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ENVIRONMENTAL TESTING PHILOSOPHY FOR A SANDIA NATIONAL LABORATORIES' SMALL SATELLITE PROJECT – A RETROSPECTIVE*

Jerome S. Cap
Sandia National Laboratories

ABSTRACT

Sandia has recently completed the flight certification test series for the Multi-Spectral Thermal Imaging satellite (MTI), which is a small satellite for which Sandia was the system integrator. A paper was presented at the 16th Aerospace Testing Seminar discussing our plans for performing the structural dynamics certification program for that satellite. Our testing philosophy was originally based on a combination of system level vibroacoustic tests and component level shock and vibration tests. However, our plans evolved to include computational analyses using both Finite Element Analysis and Statistical Energy Analysis techniques. This paper will outline the final certification process and discuss lessons learned including both things that went well and things that we should/could have done differently.

KEYWORDS

Environmental, Testing, Analysis, Satellite

INTRODUCTION

Every satellite program is faced with the question of how much testing and analysis should be done to certify that the design is robust and that the manufacturing and assembly processes are performed correctly. A paper was presented at the 16th Aerospace Testing Seminar [Cap and Rackley 1996] discussing the plans for certifying the MTI satellite for which Sandia National Labs was the system integrator.

Now that MTI has been successfully launched and is functioning on orbit, it seemed appropriate to report on the results of the MTI structural dynamics test and analysis programs and the lessons learned. Six topics of interest will be discussed: 1) identification of initial test specifications, 2) preliminary finite element modeling, 3) component analysis and testing, 4) coupled loads analysis, 5) statistical energy analysis, and 6) equivalent static loads testing.

When reading this paper, the reader should note that the term "satellite" refers to MTI, while the term "payload" refers to all payloads.

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OVERVIEW OF TESTING AND ANALYSIS EFFORTS

Our original certification process underwent several unexpected changes in direction as a result of new information and our increase in understanding of how the satellite responded. Figure 1 presents a schematic showing the flow of the final test and analysis program.

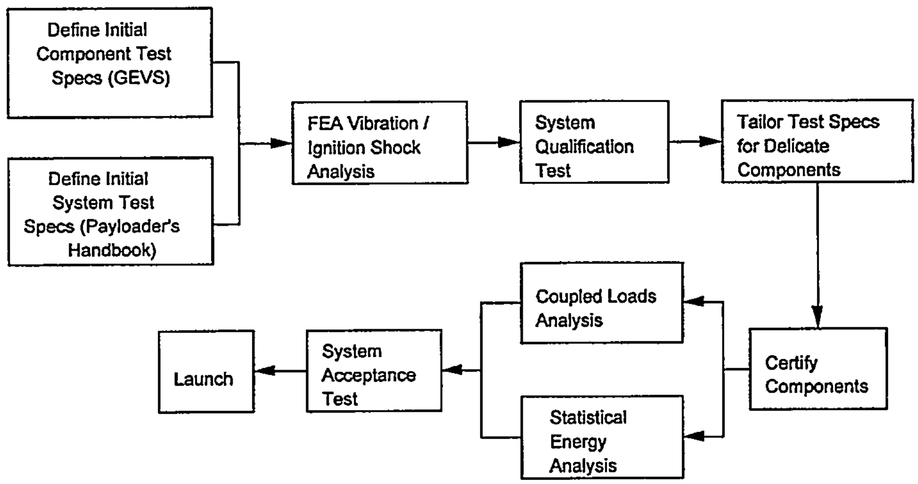

Figure 1: Summary of Final Test and Analysis Plan

Figure 2 presents an isometric view of MTI. The tags in this figure refer to accelerometer locations for which we measured data during the qualification test series.

