Tailoring of Vibration Test Specifications for a Flight Vehicle

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ABSTRACT

Most equipment are subjected to vibration environment during their useful life. It is seen that nearly half of the failures observed during the flights of satellite launch vehicles or missiles are due to mechanical vibration and shock. Thus, these stresses must be carefully considered while defining the specifications. Specifications are established for a system for use during a simulation test to show that a product meets the requirements concerning resistance to the environment. If the equipment operates smoothly during a test, there should be a very strong probability that it will perform its intended task correctly in the real environment and vice versa. Hence, the specification must be at least as severe as the real environment and also representative of the real environment. It is also required that no other item of the equipment built according to the same design should fail in operation. Specifications should take care of this and thus the envelop of data obtained during the real world environment should be considered. Generally at the design stage and the initial development stage, existing standards like the Military Specifications or Joint Service Specifications are used as guidelines for formulating the specifications. This causes either an overtest or an undertest with regards to the overall spectrum or in specific frequency bands for any given structure. To overcome this, it is essential to develop a correct specification using the telemetry data acquired for a few flights and a method is required to be formulated for deriving the specifications out of the telemetry data so obtained. This paper discusses the formulation of a specification methodology, and algorithm in general. The above method is applied to a series of flight data obtained for a particular flight vehicle to derive a specification representative of the real world environmental conditions (tailoring).

Keywords: Shock and vibration, flight vehicle, simulation, flight data, vibration test specifications, military specifications, telemetry data, vibration environment, power spectral density

1. INTRODUCTION

Most equipment are subjected during their life cycles to vibration environment, such as those during road transportation, more so the aerospace systems, which have these environment during flight as well. It is seen that most of the failures (nearly half or even more) have been due to vibration and shock. It is therefore very important to take these stresses into account at a very early stage in the design and development of the equipment, using realistically defined specifications.

Specifications are used during simulation tests to show that the product meets the requirements concerning the resistance to the dynamic environment. Specifications therefore specify the severity of the environment. Specifications also have to take into account the purpose of the test apart from the realistic environment[1] it has to undergo. The different purposes of the tests are (i) development tests: In these tests, the levels need not be the real environment levels but are selected to reveal the equipment weak spots, (ii) qualification tests of units, (iii) qualification tests with integrated systems: In this test, the interaction of the different subsystems are evaluated, (iv) a simple transfer function measurement, which identifies the intrinsic behaviour of the structure, and (v) it could be an evaluation test to assess what levels of severity the equipment is able to withstand.

The specifications should also satisfy performance criteria, such as (i) if the equipment operates correctly during the test, it is strongly probable

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that it will also operate correctly during the real environment and *vice versa*. Thus, the specification should be at least as severe as the real environment, (ii) no other item of the equipment built to the same design should fail in operation.

Initially in the absence of any data, general specifications are drawn from the environment undergone by airborne system. However, these are not representative of the actual conditions, and hence during the actual flight much attention is paid to the acquisition of as much dynamic data as possible. Tailoring a specification for vibration in general, and also tailoring the specifications of a particular airborne system from a series of consistent flight vibration data have been described here.

2. TAILORING METHODOLOGY

Mil-Std-810 F generally suggests the tailoring procedure[2,3] as shown in Fig. 1.

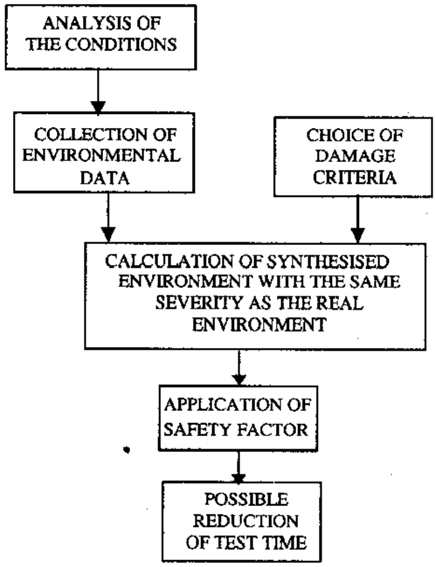

Figure 1. Tailoring procedure

Hence from the above, the determination of specifications can be divided into four main steps: (i) analysis of the life cycle profile, (ii) collection of data on the real environment, (iii) synopsis of the data, and (iv) establishment of a test program.

