APPLICATION OF THE MASS OPERATOR METHOD TO ESTIMATE THE INTERFACE FORCES IN THE VIBRATION TESTING OF AN OPTICAL PAYLOAD

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ABSTRACT

This paper addresses a vibration campaign undertaken for the structural thermal model (STM) of the Optical Unit of the ALTIUS instrument. Specifically, the use of the mass operator method is demonstrated for the estimation of the interface forces in the absence of force transducers. Along with the implementation of the mass operator method using the commercially available software Primodal, a few capability extensions using in-house tools are presented. The paper presents the approach taken starting from the test preparation until the calculation of force-based notching limits. The method is also compared with other typical methodologies to estimate interface forces. Practical considerations of a test campaign such as data availability, data processing and testing time considerations are also briefly touched upon to provide a holistic view of the use of such a methodology. The aim is to present the process which could be a starting point for a discussion on the best practices that can be followed by the testing community facing similar test objectives and limitations.

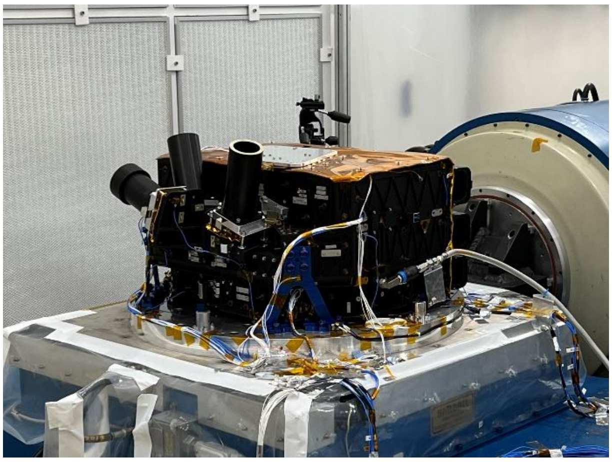

Figure 1: The ALTIUS Optical Unit instrument STM mounted on a shaker bench

BACKGROUND

Verification by means of testing is an integral part of the development of satellites and instruments launched to space. While the simulation capabilities have been ever increasing in their fidelity and efficiency, there are still major limitations to using just numerical predictions. Hence, testing is almost always an essential part of the verification process and a must to gain more confidence in the numerical models. A typical hardware item meant to be launched to space is subjected to multiple instances and multiple types of test campaigns. This paper maintains its focus on the structural testing of an instrument; specifically, the base-driven vibration testing performed on a shaker.

The broader goals of any vibration test campaign are to ensure that the hardware is robust enough to survive and function after being subjected to the harsh launcher loads. These launcher loads are defined at the interface of the launcher with the rest of the hardware chain mounted on the adapter plate. The hardware here can refer to a variety of items ranging from a full-fledged satellite to an individual instrument on the satellite or even a smaller sub-unit within any of the instruments. While fully instrument satellite level tests have to invariably be tested (often multiple times over the development lifecycle), it is also very common to test smaller modules individually. These are primarily driven by the design and development philosophy where individual items need to be qualified separately.

At every instance of this division of the structure, it is essential that the environmental loads that the item is subjected to are coherent with the initial specification of the loads that are defined, usually in the launcher manual. The specification of loads at any interface (other than the one with the launcher) are obtained either from a coupled finite element model (FEM) or through an early-stage satellite level test where accelerometers placed at the interfaces of interest measure the response under launcher loads which can subsequently be used as specifications in the individual tests of the items.

While the responses measured in the coupled configuration can be used in the standalone test of the sub-article, the severity of the same loads can be much higher owing to the fixed constraint at the bottom of the article as opposed to the more flexible conditions experienced by the same sub-article when mounted on the original item. An adjustment for the same has to be done in order to not over-test the item. One of the most common means to do this is through force-limited notching.

