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Variational Coupled Loads Analyses: Reducing Risk in Development of Space-Flight Hardware

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Before space hardware can be launched, positive structural margins of safety must be demonstrated relative to the booster-supplied math model and forcing functions. To identify appropriate structural loads on which to base such margins, several iterations of coupled loads analyses are typically performed during hardware development. Such analyses are traditionally done with a single payload dynamic math model, derived from finite element models, which are combined to form a booster/payload system-level model. Uncertainty in such analyses, relative to both the hardware's final configuration and its modes of vibration, is most often addressed with uncertainty factors selected without any insight into actual loads sensitivity. With recent advances, the analysis process has been accelerated, allowing for variational coupled loads analyses. Such an analysis can account for possible variations in the final hardware configuration: for example, frequency, weight, presence of comanifested payloads, damping, etc. The results of such a variational analysis are presented. The results demonstrate that the use of uncertainty factors can greatly penalize much of the structure with overly conservative load criterion, while at the same time being unconservative for those structural elements most sensitive to the variations. The conclusion is that the utilization of variational coupled loads analyses can result in both reduced risk and more efficient structural designs.

Introduction

UNCERTAINTY in structural loading during launch is a big problem in space-vehicle hardware development. The quasi-static accelerations associated with steady-state rocket thrust and aerodynamic pressures are easily handled because such loads are relatively easy to predict and analyze. The outstanding problem is the prediction of how the payload's modes of vibration will couple with those of the launch vehicle and then respond to transient loads, such as those from engine ignition and launch pad separation, engine shut down, wind gusts, and buffeting. Because a payload's attachment structure forms a continuous structural load path between the launch vehicle and the payload, small variations in the modes of vibration for the launch vehicle or the payload can make a significant difference in the resulting payload responses and, thus, how highly its materials are stressed.

Coupled loads analysis (CLA) is the process of predicting the relatively low-frequency dynamic responses to transient forces. (High-frequency modes of vibration tend to be excited from the acoustic or structureborne random vibration environments.) Such an analysis uses finite element based, reduced dynamic math models of the launch vehicle and the payloads, which are mathematically combined (or coupled) to represent the full system-level structural characteristics. CLAs are the accepted standard for the establishment of loads for the design and test of payload structures and for assessment of whether payloads are structurally capable of withstanding the launch loads environment (and landing for space shuttle payloads). A typical spacecraft development program entails several iterations of CLAs, using progressively more accurate math models of the payload structure as the design matures.

After structural testing is complete for the flight article, or of a qualification article built to the flight design, the payload math model is revised to correlate with the structural characteristics determined during test. A special test called a *modal survey*, in which modes of vibration are individually excited, is dedicated for the purpose of obtaining data to support such a correlation. The test-correlated model is then used in a final CLA, which is called the verification loads analysis (VLA) or verification loads cycle (VLC). As explained earlier, small changes in the model can make big differences in the resulting loads. VLAs can result in structural responses that exceed the preexisting strength certification, potentially resulting in a great deal of expensive and time-consuming analysis, redesign, and even retest, all on an accelerated schedule.

Similarly, the CLA loads for a spacecraft can increase after it is built and tested as a result of changes to the launch vehicle's math model, new flight data that change the booster supplied math model or forcing functions, or changes to the flight configuration or the manifesting of other payloads. The latter pertains to launch vehicles such as the space shuttle, which flies more than one payload at a time. The physical characteristics of the different payloads can change the overall system's structural response to the environments. Late changes in the manifest are common for the space shuttle.

In Sec. 1.4 of Ref. 1, the authors cite the following as one the keys to high quality and reduced cost: "Do sensitivity analysis to make sure your products will work despite the variables outside your control." Historically, sensitivity analyses with CLAs have seen limited use because of the cost and time associated with doing so. Execution of CLAs, with traditional processes and computer codes, entails considerable expense, including engineering hours, computational expense, and calendar time. Therefore, execution of multiple CLAs, such as parametrically varying modal frequencies or mass properties for the different elements of a launch configuration, has been impractical. For these reasons, most sensitivities analyses use the less accurate approaches of component base-drive or perturbation methods.

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In lieu of sensitivity (or variational) analysis, the standard practice is to multiply the CLA loads by a model uncertainty factor. Reference 2 suggests the following for space shuttle payloads:

> It is expected that the CE [Cargo Element] developer will incorporate a 'model uncertainty' factor (UF) during the CE design stage to cover potential changes due to subsequent changes in the CE and SSV [Space Shuttle Vehicle] math models and possible interactions with the actual flight manifest. Typical UF numbers are 1.50 for Preliminary Design Review (PDR) quality models and loads analysis, 1.25 for Critical Design Review (CDR) quality models and loads analysis . . . .

