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An assessment of spacecraft target mode selection methods

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ABSTRACT

Coupled Loads Analyses (CLAs), using finite element models (FEMs) of the spacecraft and launch vehicle to simulate critical flight events, are performed in order to determine the dynamic loadings that will be experienced by spacecraft during launch. A validation process is carried out on the spacecraft FEM beforehand to ensure that the dynamics of the analytical model sufficiently represent the behavior of the physical hardware. One aspect of concern is the containment of the FEM correlation and update effort to focus on the vibration modes which are most likely to be excited under test and CLA conditions. This study therefore provides new insight into the prioritization of spacecraft FEM modes for correlation to base-shake vibration test data. The work involved example application to large, unique, scientific spacecraft, with modern FEMs comprising over a million degrees of freedom. This comprehensive investigation explores: the modes inherently important to the spacecraft structures, irrespective of excitation; the particular 'critical modes' which produce peak responses to CLA level excitation; an assessment of several traditional target mode selection methods in terms of ability to predict these 'critical modes'; and an indication of the level of correlation these FEM modes achieve compared to corresponding test data. Findings indicate that, although the traditional methods of target mode selection have merit and are able to identify many of the modes of significance to the spacecraft, there are 'critical modes' which may be missed by conventional application of these methods. The use of different thresholds to select potential target modes from these parameters would enable identification of many of these missed modes. Ultimately, some consideration of the expected excitations is required to predict all modes likely to contribute to the response of the spacecraft in operation.

1. Introduction

This work explores the issue of identifying the vibration modes which should be considered as potential targets to correlate in spacecraft finite element model (FEM) validation activities. The studies presented herein aim to clarify the extent to which the modes of significance are inherent to the particular spacecraft structure or are dependent on the excitation being applied and coupling with the launch vehicle. Additionally, several traditional methods for target mode selection have been assessed based on ability to identify those modes which contribute most to the peak displacement and acceleration responses in the structure under loading which replicates typical qualification testing scenarios. Finally, comparisons are made to test data in order to highlight the potential to improve correlation of local modes in the structure through more focused correlation effort resulting from improved critical mode identification.

Having good correlation practices, such as target mode selection, is particularly crucial for spacecraft applications as it is not possible to conduct physical testing which truly represents the operational conditions, meaning that there is heavy reliance on the FEM to accurately simulate the spacecraft dynamic response to critical loading scenarios. In order to determine the loading levels and dynamic responses arising from significant flight events, Coupled Loads Analyses (CLAs) are carried out which couple a mathematical model of the spacecraft with a model, often multiple models for different load cases, of the launch vehicle. The spacecraft FEM is first evaluated against data gathered from vibration tests to ensure that it correctly reproduces the dynamic responses characteristic of the actual spacecraft hardware. Subsequently, a considerable amount of time and effort may be spent on FEM correlation and update; however, it is not uncommon for the final FEM to display minimal improvement over the original. As such, there is a need to ensure that correlation metrics and targets are physically meaningful, and that the procedures applied are as effective and efficient as possible.

There are many different approaches which may be applied to the issue of spacecraft FEM-test correlation. One common approach involves

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Acronyms and abbreviations

ADM	Atmospheric Dynamics Mission
CLA	Coupled Loads Analysis
COC	Cross-Orthogonality Check
DOF	Degree of freedom
ECSS	European Cooperation for Space Standardisation
ESI	Equivalent Sine Input
FEA	Finite Element Analysis
FEM	Finite Element Model
FRAC	Frequency Reponses Assurance Criteria
FRF	Frequency Response Function
JAXA	Japan Aerospace Exploration Agency
KEF	Kinetic Energy Fractions
MAC	Modal Assurance Criteria
MKE	Modal Kinetic Energy
MP	Modal Participation
MPP	Measurement Point Plan
NASA	National Aeronautics and Space Administration
RSS	Root-Sum-Square
SEF	Strain Energy Fractions
SEREP	System Equivalent Reduction Expansion Process
SRB	Solid Rocket Booster
SRS	Shock Response Spectrum
TAM	Test Analysis Model

the correlation through modal analysis and the application of Modal Assurance Criteria (MAC) [1] and Cross-Orthogonality Checks (COC) [2]. With this approach, FEM normal mode shapes from eigen-analyses are evaluated against corresponding experimental mode shapes extracted from frequency response functions (FRFs) captured during vibration tests. For large, intricate structures, such as scientific spacecraft, the modes within the frequency range of interest are typically too numerous for all modes to be dealt with in-depth during correlation and update. This requires the application of target mode selection methods to identify modes to prioritize in correlation and update activities.