In this approach, an appropriate reduction of the input loads in select frequency bands is allowed if it is demonstrated that the force introduced in the item's interface under the original loads is higher than it would experience had it been tested in a coupled configuration rather than stand-alone [1].

While a larger discussion on this topic is out of scope of the current paper, it is to be highlighted that an accurate measurement (or estimation) of the interface forces is at the heart of any successful vibration test campaign.

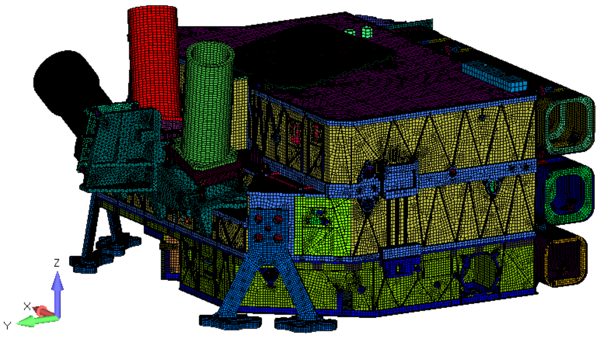
Figure 2: ALTIUS Finite Element Model

The numerical verification of the structure under vibration loads is typically performed by means of a finite element model (FEM). This model can also be used to calculate the loads at any interface within the article. However, until the test campaign is actually conducted, the accuracy of the FEM is still largely not verified. As a result, using the interface forces from this uncorrelated model without reviewing them in-situ in a test campaign runs two major risks: over or under-testing of the item. Both of these are undesirable for various reasons.

It is therefore essential that the data obtained from the test is used in estimation of the forces without relying solely on the FEM.

Force Transducer based measurements

The most accurate means of measurement would be to measure the forces directly through the use of force transducers.

The fundamental advantage of this approach is that the actual forces experienced at the interface of the test item during the test become available and are used for notching, without having to rely on numerical models. In addition, in some cases, this information may be used in real time to perform auto-notch in a closed-loop fashion. The main disadvantages are that this method adds significant complexity to the test set-up, that it requires purchasing additional test devices (transducers) and MGSE (fixtures), and that it is more difficult to set up correctly, i.e., the test operators need to be trained specifically on how to properly work with force transducers. In addition, it must be noted that in many European structural test facilities, the use of force transducers is still limited or non-existent. For this reason, indirect methods of force-estimation are needed.

Accelerometer based force estimation

Test articles are typically instrumented with multiple accelerometers to monitor the response in locations which are deemed critical. One simple means of indirect force estimation is through the use of one of these accelerometers. A location which experiences excitation in all of the major modes of the article, and which is relatively clean around the peaks is a prime candidate for such indirect estimation. Clean here means no local modes polluting the signal and one which preserves the proportion between peaks, and which exhibits similar shape as the normalized force transfer function.

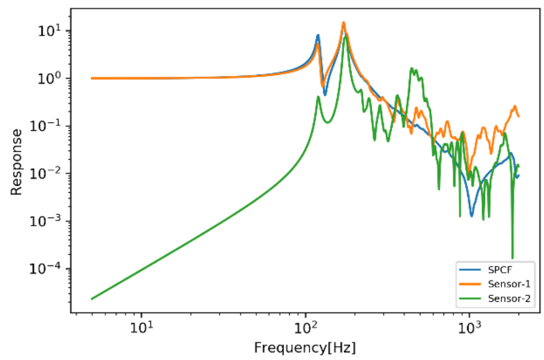

Figure 3: Example showing two sensors tracking the interface force. One of them (orange) has a much better correspondence with the interface force than the other (green)

While simple and elegant in theory, this can have a few challenges in practice. The FEM used in the predictions prior to the tests is typically uncorrelated. As a result, the prediction of the interface forces is expected to be inaccurate to some degree. At best this could be just a few percent off from what is observed in reality. However, the FEM could also be inadequate in predicting all of the observed modes. As a result, the choice of this reference sensor could turn out to be mis-guided. Depending on the nature of the inaccuracies of the FEM, some corrections are possible in-situ. However, this method could also just turn out to be unsuitable. And as the risk of finding this out only during the test is not negligible, such a method is also not the best alternative to the force transducer method.