The problem with this approach is that modes of vibration, and, thus, the loads in various structural elements, are not all equally sensitive to the subject uncertainties. The use of a blanket uncertainty factor (UF) without insight to actual sensitivities can lead to inefficiency and risk, that is, loads for insensitive structural parts may result in an unnecessarily robust design, whereas the parts most sensitive to variation may potentially remain underdesigned or undertested.

As mentioned earlier, the traditional approach to mitigate uncertainties in the payload dynamic math model is through modal survey testing, along with math model correlation to the test results. Modal survey testing is expensive and time consuming. Few programs nowadays build test-dedicated hardware because of the associated cost, instead opting to test the first-built flight article with the "protoflight" approach. Thus, modal survey testing is an event in the first vehicle's critical path to launch. With successful test correlation of the math model, standard practice is to then use an uncertainty factor of 1.0. Even with the use of UFs on the earlier analysis results, the correlated math model analysis often yields increased structural responses and loading, possibly leading to redesign or retest, which can then result in a launch-date setback. With test correlation of the models, it is all too common to see critical structural elements with negative margins because the preceding UFs were not sufficient. Such cases lead to refinement of the stress analysis, if not modification and/or retesting of the hardware itself, that may be costly.

Regarding the preceding issues, in Sec. 11.3 of Ref. 1, the authors say,

> Unfortunately, this approach usually gives us results of the validated analysis long after the flight article is built and our static test is done. We can't wait this long to find a critical error in our analysis. Analysis-validation tests should be our last check, not our first. We should use development testing and sensitivity analyses to develop confidence in our designs. . . Thus, validation begins during design as a cost-effective ingredient of verification. For relatively simple structures, using this approach might give us enough confidence without analysis-validation tests [modal surveys] and without a verification loads cycle.

Reference 3 addresses the use of UFs for the case in which the dynamic math model used for the VLA does not meet a correlation criterion:

> Again, technical justification should be provided for ignoring the cross orthogonality criteria for any other exceedances since failure to meet it could reflect an uncertainty in the model test-verification which could significantly impact the loads results. Although a model uncertainty factor is often used to deal with this problem, this is an imperfect approach which may unnecessarily penalize other areas of the structure.

The case study presented later clearly illustrates this point.

Need for Change

The authors of Ref. 4 made the following statement:

> The integration of the launch vehicle and the payload model and the subsequent computations to obtain payload loads are expensive and time-consuming. These difficulties preclude the use of exact structural loads analysis in the early design stages where frequent design changes are occurring. Therefore, approximate methods have been employed during the early design/analysis process.

Since then, the available computation power has increased dramatically; however, the problem of timely integration of design and analysis has persisted.

In 1998, NASA Johnson Space Center hosted a technical interchange meeting to solicit alternative loads assessment tools to streamline the VLA process:

> An alternative loads assessment process is desired that would permit extremely rapid assessments of changes to an Orbiter cargo bay manifest. At this time, these changes necessitate a redo of the VLA which is time consuming and impossible to fully complete if the change is identified very late in the process. The alternative technique is envisioned as performing an assessment of manifest changes that occur after the VLA had started to determine if the VLA has to be redone.

To date, none of the alternative tools presented at that meeting has been fully endorsed by NASA for VLA usage.

The complexities of dynamic structural interaction between a launch vehicle and its payloads necessitate that complete system-level analyses, that is, CLAs, be performed to provide appropriate confidence in mission success. Because of the historical expense and time required for such analyses, the analysis function has become one of proving that the hardware has positive margins of safety rather than one that is closely integrated with the design process. For example, seldom does a program reduce unnecessary structural "robustness" resulting from earlier usage of CLAs with uncertainty factors. The design and hardware are typically "too far along" since the last CLA to take advantage of any reduction in load criterion afforded by later CLAs. Thus, the series of CLAs and the final VLA serve as waypoints at which a search for negative margins is performed. In this sense, the CLA function does not proactively contribute to the betterment or optimization of the hardware design.

Recent Advancements

Recent advancements in methods and software make sensitivity analysis with CLAs practical, enabling analysts to perform variational coupled loads analyses (VCLAs). VCLAs constitute a grouping of classical CLAs, with each having a different value for a key parameter in a component in the system-level math model. In this manner, a reasonably likely range of important transient responses can be captured by accounting of uncertainties or variations in the design or in the math model of particular components. The assembly of the system-level math model can also be varied to account for uncertainties in the launch configuration, such as payload and cargo combinations.

The execution of the following reported case study uses two salient advances over classical CLA methods: First, the method employs a "multibody" approach, with each body (or component) remaining distinct within the analysis while also remaining in its native coordinate system. As a result, modal frequencies for any component can easily be varied without repetition of the component's mathematical reduction. The second key difference is that the method employs a unique mathematical space that yields tremendous computational efficiencies over the classical CLA approach. The resulting mathematics are equivalent to the classical solution methods, and, indeed, validation of the advanced tool against the classical tools yields exact comparisons. Details on these advancements are beyond the scope of this paper.