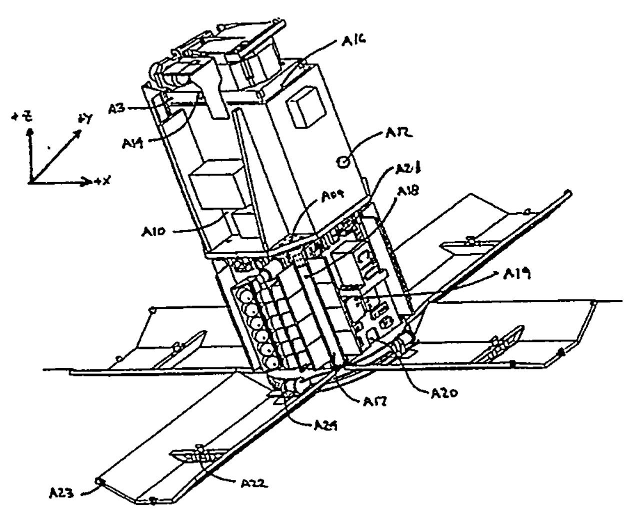

Figure 2: MTI Satellite

DISCLAIMER

INITIAL DERIVATION OF THE TEST SPECIFICATIONS

The initial test specifications for the component level certification program were obtained from the General Environmental Verification Specifications document [GEVS]. The system inputs were defined according to the payloader's handbook for the chosen launch vehicle (Taurus) with the notable inclusion of an ignition shock environment from one of the other launch vehicles that was under consideration early in the program. The environments of interest included 1) equivalent static acceleration loads, 2) acoustic excitation, 3) random vibration, 4) ignition shock, and 5) pyroshock. These system inputs were eventually formalized in the MTI/Taurus Interface Control Document (ICD). For purposes of brevity, we will hereto refer to all system requirements as coming from the ICD.

Almost from the start of the program it became apparent that several of the more fragile components could not be designed to the relatively severe levels defined in the GEVS document without undue overruns in weight, cost, and schedule. In addition, it was recognized that we would have to come up with some means of limiting the vibration input to the system level testing to avoid overdriving the satellite at its first fixed base resonant frequency (such limiting is in accordance with commonly accepted practices).

PRELIMINARY FEA MODELING EFFORTS

A preliminary analytical effort was undertaken with Finite Element Analysis (FEA) using a NASTRAN^{TM} model developed for conducting preliminary static loads analyses. This model had over 10000 degrees-of-freedom and, based on its correct representation of the satellite's skeleton mass line, was judged to correctly predict the "general" trends in the structural response for frequencies up to 1 kHz. The model was excited with the base driven shock and vibration inputs obtained from the ICD. The results from this model were used to tailor the random vibration and ignition shock inputs for three crucial, yet fragile components. At that time we did not have the correct tools for performing an acoustic analysis.

SYSTEM LEVEL QUALIFICATION TESTING

The original certification plan did not include a system level qualification test. The decision to include such a test was the result of the realization that it would be easier and more realistic to test the larger satellite subsystems (such as the bus) as part of a complete assembly rather than individually. This test was viewed primarily as a structural test so most of the components were replaced with mass mockups. However, such a test was also seen as a means for obtaining component response information so we placed as many accelerometers on the satellite as possible (as shown in Figure 2).

The biggest issue regarding the system level testing was how to best incorporate the acoustic and base input random vibration requirements presented in the ICD. It is understood that many programs use only acoustics for system level testing, while others use only base driven random vibration. However, it was this author's contention that the low frequency portion of the interface random vibration Acceleration Spectral Density (ASD) presented in the IÇD reflected energy coming up from the launch vehicle while the high frequency portion reflected energy coming down from the payload. Therefore, we chose to conduct a combined vibroacoustic system test.

Given this decision, the only question was how to blend the two inputs. The solution was to input the entire acoustic spectrum (at least down to the lowest achievable frequency, 60 Hz, for Sandia's acoustic chamber), while restricting the random vibration excitation to 20-200 Hz. While it was not be rigorously justified at the time, this was felt to be a conservative upper bound to the frequency range where energy flow comes up from the launch vehicle. The reader should note that any unnecessary overlap between the two input sources represented an overtest of the satellite.

It is generally accepted that a notch will naturally exist in the payload / launch vehicle interface ASD at the payload's 1st fixed base resonant frequency due to the payload's relatively high impedance at that frequency. Any base input random vibration test that does not include such a notch will overtest the payload. Therefore, the other major issue we had to address concerning our system level, base driven random vibration testing was how to notch the system level vibration inputs. It was decided to derive the appropriate notch depth based on a tuned Two-Degree-of-Freedom (TDOF) dynamic mass absorber model of the coupled satellite / launch vehicle such as the one described by [Scharton 1994]. Rather than manually notching the input vibration spectrum, the notch was implemented during the system qualification test using a response limiting scheme in order to allow for differences between the predicted and actual frequency of the first fixed base resonance.

The system level ignition shock, which was defined using a sum of decayed sinusoids, was also "notched" at the first fixed base resonant frequency by intentionally not placing a decayed sinusoid near that frequency. The justification for this, which is analogous to the notching of the random vibration input, is explained in greater detail in [Cap 1995]. This "notching" of the ignition shock has the added benefit of reducing the needed power requirements on the electrodynamic shakers (since any excitation at the fixed base resonant frequencies must overcome the corresponding high impedance of the test item).