It is to be noted however that if a correlated FEM is available, such as from an earlier test campaign, the risk of unforeseen inaccuracies is greatly reduced, and this method can in fact be the better choice.

Mass-operator based force estimation

A second alternative to the force transducer-based measurement is through the use of the mass-operator method. At its essence, this is a method based on Newton's second law where the interface forces are estimated combining the measured accelerations with the mass distribution of the article (obtained through FEM) [2].

$$F_j(\omega) = \Psi_{ja} M_{aa} \ddot{u}_a(\omega) \quad (1)$$

where:

Ψ_{ja} : Rigid body modes at the a-DOF due to translations and rotations introduced at the j-DOF (interfaces)

M_{aa} : Mass matrix of the reduced model. Obtained from the Guyan reduction from NASTRAN

$\ddot{u}_a(\omega)$: Measured accelerations

Even though this method uses the FEM like the response-based method, the demands on accuracy from it are much lower as the FEM is only used to predict the distribution of mass in the article. The mass of the article is typically known to a high degree of compared to the stiffness where the modelling assumptions are much more critical. As a result, even an uncorrelated finite element model can be quite accurate in its representation of mass distribution.

The mass operator method uses a statically reduced model from the FEM and combines this with the accelerometer response to calculate the resulting interface force at the base of the structure.

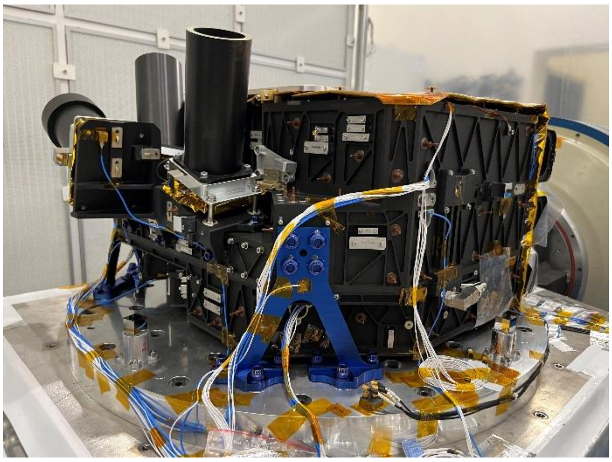

Figure 4: A close up of the ALTIUS OU instrument STM mounted on the shaker table with accelerometers

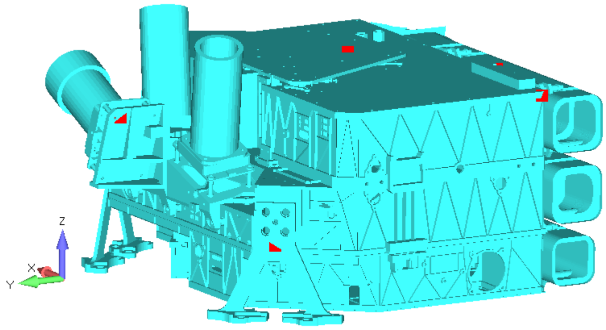

Figure 5: Sensor locations in the FEM (1/3)

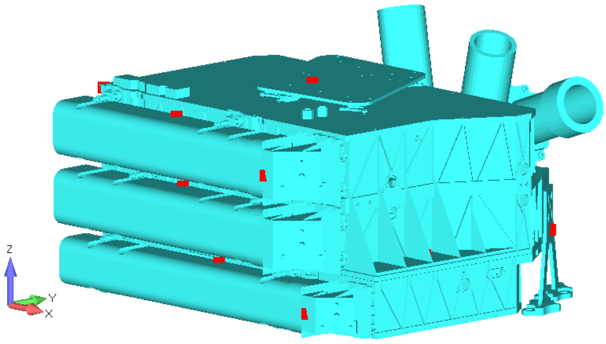

Figure 6: Sensor locations in the FEM (2/3)