These two advances yield unprecedented CLA execution speeds. The case study executed 19 complete space shuttle liftoff CLAs (each with the full compliment of 12 liftoff forcing functions) and 95 Orbiter landing CLAs (each with the full compliment of 7 landing forcing functions). A single workstation comprised the computational platform. The effort was completed in less than one calendar week and 40 engineering hours. An optimistic manpower estimate for the same effort utilizing classical CLA tools is on the order of 60 work weeks.

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The use of a multibody approach is particularly germane to a VCLA. Each component is assembled at a system level, that is, there are no intermediate math model assemblies and subsequent dynamic model reductions. In addition, the designated components' dynamic math models are easily manipulated to account for the desired variations in component mass, stiffness, frequency, or damping. Because the variations are introduced at the level of the reduced dynamic model, the variations are necessarily enforced throughout the component. For example, a stiffness variation is enforced by simple scaling of the component's entire reduced dynamic stiffness matrix. With this approach, the "granularity" of possible variations is controlled by the granularity of the components to be assembled into the system level. Note that this approach does not require the analysts to manipulate the components' finite element math models. Note also that because the stiffness, frequency, or mass variations are treated as uniformly distributed, the component math model mode shapes are not affected. Thus, the output transformation matrices are simply treated via appropriate scaling factors for each variation. (This statement is limited to "modal acceleration" method derived transformations.)

Case Study

The reported VCLA was conducted for the space shuttle/cargo elements (CEs) coupled system for the International Space Station (ISS) mission 1E. The primary objective of the analysis was to provide detailed preliminary design loads (liftoff and landing) for two manifested science payloads, the European Technology Exposure Facility (EuTEF) and SOLAR (name, not an acronym). These payloads will mount on the Integrated Cargo Carrier-Light (ICC-L) unpressurized cross-bay carrier, as shown in Fig. 1. The goal of the VCLA was to capture potential variations in EuTEF and SOLAR responses that can result from reasonable uncertainties in the modal frequencies or overall stiffness, that is, uncertainties between the PDR quality math models utilized and the final hardware build. In this study, stiffness was varied uniformly for the combined model of the two "stacks," each of which consists of the payload and its mechanical attachment structure, the small adaptor plate assembly (SAPA). (The SAPA is the mechanical interface between the payload and the carrier; it will remain with the payload and also serve as its mechanical interface aboard the ISS.) The VCLA for all analysis configurations involved a ±45% variation in stiffness (±20% variation in stack frequency), in 5% increments. [Stiffness variations were accomplished by scaling of the Craig–Bampton stiffness matrix for the combined model of the two payloads. Mass variations are also possible, but would include scaling of the mass matrix, the generalized partition of the stiffness matrix, and the acceleration-driven output transformation matrices (OTMs) utilized for the recovery of internal responses.] The small increment of stiffness variation was utilized to ensure that any potential extreme response sensitivities would be found. The EuTEF and SOLAR math models are of PDR quality (uncertainty factor of 1.5 suggested in Ref. 2), whereas the SAPA math models have been test correlated.

Note that the stated variations do not completely capture all of the possible variations in the two payloads or in the other comanifested CEs. For example, EuTEF to SOLAR structural response changes due to variations in only one of these payloads were not included in this study. At this stage of hardware development, it was deemed that the greatest variation in each payload would be its overall stiffness and that this variation would dominate the other possible manifest variations. Other variations can be analyzed as the hardware matures, that is, as gross properties such as EuTEF and SOLAR weight and stiffness become better established, interactions with other comanifested CEs' variations can be better quantified through a VCLA.

The payload response variations reported herein are absolute maxima (the highest absolute values) resulting from the space shuttle liftoff transient environments. All results are normalized to the maximum response level resulting from the nominal (baseline) stiffness. Results are plotted in the form of specific response spectra, which, for a given response parameter, show absolute maximum response (load) vs degree of variation in the designated model parameter, stiffness, in this study. The maxima are for the full compliment of the space shuttle cargo integration liftoff forcing functions.

In addition to planned launch manifest, the VCLA also accounted for the following potential cargo configurations during return from orbit and landing: 1) abort landing (same configuration as for launch); 2) contingency landing with no Columbus module; 3) contingency landing with no Columbus module and no EuTEF; 4) nominal landing with the Multi Purpose Logistics Module (MPLM) (EuTEF and SOLAR are to be launched with the Columbus module, which is to be deployed onto the ISS. Any planned return of these scientific payloads would occur on a MPLM mission); and 5) nominal

