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Satellite Vibration Testing: Angle optimisation method to Reduce Overtesting

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ABSTRACT

Spacecraft overtesting is a long running problem, and the main focus of most attempts to reduce it has been to adjust the base vibration input (i.e. notching). Instead this paper examines testing alternatives for secondary structures (equipment) coupled to the main structure (satellite) when they are tested separately. Even if the vibration source is applied along one of the orthogonal axes at the base of the coupled system (satellite plus equipment), the dynamics of the system and potentially the interface configuration mean the vibration at the interface may not occur all along one axis much less the corresponding orthogonal axis of the base excitation.

This paper proposes an alternative testing methodology in which the testing of a piece of equipment occurs at an offset angle. This Angle Optimisation method may have multiple tests but each with an altered input direction allowing for the best match between all specified equipment system responses with coupled system tests. An optimisation process that compares the calculated equipment RMS values for a range of inputs with the maximum coupled system RMS values, and is used to find the optimal testing configuration for the given parameters.

A case study was performed to find the best testing angles to match the acceleration responses of the centre of mass and sum of interface forces for all three axes, as well as the von Mises stress for an element by a fastening point. The angle optimisation method resulted in RMS values and PSD responses that were much closer to the coupled system when compared with traditional testing. The optimum testing configuration resulted in an overall average error significantly smaller than the traditional method. Crucially, this case study shows that the optimum test campaign could be a single equipment level test opposed to the traditional three orthogonal direction tests.

1. Introduction

The launch phase is the most demanding mechanical environment typical satellites experience. The launch encompasses various types of loading including: quasi-static; highly transient or harmonic low frequency excitations; high frequency shocks; and vibro-acoustic excitations (for a more in depth overview of these see Ref. [1]). Thus, all payloads must ensure they will survive the launch. This is primarily done via vibration testing. However, current vibration testing methodologies generally tend to overtest - i.e. the harshest environment a satellite and its equipment must survive is testing, not the launch. Currently, overtesting is not simply the expected levels plus a margin, but excessive increases in the acceleration and stress levels to those seen in the launch phase due to approximation in test input and boundary condition - both of which will be explained in detail later. This leads to compromises in the design process with the focus moving from surviving the launch to surviving the testing. In an industry where mass and volume are at a premium, this over design is an unnecessary cost.

The primary method to ensure a payload or piece of equipment will survive the expected quasi static loads [2,3], sine loads [4–7] and acoustic or random vibrations [8–11] is to subject it to a prescribed vibration environment, usually on a shaker and slip table. Different inputs and methodologies are used for each form of loading, but it is still possible to test all three on the same piece of equipment. However, there are a number of issues with current methods, causing testing to be unrepresentative of the launch.

The conventional method of vibration testing involves putting the test item on a shaker and shaking it in each of the three orthogonal directions (X, Y and Z) according to the provided testing specifications. This approach often leads to undue amount of stress and acceleration put on the test article exceeding what it will see during launch.

Overtesting in pre-launch satellite vibration procedures have been investigated previously [12–14]. Two main causes of overtesting have been identified: the creation of the enveloped test specification [15]

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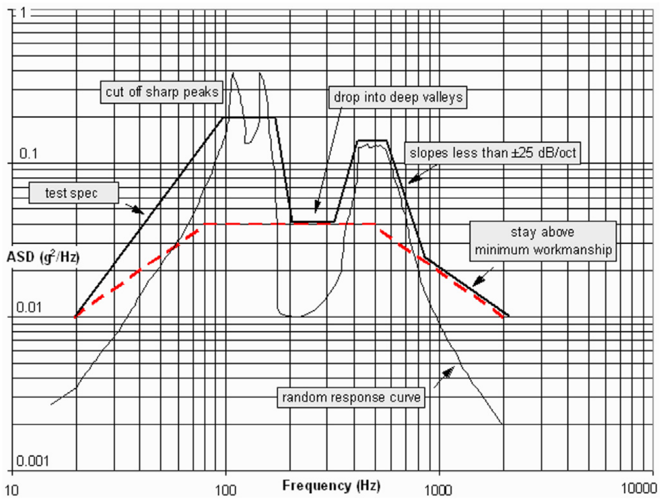

Fig. 1. Example Test Envelope Synthesis taken from Ref. [18]. The thin line is response curve and thick line is the test envelope created around it, with the dashed line representing minimum workmanship levels.

and the differing boundary conditions between flight and testing configurations [14,16]. These two causes are interlinked but opinions vary on which is the main cause. A third factor, testing direction, also plays a part. During launch, the vibration environment occurs simultaneously in all degrees of freedom, however the established test procedure is to test three orthogonal axes sequentially. Replacing a single 3D vibration environment with three separate tests can lead to serious compromises when designing tests [17].

