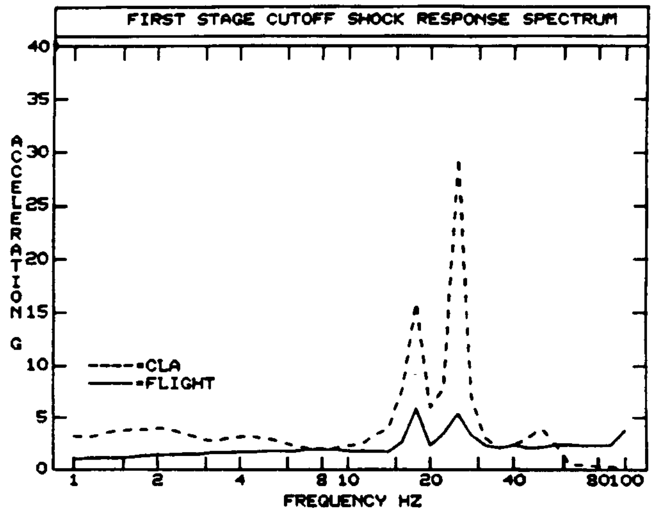
Ariane Comparison

The flight data peak measurements were compared with the Ariane coupled loads analysis peak prediction. Since the data included only two Ariane launches, the UTL is unrealistic and the absolute peak measurement from the two flights was compared with the CLA results. The CLA predictions enveloped the flight measurements for the analyzed events. However, the lift-off environment, which was not analyzed in the coupled loads analysis, produced the highest peak axial acceleration, higher than the CLA prediction!

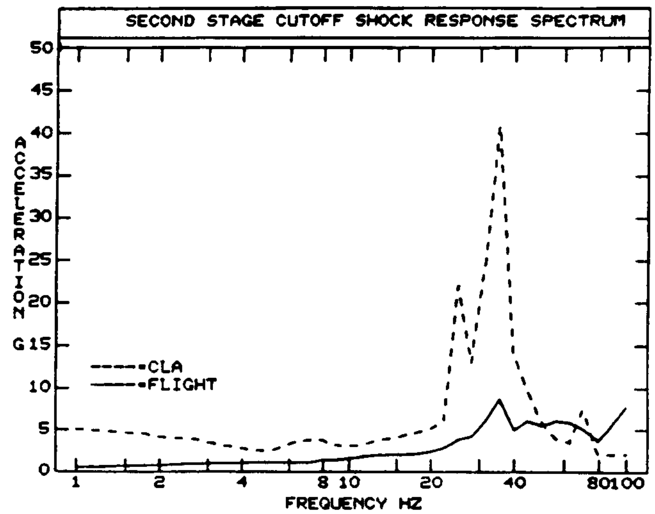
The accelerations measured during lift-off appear to be high. The acceleration time history was filtered with a low-pass filter, and processed to determine the peak. For spacecraft FM-8, the 100-Hz filtered peak was 7.6 G. As the cutoff frequency of the low-pass filter was reduced, the acceleration also decreased, with a peak of 3.75 G for 50-Hz and 2.25 G for 20-Hz filters. The lift-off environment also produced both bending moments at the separation plane and acceleration response at the sensor deck. Lift-off was not the most severe event for these lateral loads.

In evaluating individual Ariane load cases, the CLA again does not predict the load case which is the most severe. The CLA results predict that maximum aerodynamic pressure (Max αQ) will produce the most severe bending moment at the separation plane. Although the bending moment predicted by the CLA encompasses the highest measured bending moment, the measured data indicate that both first and second stage cutoff produce a greater bending moment than Max αQ. The Ariane CLA grossly underestimated bending moment for first and second stage cutoff.

The Ariane axial acceleration was examined by comparing shock response spectra (SRS). The Ariane CLA provided SRS for the first and second stage cutoff events. Shock response spectra were computed for these same events from the measured axial interface acceleration. An SRS which envelops the two Ariane launches was developed and compared with the CLA predicted SRS (see Figure 3). The analysis predicted the energy distribution for the first stage cutoff below 40 Hz. The second stage cutoff CLA SRS has peaks at ~27 Hz and ~37 Hz, while the flight SRS only has a peak of ~37 Hz. The magnitude of the SRS peaks was overestimated by the coupled loads analysis SRS.



a. First Stage Cutoff Shock Response Spectrum (Q = 50)



b. Second Stage Cutoff Shock Response Spectrum (Q = 50)

Figure 3. Cutoff Shock Response Spectrum

Environmental Test Loads Comparison

For the lateral test loads, the qualification test data were extremely conservative when compared to the flight measurements. This is due to the Shuttle CLA, which dominates the lateral loads. The axial qualification static test produced loading in excess of the Ariane lift-off peak. The acceptance testing of each flight vehicle included two flight environments for the lateral axes. The axial loading of flight spacecraft during acceptance tests is less severe than in the flight environment, but the axial acceptance test was never intended to fully load the primary structure.