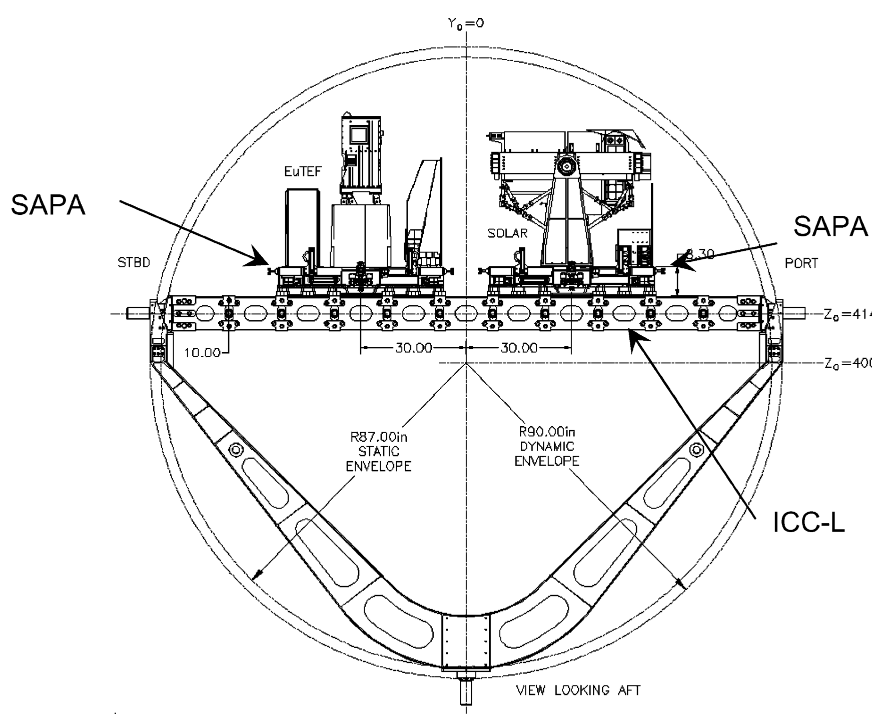

Fig. 1 ICC-L, EuTEF, and SOLAR looking aft in the Orbiter cargo bay, with the 87-in. static and 90-in. dynamic cargo envelopes depicted: $Y_0 = 0.0$ and $Z_0 = 400.0$ define the cargo envelope centerline.

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landing with MPLM and no EuTEF. Counting launch and landing as separate CLAs, the total number of CLAs conducted in this VCLA study is 114 (6 manifest configurations times 19 stiffness variations).

The subject VCLA used NASA's baseline diagonal system damping approximation; that is, for the liftoff transient analysis, the coupled system generalized response is damped at 1% of critical for frequencies at or below 10 Hz and at 2% above 10 Hz. For the landing transient analysis, the damping ratio is a constant 1% of critical. The generalized system is truncated at 35 Hz per NASA criterion. The hi-fidelity space shuttle math models and CLO1000 series liftoff forcing functions used in this analysis were provided by the Boeing Company.

As stated earlier, the EuTEF and SOLAR math models are of PDR quality, the analysis being performed to form the basis of the PDR structural assessments for these two science experiments. As will be shown hereafter, the analysis yielded a "richness" of detailed data unattainable through the simple use of uncertainty factors. The degree to which the pertinent EuTEF and SOLAR hardware contractors took advantage of these data is not known. To the authors' knowledge, the reported analysis is one of the very first such VCLAs; thus, there has not been any form of historical record on hardware benefits afforded by such analyses. However, on review of the following case study, it should be apparent that such analyses do offer the potential of significant reduction of the risks associated in the development of space flight hardware and of making structural designs more efficient.

EuTEF

The math model of the EuTEF/SAPA assembly represents a total weight of 668 lb with the first modal frequency at 33.7 Hz when constrained at the carrier interface. Figure 2 presents the study results for EuTEF net load factors, normalized to the baseline results. [Net load factors are calculated by summation of the interface forces about the element's center of gravity. Translational summations are divided by the total weight. Moment summations are divided by the respective mass moment of inertia (again, about the center of gravity). The subject interface is between the adaptor plate and the carrier structure.] The 1.5 uncertainty factor suggested in Ref. 2 for preliminary CLAs is included in the plot. Net load factors most often drive the preliminary structural design.

Stiffness was varied over the range of 55–145% of nominal in 5% increments. As a result, net load factor responses varied between 55 and 140% of the nominal predictions. Multiplication of the nominal predictions by a 1.5 uncertainty factor would cover the uncertainty in this case, but would be excessive. Figure 2 shows that adequate uncertainty factors for a net load factor design criteria would be 1.4 for X translational loading, 1.22 for rotational acceleration about the Z axis, and between 1.0 and 1.1 for the other load factors.