The qualification test series was a success and the component response information gathered during the test was used to correct errors in the tailored component test specifications. The reader should note that we would have tested some components to incorrect levels (some high and some low) if we had relied solely on the FEA model to tailor the GEVS test levels. Although in fairness to the FEA model, the errors observed in the FEA predictions are attributed mostly to the fact that the "as measured" response turned out to be due to acoustics, while the FEA model only considered the base driven random vibration inputs identified in the ICD.

This points to two items of note: 1) the need for either high fidelity vibroacoustic models or a system level vibroacoustic test prior to attempting to tailor component test specifications, and 2) the fact that base input random vibration is not a valid substitute for acoustics if the payload is susceptible to acoustic excitation.

COMPONENT MODELING

In addition to the system level FEA models, FEA models were also developed to address specific design issues for several individual components. These models focused mainly on questions of relative displacement (i.e., would an antenna touch the launch vehicle shroud?) and/or peak load capacity.

COMPONENT TESTING

This section looks at three component level test series from which valuable lessons were learned: 1) the Optical Assembly test series, 2) the Focal Plane test series, and 3) the "golden wire" component random vibration test.

OPTICAL ASSEMBLY TEST SERIES

The most complex of the component level test series was the optical assembly (OA) qualification. The OA input vibration levels for this test were defined using measured response data from the system qualification test. It was imperative that we did not allow the mirrors to experience peak acceleration levels in excess of the design limit of 25g. FEA models of the OA predicted that we would overtest some of the critical internal hardware if we did not limit the input spectrum during the OA random vibration testing.

To aid in our efforts to prevent overtesting of the OA, tri-axial accelerometers were mounted at six critical points within the OA. The in-axis responses at the six locations were measured during preliminary, low level tests and the results were used to manually notch the full level input so as to prevent the mirrors from being overtested. We briefly considered using a multi-point extremal control scheme to accomplish our goals, but the idea was dropped for fear that the loop time for the control system would be too slow to protect the OA from being overdriven for short periods of time before the control system could bring the test levels within tolerance. Whether or not this was true will never be known. However, as it turned out, our understanding of how the mirrors responded was not accurate enough, so that any extremal limit spectra based on our FEA predictions would not have provided the needed protection. Therefore, the manual notching technique ended up providing us with a chance to accommodate the true OA response.

Two points must be made concerning this effort. First, as a result of the long lead time needed to manufacture the OA, the 25g limit for the OA mirrors was chosen somewhat arbitrarily rather than being based on any hard source of response data. This again demonstrates the need for high fidelity modeling and/or system mass mock testing prior to developing component requirements.

The second point is the fact that when one is conducting a random vibration test that includes the limiting of the response at multiple internal points considerable attention must be paid to the details of how the test is implemented in order to account for unexpected circumstances.

FOCAL PLANE TEST SERIES

The focal plane testing is significant from the point of view that the qualification unit suffered physical damage when subjected to the original test levels derived from GEVS and survived all subsequent "tailored" component testing as well as the system level testing and flight. This would appear to justify our decision to tailor the component test levels.

"GOLDEN WIRE" COMPONENT VIBRATION TESTING

The third component test of note was a random vibration test in which intermittent electrical shorts were observed for one of the flight components. It turned out that a small length of gold wire was inadvertently left dangling from a solder joint and the vibration test caused it to short out the system. The problem was fixed and the component showed no additional problems. The moral of this story is that component random vibration testing can identify certain types of manufacturing defects.

SYSTEM LEVEL ACCEPTANCE TESTING

In preparation for the final flight certification (acceptance) testing we wanted to provide a more refined set of system inputs. To this end we took advantage of two resources that were not available when we were developing the inputs for the system level qualification test series: 1) the Coupled Loads Analysis (CLA) and 2) a Statistical Energy Analysis (SEA) model.

COUPLED LOADS ANALYSIS

The primary objective of the CLA is to identify all possible quasi-static loading conditions on the satellite and launch vehicle. Indeed, the CLA predicted that a sinusoidal resonant burn environment that had not been specifically identified in the ICD was indeed a design driver for the satellite. Owing to the fact that the CLA was conducted relatively late in the development program, the problem had to be solved using a "whole satellite" isolation system.

An interesting side note on this subject was the fact that the ignition shock conducted during the system qualification test series, which we had "borrowed" from another launch vehicle, proved invaluable in demonstrating that the satellite could indeed withstand most of the CLA forcing functions. Without this test, we would have been forced to rely totally on analysis to verify that MTI would survive the CLA loads.