2.1. Analysis of Life Cycle

The entire life cycle is split into the various phases or situations, such as storage, transport (road, rail, air, ship, helicopter) and handling. Considering a flight vehicle as an example, this cycle is depicted as a flow chart in Fig. 2.

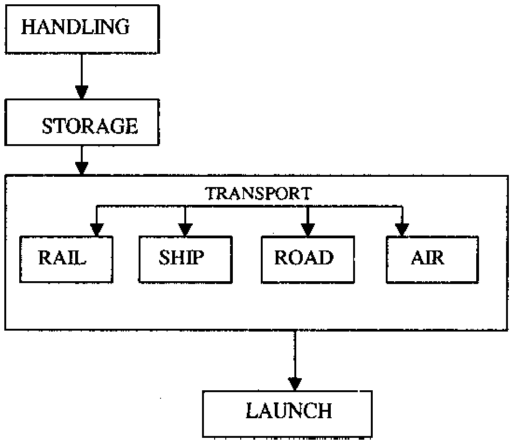

Figure 2. Life cycle

For each of the above specifications, the environmental parameters, such as vibration, shock, temperature, acoustics, etc. that could degrade the equipment performance are listed qualitatively.

2.2 Real Environmental Data Associated with each Situation

This data on the real environment associated with each situation can be obtained in any one of the following ways:

(a) Measurements are made under real environment (real vehicle, representing roads-actual track trials.

(b) Measurements are made on another type of vehicle in the same category. This would be a good approximation and can be used in the initial stages of development of another vehicle by extrapolation.

A test must now be defined from the data collected for each environment for each phase of the life cycle profile and it must meet the following requirements:

(a) It must have the same severity as in the real environment.

(b) Using standard test equipment, it must be possible to simulate the real environment.

(c) The damage potential of the real condition and the simulated environment should be the same. To satisfy the condition at (c), it is required to generate a method for equivalence in terms of the damage potential. From literature survey, the following methods are found to be widely acceptable and these methods are called the synopsis methods.

The main methods used for vibration are the power spectral density envelop, and the equivalence of the maximum response and fatigue damage spectra.

2.2.1 *Power Spectral Density Envelop*

The power spectral density envelop method is widely used and its applications to a set of power spectral density data obtained during actual flight has been described here.

In this method the specification is taken from the environment PSD, its pattern is simplified by broken straight lines. This process is represented in Fig. 3.

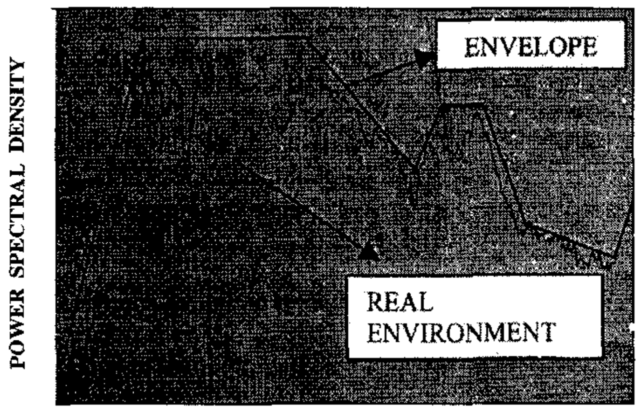

Figure 3. Example of power spectral density

Unfortunately, though this formulation of the envelope is fairly simple, it suffers from two apparent disadvantages. These are:

(a) The result obtained depends upon the specifier.

(b) As the trend is to encompass all the peak values of the reference spectrum, the effective value deduced would be much larger than the value of the initial PSD, so will the overall g_{rms} levels. Sometimes the factors can be as high as two.

The effects of the higher levels can be reduced by reducing the specification application time.