Another approach is the direct comparison of test and analysis results obtained in the frequency domain; such as using the Frequency Response Assurance Criteria (FRAC) [3]. FRF based methods have the advantage that the FRFs from the test can be used directly in the correlation, without requiring the extraction of modal parameters and identification of target modes [4]. This is a benefit in that it not only circumvents the effort required to extract the modal parameters, but also avoids the uncertainty introduced to the test data as a potential consequence of modal parameter estimation issues. Conversely, it should be noted that there are also drawbacks to the frequency based approach. For example, while FRF based comparisons may somewhat negate the issue of target mode selection, more care must be taken in deciding which responses are considered most critical, as testing can include hundreds of accelerometers therefore generating a large amount of data to use as potential correlation targets. Additionally, in normal modal analysis, damping may be neglected, whereas when comparing responses in the frequency domain it is necessary to introduce a damping model to the FEM [5]. The inclusion of damping is an added level of complexity and uncertainty not present in purely modal comparisons. Consequently, modal based correlation is a common approach and is mandated by the European Cooperation for Space Standardisation (ECSS) modal survey assessment [6] and corresponding NASA documentation [7]. Due to the frequent application of modal techniques, the results of modal correlation checks are arguably more widely understood and values indicating good correlation are well established. The required level of correlation in terms of FRF based methods on the other hand is currently less clear [8]. As such, modal correlation remains an industry standard, making target mode selection a topic of continued relevance.

Over the years, not only has the intricacy of spacecraft structures increased, but the analytical representation of the structure in the FEM has become more detailed and meshes more refined. With ever increasing numbers of degrees of freedom, the numbers of modes represented in these models are also increasing. In many cases, there is also a high modal density within the frequency range of interest. Additionally, the increased complexity of FEMs raises the number of parameters which have potential to become variables during FEM update. As such, more than ever, an emphasis on containment of the problem, and focus on the most important aspects, is crucial to effective correlation activities. Thus there is a need: to assess whether traditional methods, even with considerable heritage, are still suitable with respect to state-of-the-art applications; to ensure that these methods are being implemented appropriately; and to consider newer alternative approaches which present potential benefits.

This study has therefore been conducted in order to: determine the extent to which the structure itself dictates the modes of significance, versus the influence of the applied excitation; to assess several commonly applied methods used to select target modes for correlation; and to explore potential for improvement in the levels of correlation of these critical modes to test data. Primarily, modal characterization from normal modes analysis is to be evaluated against an alternative measure of mode significance which accounts for excitation levels derived from CLA loading scenarios [9]. This provides a means to assess the ability of the more standard target mode selection criteria to identify the modes which are ultimately the most significant to the spacecraft during qualification testing, and eventually in launch/flight.

Among the most commonly used target mode selection criteria is modal effective mass [10]. It is referenced as an indicator of mode importance in both the ECSS Modal Survey Assessment documents [6] and corresponding NASA documentation [7]. Modal effective mass is a measure which is used to identify modes typically associated with notable loads through the base of the spacecraft, and which are therefore expected to have an influence in the interaction with the launch vehicle during the CLA. These modes are therefore often considered as the most important to correlate as they contribute not only to responses within the spacecraft, but also to the dynamics of the coupled system when mounted in the launch vehicle. Nevertheless, modes with relatively low effective mass may also be extremely significant in terms of excitation of the equipment on the spacecraft itself. Local modes, only affecting particular components or sub-systems in the structure, can have serious consequences for the operation of the spacecraft and its ability to successfully complete its mission. Identifying locally, as well as globally, significant modes is therefore a key consideration when developing target mode selection procedures. [11,12]

Parameters which are able to highlight modes demonstrating prominent dynamic activity in a particular region of the structure must therefore also be examined. A common method to identify these local modes is the examination of energy fractions. For each mode, the energy fractions are essentially an indication of the amount of energy of the total system which is contained in any given component/sub-system. This can take the form of kinetic energy or strain energy fractions (KEF and SEF, respectively). These energy fractions are often calculated in order to identify local modes which may be missed by modal effective mass identification due to their minimal impact on the response of the overall load levels [11], but which are nonetheless critical when attempting to ensure the successful operation of the spacecraft. As such, Chung and Sernaker [11] proposed that both the modal effective mass and the energy fractions should be considered in conjunction in order to include both global and local modes of note as targets.