The EuTEF math model included 570 internal response recoveries. (Internal recoveries are derived via OTM. OTM responses can include internal structural element force resultants, stresses, strains, relative motion, etc.) Internal responses do not necessarily behave/correspond directly to the net load factors when the component has modes of vibration that are in the frequency range of the analysis or that couple with the launch vehicle's modes of vibration within that range. Figure 3 shows the resulting predicted variation of the 50 most sensitive response recoveries. (In this paper, a "sensitive" response load is one that increases significantly when stiffness is varied either up or down within the range considered.) In addition to net load factors for the EuTEF/SAPA assembly, the response recoveries included the SAPA interface forces to the cross bay carrier, net load factors, and interface forces for six different scientific

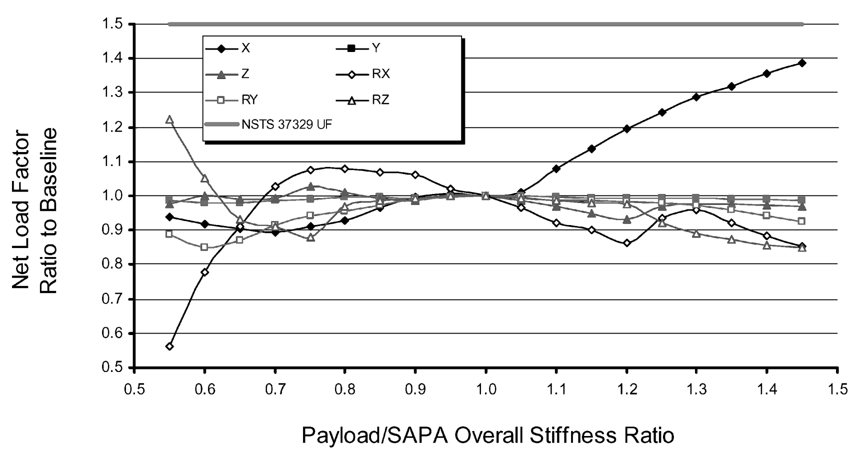

Fig. 2 Variations in EuTEF net load factor response for liftoff, showing how computed maximum load factors vary with stiffness as a ratio to baseline (X load factor most sensitive, ranging up to 40% higher than value calculated with the nominal model; bold line indicates values typically used for preliminary design, corresponding to a 1.5 uncertainty factor).

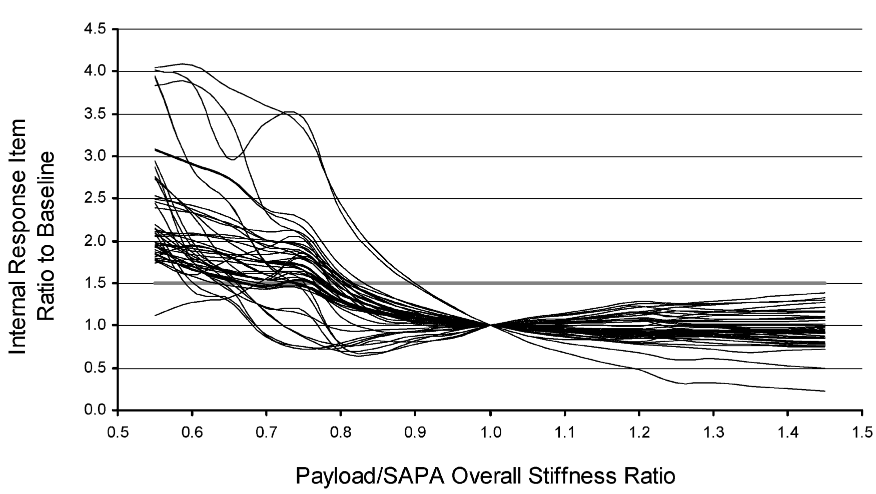

Fig. 3 EuTEF 50 most sensitive internal response items for liftoff.

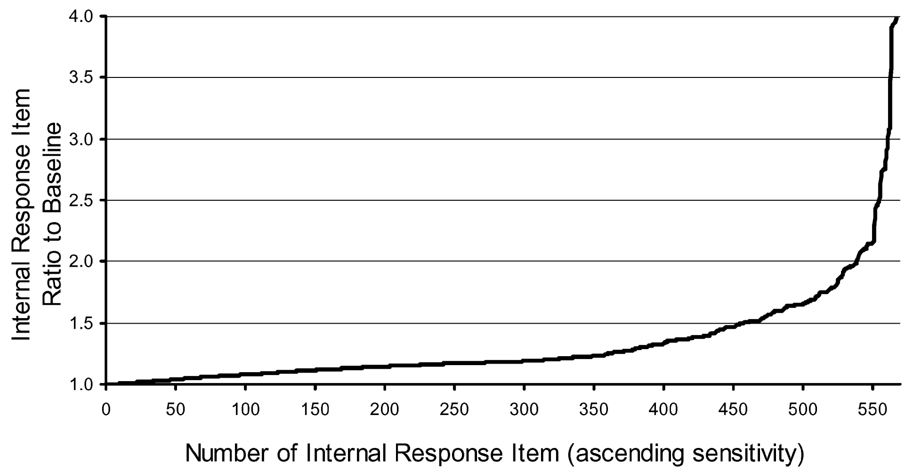

Fig. 4 EuTEF internal response sensitivity (response item number on horizontal axis in ascending order of sensitivity to variation on EuTEF/SAPA stiffness).

