Aerospace Science and Technology 33 (2014) 82–91

Contents lists available at ScienceDirect

Aerospace Science and Technology

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A correlation study of satellite finite element model for coupled load analysis using transmissibility with modified correlation measures

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A R T I C L E I N F O

Article history:
Received 26 July 2013
Received in revised form 15 December 2013
Accepted 3 January 2014
Available online 10 January 2014

Keywords:
FE model updating
Coupled load analysis (CLA)
Sensitivity analysis
Output transformation matrix (OTM)
Nonlinearity
Transmissibility
Amplification factor (Q)

A B S T R A C T

In this paper, a correlation study of satellite finite element (FE) models for coupled load analysis (CLA) using transmissibility and modified correlation measures is reported. CLA is performed with the launch-vehicle company to assess the structural integrity of satellite structure as well as the safety of its payload and electronics as a final verification by investigating the calculated acceleration, gap, and interface loads under launch environment conditions. To increase the accuracy of CLA, the complex FE model has to be validated via FE model updating with the results from dynamic tests, such as sine vibration testing, with proper criteria of correlation. When comparing modal properties obtained by analysis and testing, such as natural frequencies, mode shapes, and frequency response functions (FRFs), transmissibility measured from accelerometers with known input acceleration, but not input force, is used as a reference test data because it is often difficult or impossible to measure excitation force directly in many industrial structures.

To match analysis results with the test results showing weak nonlinearity with respect to excitation level, several peaks of acceleration as well as modal properties are taken from transmissibility according to the excitation level, and then the FE model is updated using the sensitivity analysis with several correlation measures, such as frequency deviation error, frequency domain assurance criteria (FDAC), frequency response assurance criteria (FRAC) and modified versions of them to customize the correlation measures for CLA.

Finally, it is shown that the proposed approach with transmissibility and the modified correlation measures is quite efficient and reliable for preparing a FE model for CLA, while meeting the standards of many aerospace agencies.

1. Introduction

Since the first satellite, Sputnik 1, was launched in 1957, approximately 80 orbital launches and launch attempts have existed according to a recent survey [17]. Many of the recently-launched satellites have important missions such as earth disaster monitoring, city planning, communication, and so forth. Also, it requires extreme expense from hundreds of millions to thousands of millions of US dollar. Therefore, before the launching of satellites, stringent testing and analysis are routinely carried out.

The structural and functional soundness of small and mini satellites is verified before launch by environmental tests instead of analysis because they may not respond structurally to low-frequency vibration [33]. However, in the case of medium-sized and large satellites weighing over a few hundred kilograms [36], their structural weight has to be minimized as much as possible to give much mass allocation to payloads. Accordingly, many of the natural frequencies of satellites are placed in the region lower than 100 Hz; thus, the possibility of dynamic coupling between satellites and launch vehicles is increasing. To clarify the coupling effect, coupled load analysis (CLA) is performed with the launch-vehicle company to predict its transient dynamic behavior subjected to launch loads highly concentrated in the low frequency region caused by the critical launch events, including lift-off, stage separation, and maximum gust. As the result of CLA, maximum acceleration, minimum gaps between adjacent parts, and maximum stress at the critical area can be predicted, and they are used as a final verification of satellite design [23,5,20,19]. Therefore, it is said that the accuracy of CLA is directly proportional to that of a satellite FE model. To obtain a reliable result, a FE model has to be properly updated to match test results such as sine vibration testing from 0 Hz to 100 Hz because many of the launch-vehicle loads are concentrated in the low frequency range.

Typically, updating FE models of complex aerospace structures up to a certain level showing excellent agreement with all test results is quite difficult or impossible because it is an extremely laborious task to obtain satisfactory results. Moreover, if

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1270-9638/$ – see front matter
http://dx.doi.org/10.1016/j.ast.2014.01.002

the tolerance of the correlation criterion is too tight, it cannot be converged in time. In such circumstances, there is a trade-off between time and accuracy. Moreover, sine vibration test results of satellites typically show weak nonlinearity, which makes it difficult to choose an appropriate reference for comparison with the analysis results.

As of early 1990s, to increase the accuracy of mathematical models, research on FE model updating methods combined with vibration testing and optimization techniques have been have been actively pursued in academic and industrial fields, in parallel with increased computing power. There have been numerous works on methodology, including direct methods and iterative methods [12,9]. In direct methods, the stiffness and mass matrices are modified to reproduce the test data exactly, but such methods have little physical meaning due to modification of the matrices. Also, they do not guarantee the absence of extra zero energy modes in the frequency range of interest. On the other hand, iterative methods combined with the sensitivity analysis have been widely adopted, but users have to set the parameters, such as mode pairing, proper correlation criteria, and so forth. However, setting the parameters is not so straightforward due to many uncertainties: the stiffness of joint and contact surface, the nonlinearity of damping associated material hysteresis and friction. To overcome the aforementioned problems in deterministic approaches, stochastic approaches have been proposed by several authors [16,3,32]. They perform FE model updating by considering the scatter of all physical parameters via optimization with Monte Carlo simulation. However, considering current computing power, they are still complex and much more computationally expensive than the deterministic approach.