Test specifications themselves are considered a main cause of overtesting, this is due specifically to the way they are created. The testing specifications are derived from response data collected either during previous launches or system level testing and analyses - i.e. the coupled system - at the interface between the test item and the rest of the structure. The final test specification input covers the peaks (which are often truncated) and usually eliminates the valleys, as shown in Fig. 1. This smoothing over the peaks and valleys is done to both simplify the testing specification and to include a safety margin [15]. When the anti-resonance frequencies of the couple system coincide with a resonance of the load system, the elimination of these valleys becomes a major issue. The smoothing of valleys can lead to overtesting by 10 dB–20 dB [13].

Additionally, the dynamics of the two systems - flight configuration vs testing configuration - are vastly different thus any input derived from responses from the flight configuration and applied directly to the testing configuration will not obtain the same responses seen during flight. This system mismatch is the second key cause of overtesting. The boundary conditions differ significantly between the flight configuration and the testing configurations. The flight configuration is a coupled system of either launch vehicle and payload or full satellite and component equipment, while the test configuration is simply the test item and the shaker table. In literature relating to vibration testing, the pair of structures in the coupled system are often referred to as 'source' (the higher level assembly - i.e. launch vehicle or full satellite) and 'load' (item under test - i.e. payload or piece of equipment) [19]. Additionally, the coupled system is often modelled as a simple two mass system, as shown in Fig. 2.

There are several methods currently used to reduce the overtesting due to these two causes. The most common is termed 'notching'. This involves altering the testing specification by lowering or limiting the shaker input levels usually around the resonant frequencies - i.e. put a 'notch' into the input [9,20,21]. There is no universally accepted notching method for random vibration testing [22], and many are available. Choosing the method for determining the notch is a key step

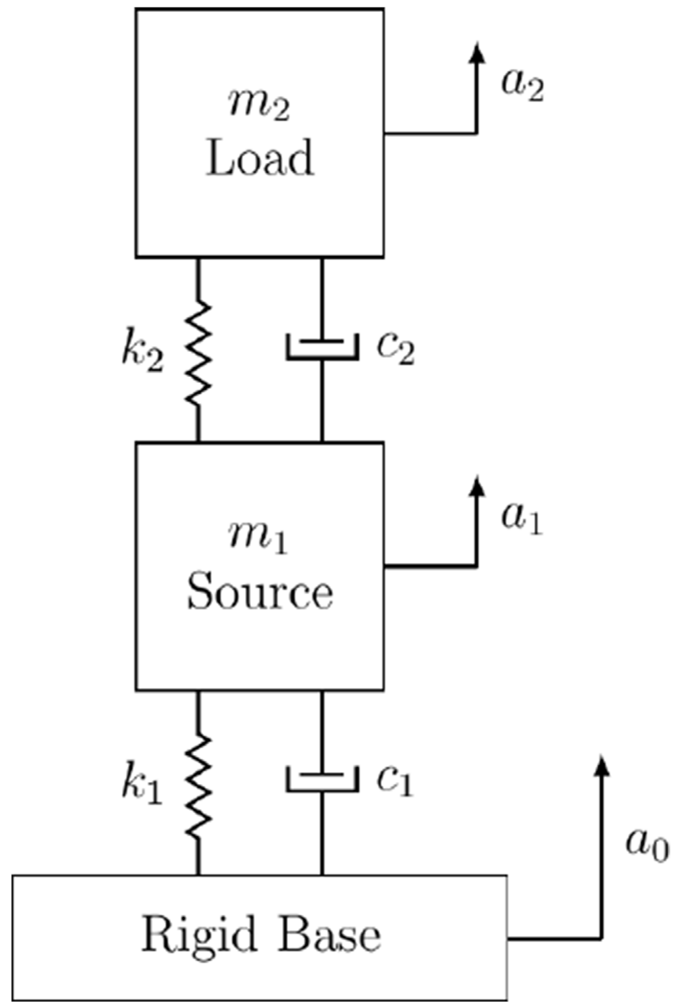

Fig. 2. Simple two DOF coupled system.

in developing a test campaign as it is important to ensure an accurate and representative input that minimises overtesting while also avoiding under testing. There are two main branches of notching methodologies. The first, called Response Limiting, directly notches and monitors the acceleration input. The second notches the force input and this is called Force Limiting [13,23–25]. In addition, both the payload manufacturer and the launch vehicle or higher assembly authority must agree upon the notching method - the manufacturer wants to limit overtesting to prevent the payload breaking during testing and the higher level authority does not want the payload to break during launch. They must set a testing specification they feel ensures this and are reluctant to allow excessive lowering of the test specifications.

Both types of limiting attempt to predict the in-flight responses or forces on the test item, measure that response/force during test and then notch the test acceleration input to keep below the predicted levels; of the two, force limiting is the more common [13]. The basis of all force limiting methodologies is basic definition of force: $F = ma$. The complication lies in the fact the dynamics of the two configurations are so different specifically the interfaces - as mentioned above. The coupled, or flight, configuration can be simply described as a two mass system (see Fig. 2) while testing is a single mass system (akin to removing m_1 from Fig. 2). The effect on m_2 of having m_1 present is known as the dynamic or vibration absorber effect and lies at the heart of the boundary conditions issues that lead to overtesting. The full theoretical explanation and background can be found in mechanical vibration text books [26].