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Spacecraft base-sine vibration test data uncertainties investigation based on stochastic scatter approach

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ABSTRACT

This article describes some results of the study "DYNAMITED". The study is funded by the European Space Agency (ESA) and performed by a consortium of European industries and university, led by EADS Astrium Satellites.

One of the main objectives of the study is to assess and quantify the uncertainty in the spacecraft sine vibration test data. For a number of reasons as for example robustness and confidence in the notching of the input spectra and validation of the finite element model, it is important to study the effect of the sources of uncertainty on the test data including the frequency response functions and the modal parameters.

In particular the paper provides an overview on the estimation of the scatter on the spacecraft dynamic response due to identified sources of test uncertainties and the calculation of a "notched" sine test input spectrum based on a stochastic methodology.

By means of Monte Carlo simulation, a stochastic cloud of the output of interest can be generated and this provides an estimate of the global error on the test results. The cloud is generated by characterizing the assumed sources of test uncertainties by parameters of the structure finite element model and by quantifying the scatter of the parameters. The uncertain parameters are the input random variables of the Monte Carlo simulation.

Some results on the application of the methods to telecom spacecraft sine vibration tests are illustrated.

1. Introduction

The development of a spacecraft structure involves both analytical and test activities which must be combined to improve performance and reduce schedule and costs. Base-drive sine vibration testing plays a crucial role in the qualification of the spacecraft structure as well as in the validation of the structural finite element model. Test data reflects not only the specimen behaviour, but other phenomena such as the influence of the test fixture, the overall shaker configuration, the sine sweep rate effect, signal processing, etc. Moreover, the structure itself may have strong nonlinear behaviour which could interfere with the testing and adversely affect the measured data. Without adequate test procedures and computational methods to identify and quantify the various sources of problems, uncertainties and error in test data, the ensuing structure qualification and mathematical model validation processes may be largely compromised.

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Within this context, the European Space Agency (ESA) has funded the study ‘‘DYNAMITED’’ [1], acronym for ‘‘DYNamics: AssessMent and Improvement of TEst Data’’. The study has been performed under the technical management of ESA by a consortium of European industries and university, led by EADS Astrium Satellites. This paper provides an overview on two investigations in the area of the development of pre-test methodologies: the estimation of the scatter on the spacecraft dynamic response due to identified ‘‘sources’’ of test uncertainties and the calculation of a ‘‘notched’’ sine test input spectrum with stochastic uncertainties taken into account, here referred as ‘‘stochastic notching’’ [2,7].

The study ‘‘DYNAMITED’’ included other subjects of investigation in the area of pre-test and post-test methodologies [2], for example the accurate measurement of the shaker-spacecraft interface forces, the effects of the shaker parasitic motions, improved methods of sensor positioning for vibration mode observability [3], accurate estimation of the effects of the sine sweep rate on the test data, detection and localisation of non-linear structural behaviours.

Most of the developments have been tested during the test campaign of the structural test model (STM) of the ESA spacecraft SWARM and telecom spacecraft.

2. Material and methods

2.1. Test uncertainties

Space structure shall be strength enough to survive the severe launch environments, which is verified by mechanical testing. The spacecraft mechanical behaviour is analysed by finite element model (FEM) for both launcher couple load analysis and test to avoid over testing or spacecraft damage on the shaker table. Finally, the spacecraft behaviour on the shaker shows discrepancies with the FEM numerical behaviour.

Structural vibration tests are subject to a number of uncertainties that can prevent to predict accurately by analysis the vibration test reality. The objective is thus to identify and quantify the test uncertainties and estimate their influence and associated dispersion that may be expected on the test data.

The uncertainty is a combination of several types of elementary uncertainties, grouped as follows:

- specimen/transducer interface: the uncertainties relate to the transducer location and orientation as well as to the way the transducer is connected to the specimen
- acquisition chain: the uncertainties relate to the transducer, its conditioner, and its digitalizer
- post-processing: the uncertainties are related to the post-processing techniques of the raw test data

Within the study the test uncertainties have been identified, quantified and combined according to current recommendations for practice ([8,9,12,13]). The goal is to generate, by means of Monte Carlo simulation (MCS), a stochastic cloud of the output of interest and this provides an estimate of the global error on test results. The cloud is generated by characterizing the assumed sources of test uncertainties by parameters of the structure FEM and by quantifying their scatter. The uncertain parameters are the input random variables of the MCS. If the finite element model represents adequately the structural behaviour and the assumed scatter in the input variables takes properly into account the test uncertainties, the simulation may anticipate the dispersion in the test results ([12,13]). Direct MCS is very simple, but at the same time tremendously powerful. If the test data are available, an expected result could be that the predicted envelope of sine test responses includes sensor responses measured during the vibration test.

Another aspect which has been analysed is the so called ‘‘stochastic notching prediction’’. By starting from the outcome of the previous calculations, both test and FEM uncertainties are applied to finite element model sine responses to get a notched envelope of the sine test input spectra. The objective is thus to characterize the robustness of the FEM prediction, or the FEM sensitivity to both test and model uncertainties, to anticipate problems (e.g., large dispersion on critical sensor responses) and to facilitate negotiation with the ‘‘Launcher Authority’’ by raising soon before the test potential not predicted notchings and/or notch depth. A quite risk assessment can be provided soon to save time during the tight test context.

2.2. Test uncertainties classification and modelling

All the test uncertainty parameters can be classified with respect to the output they modify in a FEM analysis. The test uncertainties which are considered in the study are reported in Table 1. It can be recognised that the natural frequency identification is not sensible to sensor orientation while the mode shapes and therefore the modal assurance criterion (MAC) values are affected. The MAC is normally used to quantify the correlation degree between test and analysis mode shapes. It should be noted that the sine response analysis, which is crucial in this study since it directly relates to the test measurements, is affected by all the listed test uncertainties. Other classifications can be found in literature, e.g., [10,12].

All the uncertainties are modelled as NASTRAN parameters.

The reference FEM shall be adequately modified to model by different ways all the types of uncertainties. It is thus of prime importance to avoid modifying the responses of the reference FEM. This is not always a simple task [4].

The error on the location of the transducer is a rather difficult uncertainty to take into account in a NASTRAN finite element model. Two methods are proposed: the MPC and the tangent plane methods [4]. The uncertainties and errors in the sensor orientation are mainly due to difficulties to access to the prescribed location of the spacecraft. This error may