Considering the fatigue damages, if x_{eff} is the effective value of vibration characterised by the reference PSD (real environment), T_E is the duration of the event considered and X_{eff} the PSD effective obtained by the envelope, then the duration T_R for applying the envelope PSD can be calculated by the formula:

$$T_R = T_E\left[\frac{x_{eff}}{X_{eff}}\right]^b$$

where the ratio $\frac{X_{eff}}{x_{eff}} = E$ can be called the exaggeration coefficient ; and b = material constant.

If the value of E is high the duration of the specification T_R would be very less, and the instantaneous stress values would become very high, compared to the real environment. In such a case, a reshaping of the envelope would become essential. The value b depends on the material. Lower values of b indicate that the fatigue strength drops faster when the number of cycles are increased. The normal range of variation of b is between 3 and 25. Mil-Std-810 D, E and F give the values of b.

2.2.1.1 *Safety Factor*

To take into account all the uncertainties existing when the test specifications are written, the severities are often multiplied by a factor called safety factor. The parameter, which describes the characteristic environment, can generally be assimilated to a random variable and represented by a type of distribution, a mean and a standard deviation. Similarly the capability of the equipment to withstand the stress can be considered to be a random variable. Mostly the type of variation is log normal or Gaussian distribution. If these distributions are known, the probability that a specimen will not withstand its environment can be calculated.

P_0 = Prob (Environment > Strength), where P_0 = Probability of failure. Graphically the above equation can be represented by Fig. 4.

For Gaussian and log normal distributions of a given standard deviation it can be shown that P_0 depends on the ratio

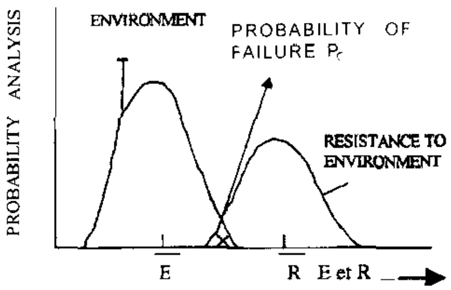

Figure 4. Gaussian and lognormal distributions

$$K = \frac{\text{Mean equipment strength } \bar{R}}{\text{Mean real or specified environment } \bar{E}}$$

where, K is the safety factor.

The application of this calculated safety factor becomes critical if the values of the environment at each frequency is considered. Instead, if an envelope spectrum is considered, an arbitrary safety factor, say 1.2 is generally acceptable. Thus, a safety factor of 1.2 has been applied to the PSD envelop in this study.

2.3. Synopsis of Data

An aerospace vehicle was instrumented with three vibration sensors to study the flight environment. Onboard vibration levels were measured through telemetry during the four flights. The recorded data was analysed to deduce the information about the flight vibration pattern, maximum vibration levels experienced, the vibration spectra and generation of a vibration envelop for reviewing the vibration test specifications. The frequency bandwidth catered for the three vibration channels was 2 KHz.

2.4. Application to Flight Data of Aerospace Vehicle

Based on the flight data of an aerospace vehicle, the linearly averaged spectra for four flights were estimated for each of the three axes as shown in Figs 5-7 respectively. These spectra are shaped according to the guidelines discussed earlier and the tailored spectra are obtained. Using these spectra, the break points are decided and a safety factor of 1.2 is applied on every break point to tailor the vibration specifications. The tailored vibration spectra in X, Yand Z axes are shown in Figs 8-10 respectively. Experimental implementation of the tailored specifications has been confirmed.