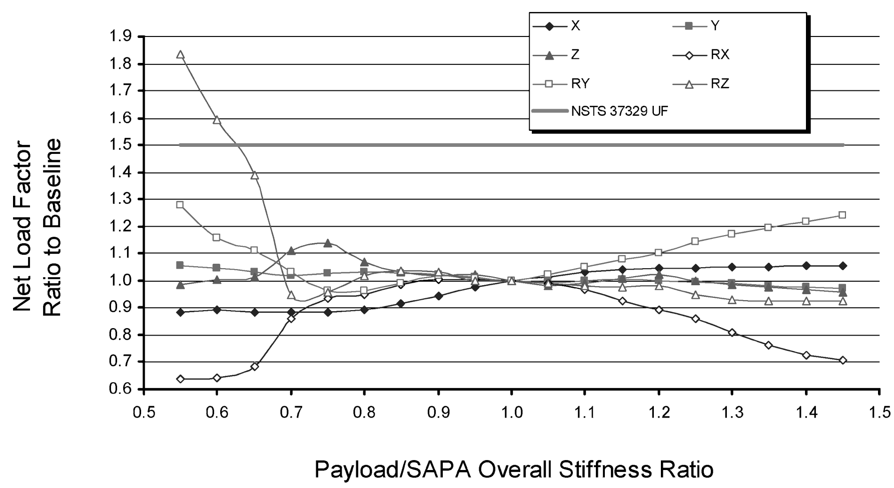

Fig. 5 Variations in SOLAR net load factor response for liftoff.

experiments and a number of grid point accelerations. Note that in Fig. 3 within the stiffness range considered, some computed response loads were four times the levels calculated with the baseline model, and many responses are above the 1.5 ratio corresponding to the standard 1.5 uncertainty factor (bold line).

In Figs. 2 and 3, response item values all near 1.0 on the vertical scale indicate little sensitivity to stiffness change. Clearly, the 1.5 uncertainty factor would not have been sufficient for the most sensitive parameters. Unfortunately, because such sensitivity analyses are not commonly done, the engineers doing the loads analysis and the structural sizing seldom have insight as to which parameters will exhibit such sensitivities.

Figure 3 is consistent with the EuTEF/SAPA assembly, being relatively stiff, that is, 33.7 Hz nominally vs the system truncation frequency of 35 Hz. In other words, as the assembly is stiffened, its fundamental frequency rises, resulting in less and less dynamic participation below the 35-Hz system-level truncation frequency. Increased dynamic interaction would be expected as the EuTEF/SAPA frequency is decreased, as is indicated in Fig. 3.

Figure 4 shows the internal OTM response recoveries for EuTEF sorted in order of ascending sensitivity.

Of the 570 internal responses computed for EuTEF, approximately 460 showed a less than 50% increase when stiffness was varied by $\pm 45\%$. Any parts of the structure designed based on these parameters would be unnecessarily penalized by the blanket 1.5 uncertainty factor. The remaining 110 responses showed sensitivity greater than 50%. It is these sensitive responses that may not become apparent until late in the program and can then trigger reassessments of margins, retesting to increase demonstrated strength, or even hardware modifications. Worse yet, these potentially higher responses may never be detected, resulting in flight hardware not certified to the desired or intended criteria, and possibly even structural failure during launch.

SOLAR

The SOLAR/SAPA assembly math model represents a total weight of 747 lb, with the first modal frequency at 25 Hz when constrained at the carrier interface. Figures 5–7 present the study results for SOLAR. Note that in Fig. 5 rotation acceleration about the Z axis is most sensitive and is the only net load factor exceeding the 50% increase permitted by the standard 1.5 uncertainty factor (bold line).

SOLAR net load factors varied between 63 and 183% of the nominal baseline analysis. Multiplication of the nominal by a 1.5 uncertainty factor would cover the uncertainty for all but the net rotation about the Z axis.

The SOLAR math model included 500 internal response recoveries. Figure 6 presents the 50 most sensitive SOLAR internal responses. The SOLAR internal recoveries included the SOLAR/SAPA net load factors, the SAPA interface forces to the cross bay carrier, the SOLAR net load factors, the SOLAR interface forces to the SAPA, net load factors and interface forces for three different scientific experiments, and a number of grid point accelerations.