A byproduct of the CLA was the predicted response of the satellite during the transonic and max Q events that form the basis for the random vibration requirements in the ICD. As was discussed earlier in this paper, it is commonly accepted that the random vibration input to the satellite can be notched at the first fixed base resonant frequency. While identifying the fixed base frequency is trivial, there are two methods known to this author for determining the depth of the notch: 1) coupled impedance models (of which the TDOF model discussed earlier in this paper is a good example) and 2) the simple technique of not allowing the peak acceleration of the payload's cg to exceed the equivalent static load (ESL) as defined by the CLA (this is the method recommended in GEVS).

The impedance model technique relies on the engineer's judgement as to the relative impedance of the satellite and the launch vehicle, which in turn determines the depth of the notch. Conversely, the ESL method would appear to produce different notch depths depending on the selected upper cut-off frequency of the random vibration test (i.e., a higher cut-off frequency vibration test would artificially increase the peak acceleration at the cg, thereby requiring the deeper notch to compensate).

It is this author's contention that the true purpose of the notch is to produce a more realistic "whole body" response by preventing the response at other locations within the payload from being overdriven by the arbitrary "straight line" input ASD. The correct "whole body" response is not typically documented in the ICD. However, the CLA provides us with the response of the payload for a given interface response. While the absolute vibration responses predicted by the CLA were not in particularly close agreement with earlier Taurus flight data, this relationship was deemed to be sufficiently accurate to permit us to establish the correct notch depth for the random vibration testing.

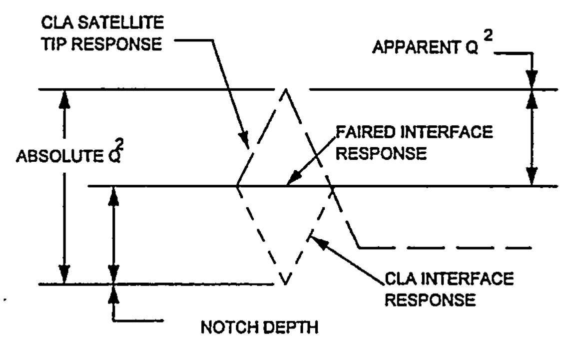

Figure 3: Illustration of the ASD Notch Derived from the Coupled Load Analysis

The process for deriving the notch depth is illustrated in Figure 3. The first step is to overlay the predicted CLA ASDs for the satellite interface and the top of the satellite. We then defined the faired interface response (which is analogous to the "straight line" ASD in the ICD). The absolute Q identified in Figure 3 is related to the Q that would be measured during a fixed base test of the satellite. However, the "apparent Q" identified in Figure 3, which is defined to be the ratio of the response at the top of the satellite divided by the faired interface response, is intuitively what the reader's eye would identify as the Q of the coupled system. The notch depth is defined as the difference between the absolute and apparent Q values. As was the case for the system level qualification testing, this notch was implemented using an extremal limit spectrum applied to the top of the satellite.

It should be noted that the actual CLA predictions were not as clean as the simplified schematic example in Figure 3, and it was still necessary to include a good dose of engineering judgement in order to produce a credible result. However, the CLA predictions did provide insight into the response of the satellite when it was coupled to the launch vehicle.

I would like to point out two valuable lessons from our experiences with the CLA. First, the earlier the CLA is performed, the better. The need for an isolation system might have been avoided if we had known about the impact of the resonant burn environment, and we certainly would have included some sort of swept sine excitation in the system level testing. Secondly, the CLA can be used to aid in establishing the depth of the notch for limiting random vibration test inputs, although the credibility of the predicted notch could stand improvement. Such improvements would be realized with improvements in the accuracy of the CLA predictions for the transonic and max Q events.

SEA MODELING

As was discussed earlier in this paper, the upper bound on the base input random vibration for the system test was defined to be 200 Hz. This value was based on the assumption that at high frequency the response at the payload interface is dominated by energy flow down from the satellite while the low frequency response is dominated by energy flow up from the launch vehicle. Based on this assumption, we had somewhat arbitrarily chosen the upper cut-off frequency for the base input random vibration ASD to be 200 Hz for system qualification testing. It was our desire to obtain a more rigorous quantitative estimate for this cut-off frequency. It occurred to us that Statistical Energy Analysis (SEA), which is particularly good at predicting power flows, could possibly predict this cut-off frequency more accurately using a coupled SEA model of the satellite and the launch vehicle.