The INTELSAT V environmental test program considered three launch vehicles: the Space Transportation System (Shuttle), Atlas/Centaur, and Ariane. The lateral test loads were dominated by STS compatibility. It is therefore understandable that the lateral qualification and acceptance test loads appear excessive when compared to Atlas/Centaur and Ariane lateral flight data.

Spacecraft Dynamic Characteristics

The launch data were examined to determine how the spacecraft dynamic characteristics influence the interface motions. The spacecraft response frequencies were recovered from the Atlas/Centaur flight data via a transfer function. This transfer function was computed with the Centaur spacecraft interface lateral acceleration as the input and the spacecraft's sensor deck lateral acceleration as the output. Selected transfer functions for the INTELSAT V F-4 BECO event along with the corresponding interface acceleration are shown in Figure 4.

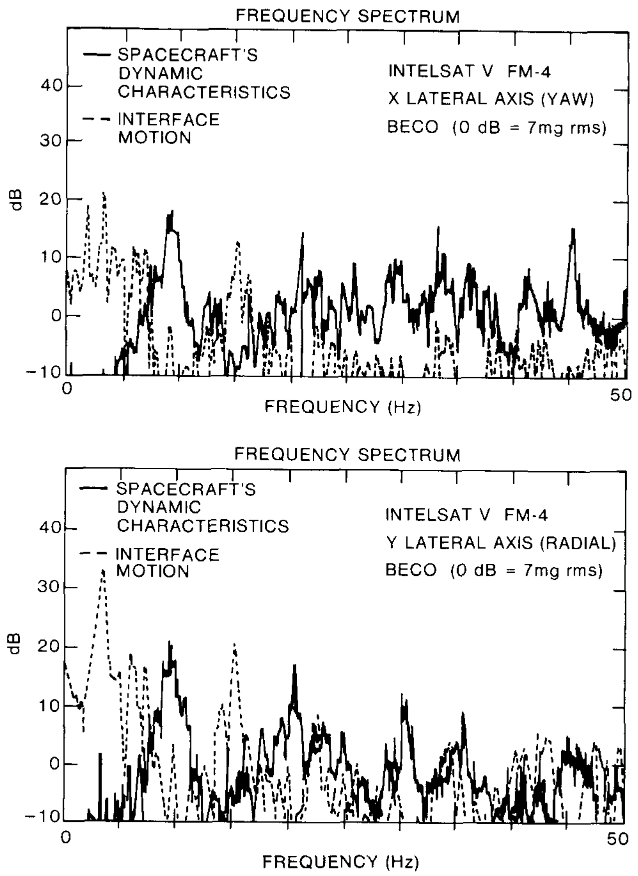


Figure 4. Frequency Spectrum

The transfer function displays energy primarily around 8-10 Hz and 20-22 Hz for the lateral axes. This corresponds to the lateral frequencies of the spacecraft. It is evident that the interface acceleration spectrum does not contain significant energy in these frequency ranges. The dynamic characteristics of the spacecraft influence the interface motion by absorbing energy at the spacecraft frequencies. This phenomenon, seen in the INTELSAT V flight data, is the basis of the approach to updating spacecraft launch load predictions outlined in Reference 1.

Conclusion

The launch loads measured during the first 10 INTELSAT V spacecraft launches have been compiled and analyzed. A comparison of the coupled loads analysis predictions and the measured flight loads found the analysis margin to be approximately 1 for peak axial acceleration and between 1.25 and 2.25 for the lateral loads considered. Both the Atlas/Centaur CLA and the Ariane CLA overpredicted the lateral loads. The particular flight event that produces the most severe lateral loading was not always predicted by the CLA. Some flight events not considered in the coupled loads analysis are found to be significant.

The Ariane lift-off event for the INTELSAT V spacecraft was found to be a dynamic environment. The peak axial acceleration measured on the FM-8 lift-off exceeded the Ariane quasistatic design load factor. There was a wide scatter in the two Ariane launches, making it difficult to draw strong conclusions. However the Ariane lift-off environment merits further investigation.

The effects of the spacecraft's characteristics are evident in the interface accelerations. The lateral interface acceleration does not contain significant energy in the frequency range corresponding to the spacecraft's natural frequency. The INTELSAT V flight data confirm this well-known phenomenon.

References

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