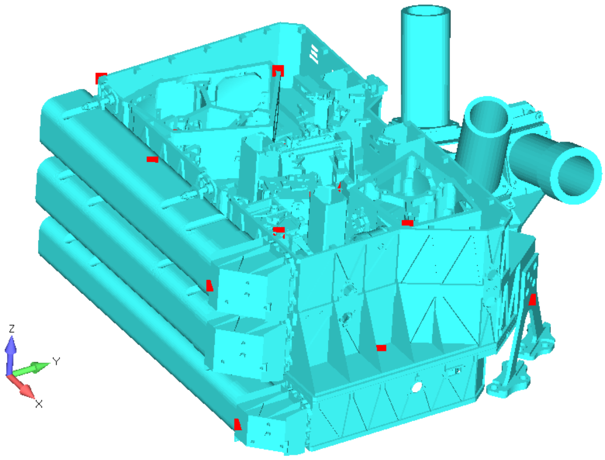

Figure 7: Sensor locations in the FEM (3/3)

The inherent advantage of this method is in the use of real-time data from the test. This way, no approximations are made, and the force estimation is expected to be accurate to a high degree. The one limiting factor could be availability of adequate number of accelerometers and their distribution across the item. If the article is too small, placing a lot of accelerometers might introduce sensor-induced effects which are undesirable. Whereas if the article is too large, there is often a limitation on number of channels available at the test facility for the purposes of data extraction which may limit the accelerometer usage and introduce inaccuracies.

PRACTICAL IMPLEMENATATION OF THE MASS OPERATOR METHOD.

For the work discussed in this paper, the commercially available software Primodal is used to perform the mass operator calculations. The reader is directed to the manual of the software for more details on the implementation of the same [2].

For doing this calculation, Primodal needs the reduced model information along with the details on the correspondence between the nodes (in the reduced FEM) which correspond to any given sensor from the test (identified by a unique label).

The reduction is a static Guyan reduction of the FEM performed in NASTRAN using the SOL 101 routine where the locations preserved (A-SET) correspond to the accelerometers in the test.

With these inputs in place, the mass operator method can be implemented in the NOTCH module of Primodal to generate the transfer functions of the interface forces. Before using these along with the input loads to assess the actual forces, a few checks are deemed necessary.

While due to the usage of real time test data, the mass operator method is inherently more robust, errors in the prediction can still occur in the implementation of the method. The two most common sources of error are inaccuracies introduced in the static reduction process or incoherent sensor orientations.

FEM internal consistency check

The first aspect about the accuracy of the reduced model can be verified prior to the test using just the finite element method. This can be done by means of a frequency response analysis from which the accelerations at the desired sensor locations are to be extracted along with the interface force at the location of constraint (referred to as *SPCF* in the Figure 8).

Separately, using the statically reduced finite element model along with the FEM derived accelerations, the interface forces can be estimated (referred to as *IF: Mass Operator* in the Figure 8). A comparison of these two forces is an indicator of whether the calculations are internally consistent or not.

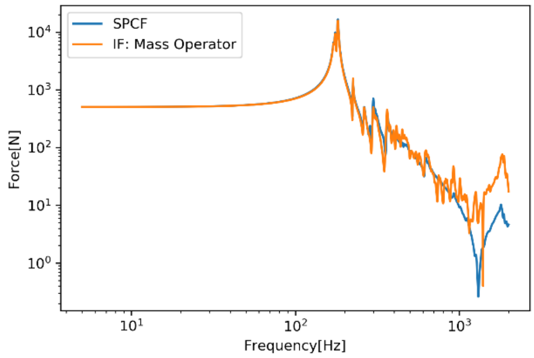

Figure 8: Comparison of the interface force calculated directly from the FEM (orange) and the interface force estimated through the mass operator method (blue)

A deviation here would most certainly be the result of insufficient number of sensors or unsuitable locations.