Figure 7 shows the internal OTM response recoveries for SOLAR sorted in order of ascending sensitivity. Overall, computed loads for SOLAR are much less sensitive to stiffness variation than those for EuTEF (Fig. 4), with only 10 of 500 calculated responses exceeding

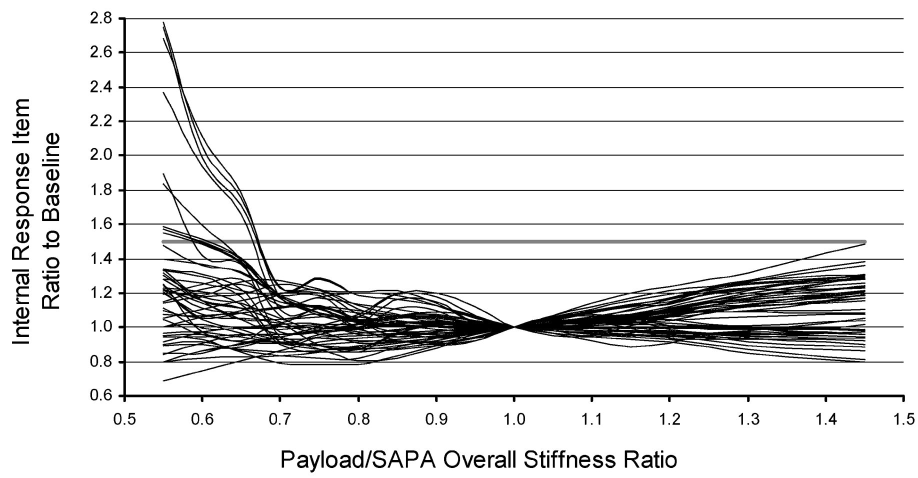

Fig. 6 SOLAR 50 most sensitive internal response items for liftoff; most parameters stayed below bold line, which shows 1.5 uncertainty factor commonly used for preliminary design, but some loads increased by nearly 180%, warranting a 2.8 uncertainty factor.

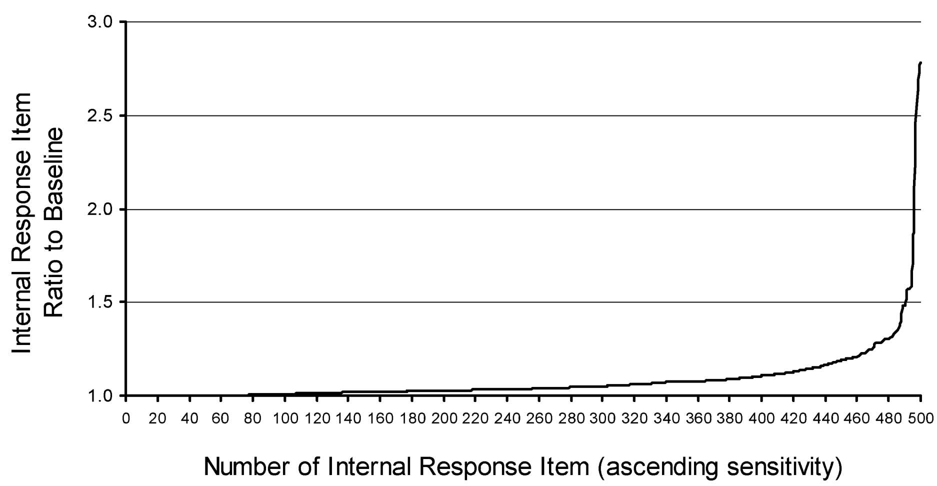

Fig. 7 SOLAR OTM sensitivity.

the 1.5 ratio. For SOLAR, 490 of the 500 internal loads showed a less than 50% increase when stiffness was varied by ±45%, with 394 being less than 10%. Any parts of the structure designed based on these parameters would unnecessarily be penalized by the blanket 1.5 uncertainty factor. Only 10 internal load parameters showed sensitivity greater than 50%.

It is apparent that the SOLAR is much less sensitive to the frequency variations than the EuTEF. Note, however, that the SOLAR/SAPA fundamental frequency is 25 Hz and that in the space shuttle liftoff environment, for both analytical and flight data, 25 Hz exhibits the maximum shock response spectra. (These shock response spectra are driven by acceleration time histories from both measured flight data and analysis time histories. Comparisons between the two are examined to ascertain that the resulting analysis environment does envelop the flight environment.) Therefore, reduction in transient response can be expected with any changes away from that frequency, up or down. (Admittedly, this observation neglects the coupling with other structural elements that will result in a lower frequency than 25 Hz at the system modal level.) Clearly, a 1.5 uncertainty factor for design or assessment of SOLAR is excessive.

Uncertainty with Test-Verified Math Models

Standard practice is for the payload developer to generate a test-correlated math model for use in the VLA. Reference 5 explains this as follows:

> The CE developer shall provide a test-verified dynamic math model to the SSP [Space Shuttle Program] for use in predicting flight loads and deflections that shall be used for the final structural verification of the CE and its components .... If the math model correlation is judged to be inadequate, the SWG [Structures Working Group] can require additional effort such as additional testing, additional analyses, and/or assign a model Uncertainty Factor (UF) that shall be applied to all results obtained from the use of the math model.