A validated [VAPEPS] SEA model of the Taurus launch vehicle already existed, so we also used VAPEPS to develop the satellite SEA model. We were able to validate the satellite SEA model using response data from a low level (-6 dB) acoustic test performed as a part of the preparations for the system level qualification test series [Cap and Tracey 1999]. This greatly improved our confidence in the resulting coupled SEA predictions.

The result of this analysis showed that energy flow was primarily from the satellite to the launch vehicle for frequencies above 100 Hz. This permitted us to reduce the upper frequency range of the random vibration input from 200 Hz to 100 Hz, thereby reducing the overconservatism of the overall system level acceptance testing.

EQUIVALENT STATIC LOAD TESTING

During the qualification test series, the system was subjected to a closed loop sine dwell test in order to simulate the equivalent static loads (ESLs) identified in the ICD. However, the satellite design team got a collective case of weak knees when they saw how long the satellite was excited in the process of performing a closed loop sine dwell test (although much of the time was spent as reduced test levels achieving equalization of the control signal). As a result of this experience, it was decided to simulate the ESLs with an open loop sine dwell "chirp". The chirp consisted of a ten cycle, constant amplitude burst of sinusoidal energy with leading and trailing sinusoidal ramps lasting five cycles each. This greatly reduced the duration of the sine dwell test.

While the sine burst worked in principal, our close scrutiny of the open loop test caused us to notice one shortcoming of using a sine test for approximating ESLs – no matter how low the frequency of the sine dwell (we used the lowest frequency possible without exceeding the displacement limits of the electrodynamic shaker) there will always be some amplification. The result of this was that we were experiencing a 5-10% gradient across the length of the satellite with the highest peak g levels near the top of the satellite. The compromise was to aim for the desired levels at the cg (where the CLA would be predicting the ESL levels) and hope that the gradient would be no worse than the natural gradient associated with the moment portion of the ESLs.

LESSONS LEARNED AND RECOMMENDATIONS

In conclusion, the MTI testing and analysis did appear to contribute to the overall success of the program. However, I would like to re-iterate several points that became apparent as a result of our trials and tribulations during the certification program.

The CLA will always be useful for identifying insufficient margin in the payload design, and indeed a negative margin was identified for our satellite. However, the relatively late completion date for the CLA made the necessary design changes more difficult to implement and indeed limited the possible number of solutions. Therefore, I would wholeheartedly encourage the running of a CLA as early in the design process as possible. In addition, there appears to be some promise in the use of the CLA for defining response limited vibration inputs for the payload based on the overall response of the payload in the flight configuration.

There will always be programmatic restrictions that make it necessary to certify payload assemblies wholly using only either acoustic or base input random vibration. However, it would appear that a combined vibroacoustic input has the potential to be more realistic, and if a combined vibroacoustic test is conducted SEA appears to be a viable technique for addressing the question of how to balance the contributions from base input random vibration and acoustics.

The testing of the payload to the ESL using sine dwells would appear to present a certain amount of uncertainty as to exactly what levels the payload has indeed experienced. While this author knows of no practical alternative, it would seem prudent to implement an FEA analysis of the satellite's response to the sine dwell. This might at least provide a better understanding of how to best scale and control the sine dwell to produce the desired loading of the payload with the minimum of overloading.

Based on my observations of the launch vehicle community, very few payloader's handbooks identify a set of test specifications tailored to simulate the various transient and/or sinusoidal forcing functions associated with launch even though they appear to be included in the CLA. They are instead addressed using the ESL steady state accelerations. While this is considered adequate for primary structure, the same can not be said for secondary structure (which in many cases is just as critical to mission success). The inclusion of a set of transient/sinusoidal requirements such as the ignition shock test we performed for MTI would seem useful for improving the preliminary design of the payload through more detailed analysis and/or test.

While GEVS proved to be conservative in almost every instance, it would have placed undue hardships on certain, fragile components. Conversely, our efforts to tailor the component requirements met with some problems due to the lack of fidelity in our analytical models and mass mock system tests. In addition, our efforts to tailor component test levels were somewhat hampered by our inability to "nail down" the system inputs. This was due to the fact that Taurus was a relatively young launch vehicle. In an effort to provide the latest in design guidelines, the Taurus project team adjusted system requirements (sometimes up and sometime down) when new flight data became available. I believe that this was the right thing to do since knowledge of the "best" inputs is important. My only suggestion regarding this issue is a recommendation to not be overly zealous in fine shaving the excess test margin off of component requirements when dealing with a young launch vehicle.

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