In the paper, we limit our attention to iterative methods combined with sensitivity analysis and focus on resolving the problems of complex aerospace structures like satellites and aircrafts having many natural frequencies lower than 100 Hz [15,35,8].

From the viewpoint of modal parameter identification, the most widely adopted approach uses frequency response function (FRF) based on forces such as inertance (acceleration versus force), mobility (velocity versus force), and receptance (displacement versus force).

In the case of transmissibility consisting of output-only data, which is a normalized FRF, modal property extraction is not so straightforward due to the loss of information about mass, although many alternative approaches have been proposed to overcome this issue [6,34]. However, in the case of sine vibration testing, the excitation location is known and fixed, and an accelerometer is properly installed at the excitation location [27,28]. Therefore, the pole of transmissibility simply becomes the system's pole indicating natural frequency, and other helpful properties for mode identification can be achieved as verified by previous work [34]. In this work, we follow the aforementioned approach based on transmissibility because it is absolutely difficult or impossible to measure excitation force directly in many industrial structures.

The objective of this work is to perform a correlation study for CLA to match with sine vibration results having slight nonlinearity with respect to the excitation level using transmissibility with correlation measures including frequency deviation error, frequency domain assurance criteria (FDAC) and frequency response assurance criteria (FRAC), and their modification of FRAC to assess the quality of FE models.

The remainder of this paper is organized as follows. In Section 2, the theoretical background of CLA is briefly summarized. Then, in Section 3, the proposed procedure of FE model updating with a satellite FE model (see Fig. 1 and Table 1) is explained. All results with modified correlation measures are also compared with test results and a rigorous discussion is presented in Section 4. Finally, we close the paper with concluding remarks in Section 5.

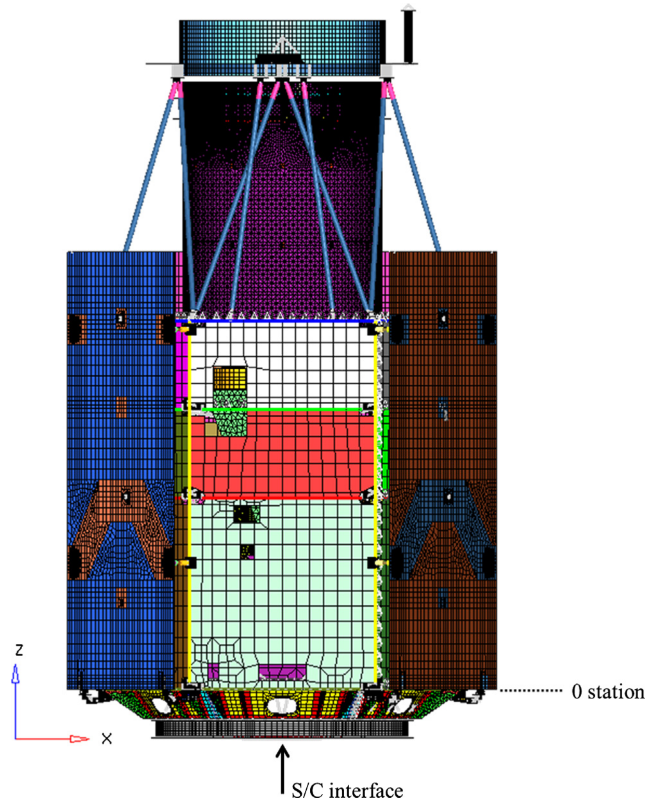

Fig. 1. FE Model of a satellite.

Table 1
Summary of a satellite FE model.

Subject	Summary
Dimension	Diameter 2.02 m × Height 3.47 m (Stowed configuration)
Total weight	967 kg
Number of nodes	269,039
Number of elements	365,644

2. Coupled load analysis

2.1. Background

CLA is carried out together with the launch-vehicle company to predict the maximum flight loads of satellites which are amplified by the dynamic interaction between the spacecraft and launch vehicle. CLA usually is performed several times during the course of development of a satellite, e.g. preliminary coupled load analysis (PCLA), verification coupled load analysis (VCLA). The objective of PCLA is to predict transient dynamic loads during launch and compare the values with the design limit load (DLL) to check whether or not every component is safe, and the results may be used for subsequent sine vibration testing to prevent the satellite from being over-tested [36]. VCLA aims to verify the safety of the satellites design by comparing flight loads with DLL as a final assessment.

Usually, before CLA is performed, the FE model is properly updated with the sine vibration test results within reasonable tolerance limits. After the FE model is updated, the satellite FE model is condensed via Craig–Bampton reduction, which is a method for reducing the size of a FE model with the assumption that several boundary points remain fixed [5]. The condensed model is then transferred to the launch-vehicle company in the form of the output transformation matrix (OTM), comprised of the acceleration transformation matrix (ATM), displacement transformation matrix