Low frequency force check

While the check above would show the consistency of the model reduction and the mass operator calculations, it could still have errors in the prediction. An additional check to perform is to confirm if the low frequency force value is equal to the mass of the article (under a load of 1g). With the article moving as a rigid body, there is no dynamic amplification expected hence the force should be exactly equal to the mass.

The same check shall be repeated once the first test data is available to verify the sensor orientations. With all the sensors experiencing excitation in phase to the source and under the absence of any dynamic amplification, the response should just be equal to the excitation acceleration times the mass of the article.

Any deviation here indicates one of two possible issues: either the sensor orientation used in the mass operator method is inconsistent with respect to what is implemented on the hardware, or the sensor has faulty readings.

In case visual inspection is possible, this is always recommended to make sure the orientations implemented in the software match those of the accelerometers.

Sine vibration

A typical sine vibration loading is applied as a frequency sweep between 5-125 Hz to the particular load levels. The loads are applied in steps of increasing intensity to verify structural integrity at every level. Typical steps could go from:

-6db : -3db : 0db

For the initial Sine run (-6db), the forces can be calculated using the low-level sine sweep (LLSS) (or more commonly referred to as resonance search) data.

And the resulting data from this run (-6db) can be used to refine the estimate of the forces for the next run and so on, until the final run is completed. The reason for this refinement is the possible change in amplification depending on the applied load levels.

A comparison of interface force calculation using just the LLSS along with the same done with half sine and eventually the full sine data is shown in Figure 9 and Table 1. It is seen that, in this particular case, the amplification is significantly higher at higher load levels. Not taking this into account would result in under-estimation of forces which eventually would result in less notching and a higher load input into the item risking the hardware.

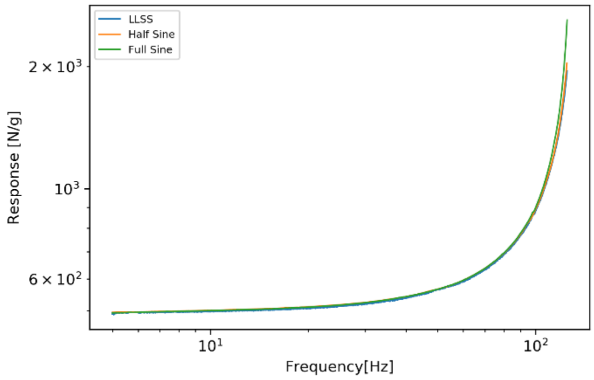

Figure 9: Comparison of force under sine loading obtained using mass operator method using multiple low level sine data

Table 1: Comparison of the interface forces for multiple cases in sine loading

Data Set	Peak Interface Force [N]	Delta [%]
Low Level Sine Sweep	19130	-
Half Sine	20003	5%
Full Sine	25535	33%

Random vibration

For the evaluation of the interface forces under random vibration loading, the same transfer functions generated using the low-level sine sweep (LLSS) run data using mass operator method can be used.

Similar to the sine vibration test, the random excitation is also applied in steps of increasing intensity to verify structural integrity at every level. Typical steps could go from:

-9db : -6db : -3db : 0db

However, unlike the sine vibration, in the random vibration runs, the phase information is typically not available. As a result, the data from each random run is not adequate to perform the mass operator method. This poses a challenge to refining the estimate of the interface forces based on the intermediate random runs. The motivation behind the load refinement is still the same as in the sine loading.

At ATG Engineering, a methodology was developed which enables using the intermediate random data for interface force refinement. The approach consists of combining the random data in amplitude form with the phase information from previous sine sweep runs to obtain a modified response function for each sensor. Using this composite data, the mass operator method is repeated, and an estimate of the interface force is obtained.