If the math model meets the correlation criteria, natural frequencies agreeing with test within 5% for primary modes and within 10% for secondary modes,[5] the results of the verification loads analysis will not require an uncertainty factor.

Figure 8 repeats the data shown in Fig. 3, this time reformatted to show response variance relative to change in EuTEF's natural frequencies. Only the range of ±10% for frequency is shown to illustrate structural response sensitivity within the criteria used to consider a model test verified.

Within the 5% criteria on primary modes, Fig. 8 shows that a few of EuTEF's sensitive response items can vary by as much as 1.5 (the uncertainty factor recommended in Ref. 2 for preliminary load cycles) for a math model deemed to be highly accurate, that is, test verified. If the two most sensitive load parameters shown in Fig. 8 were driven by response of secondary modes (not known by the authors), for which ±10% frequency correlation error is acceptable, the full sensitivity shown in Fig. 8 applies. (Note that the EuTEF model used in this study is not test verified. The study is, however, indicative of what might be the case with a test-verified model.)

Although the EuTEF is only a single example, it does show that, without account taken of uncertainty with sensitivity analysis, risk exists even when CLAs use test-correlated math models.

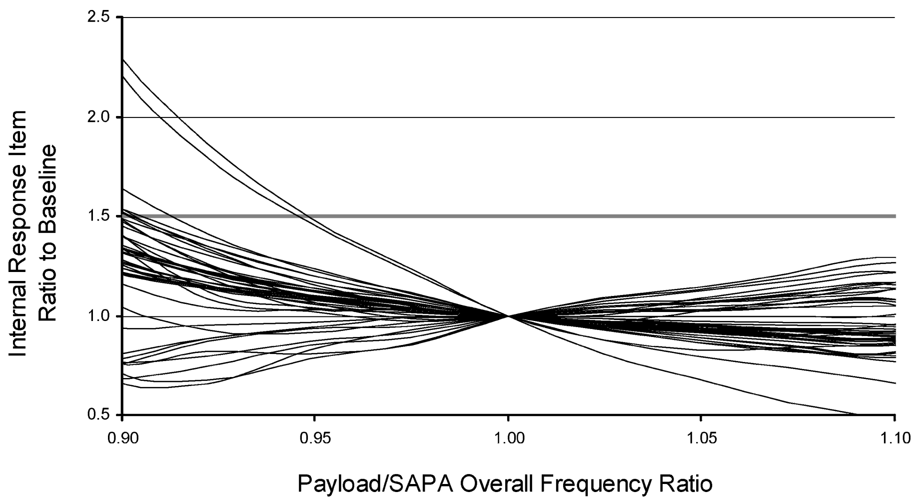

Fig. 8 EuTEF 50 most sensitive internal response items for liftoff (plots show sensitivity within a ±10% change in natural frequency).

Conclusions

As shown in the preceding case study, the application of uncertainty factors in lieu of sensitivity analysis will most likely result in structural elements that are overdesigned. Unnecessary weight to orbit is certainly a waste. The cost of this waste could be judged as the cost per pound to orbit. However, a more appropriate measure can be made in terms of number of science instruments or transponders not flown, amount of orbit station-keeping propellants not flown, or the cost of a payload having to go with a larger, more expensive launch vehicle.

This study also shows that uncertainty factors may not cover the range of loads expected throughout the structure, given uncertainty in math models and the flight configuration. In other words, because of "shooting blindly" with blanket uncertainty factors, a program runs a high risk of discovering in the VLA that some parts of the payload structure, which is at this point already built and tested, are not capable of passing flight certification with the updated structural responses. Such a late discovery has, indeed, not been uncommon.

Finally, the study shows that it can potentially be unsafe to rely solely on loads analysis done with test-verified math models when the correlation is not exact. Even the small uncertainty remaining in a test-verified model can lead to dynamic loads that may vary significantly. VCLAs can be a useful tool for the reduction of risk presented by such uncertainty.

Sensitivity analysis such as that done for the preceding study leads to valuable insight to support the design of robust, efficient structures. As should also be clear, because of today's computing speed and recent advances in software, sensitivity analysis can become an efficient part of the design process. Because of software efficiency, the reported study, accounting for all load cases typically required for a space shuttle mission, took approximately 40 work hours and one week of calendar time, as compared with many times that effort with traditional methods and software. The suggestion here is that the envelope of responses computed in studies such as the one described are now practical and can be used for design and assessment of space hardware in place of nominally produced transient responses multiplied by an unsubstantiated uncertainty factor.

The capability of performing VCLAs in a timely manner can lead to a more synergetic relation between the design function and the structural analysis function, resulting in lighter-weight flight hardware, greater confidence that uncertainties are enveloped by the analyses, and, for some designs, possible elimination of costly modal survey tests.

The space industry can no longer afford to "shoot in the dark" regarding launch loads. The knowledge, tools, and capability exist to change this process to one of intelligent risk management with variational coupled loads analysis, even when test-correlated math models are used.

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