Note: This approach is valid as long as the modes do not change drastically between the low-level sine sweep and the subsequent random runs. In case large deviations in modal frequencies or modal behaviour are observed then the method is deemed unsuitable.

An example of such a force refinement is shown in Figure 10 and Table 2. It is seen clearly that there is a slight shift in modal frequencies as compared to the initial LLSS. A deviation of this magnitude can be accommodated within this methodology. Additionally, it is also seen that the interface force increases with increasing load. This is a similar trend to what was observed in the sine loading. The deviations here are significant and not accounting for this increase in amplification can result in input load levels much higher than needed.

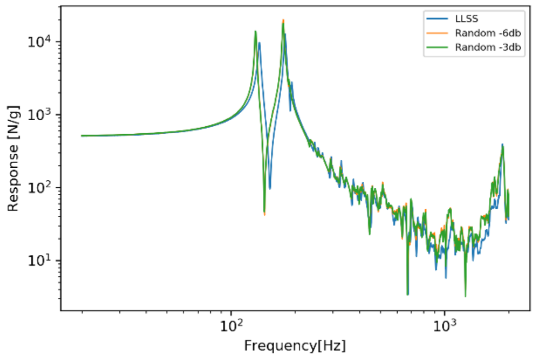

Figure 10: Comparison of interface force under random loading using mass operator method using only low-level sine data and with intermediate random runs

Table 2: Comparison of the interface forces for multiple cases in random loading

Data Set	Interface Force: Peak 1 [N]	Delta [%]	Interface Force: Peak 2 [N]	Delta [%]
Low Level Sine Sweep	95510	-	124440	-
Random - 6db	129904	36%	196161	58%
Random - 3db	137075	44%	174677	40%

Notching

Using an accurate estimation of the interface force, the input load levels can be notched to the levels justifiable using the force-limited notching method. Here, with refinement of the force estimate at each intermediate level, a corresponding refinement of notch can be expected as well. The result, is an input load profile where the excitation is scaled down at those locations where the forces are notched, as shown in the Figure 11.

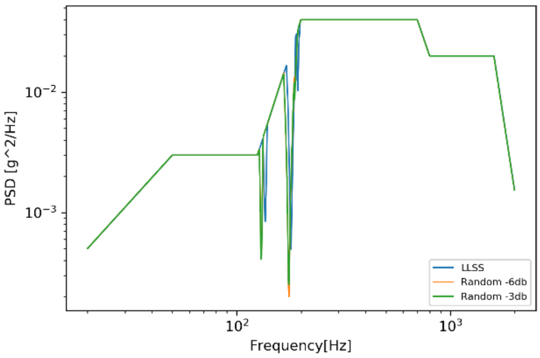

Figure 11: Differences in the analytically calculated notch profiles with revision of the interface loads.

In practical terms, however, it is more convenient to template the input load so that the notches are defined by a few points. This is more convenient for the test operator, and also overcomes some other limitations such as potential shaker controller issues.

It is also considered good practice to always have some margin on the notch (i.e. notch less than possible) such that even if unexpected amplitude changes happen in the subsequent run(s), the objectives of the test run are still met (i.e. the article is not under-tested). Having said that if certain items are critical and there is a real risk of over-testing resulting in damage of the article, a more careful look at the notch levels may be warranted.

Additional practical considerations during the test

While every test campaign is with its own challenges, the usage of mass operator method adds a layer of complexity which needs to be managed well. The impact this has on the logistics and on the additional time needed has to be understood by all relevant stakeholders. It is highly recommended to include the steps involved in this methodology in as much detail as possible in the step-by-step test procedure. Doing this ensures that the adequate amount of time is available to perform these calculations.

In case of limited number of sensors, a decision on whether or not a refinement is needed can also be made by going through the sensors data on the operator's screen to see the relative shift between runs. If the change is minimal or non-existent, there is likely no meaningful change to be expected using intermediate data. This is recommended as a general good practice to avoid spending valuable time between runs.

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