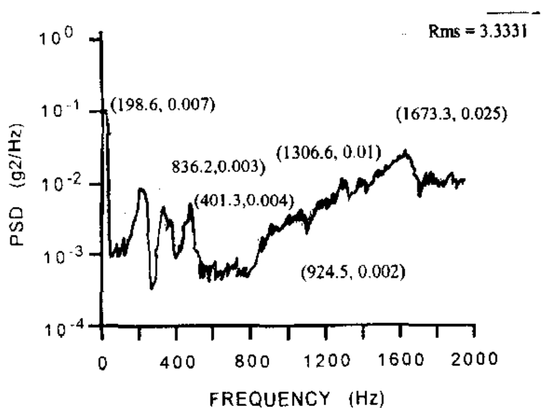

Figure 5. Linearly averaged spectra

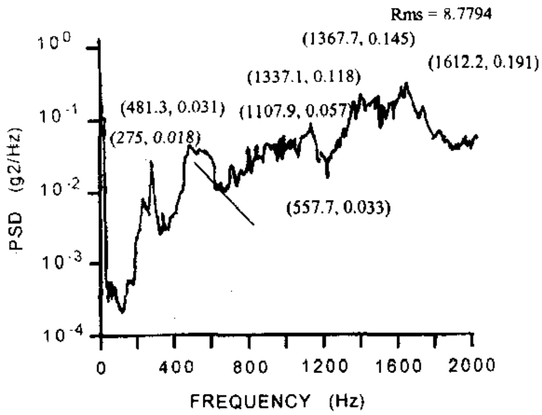

Figure 6. Linearly averaged spectra

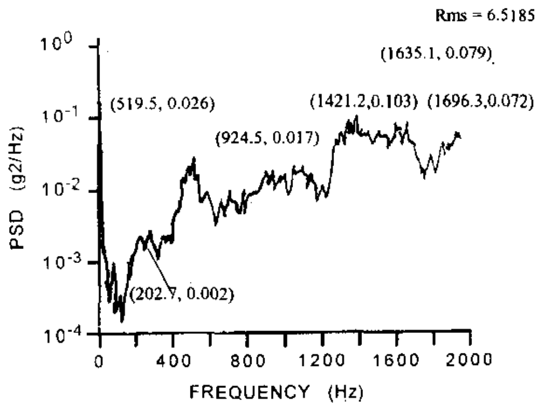

Figure 7. Linearly averaged spectra

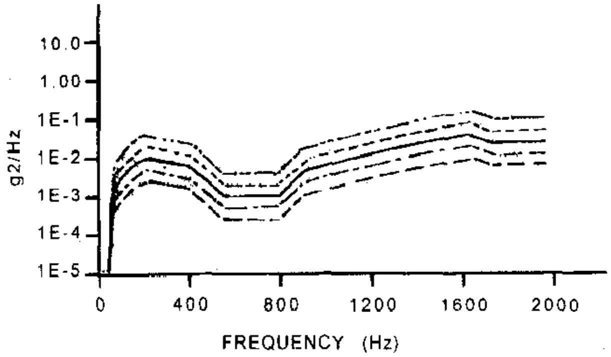

Figure 8. Tailored vibration spectra

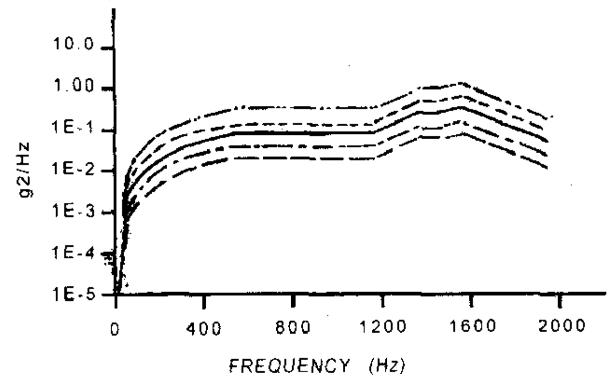

Figure 9. Tailored vibration spectra

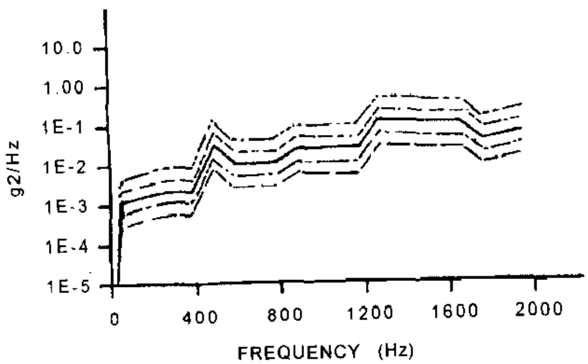

Figure 10. Tailored vibration spectra

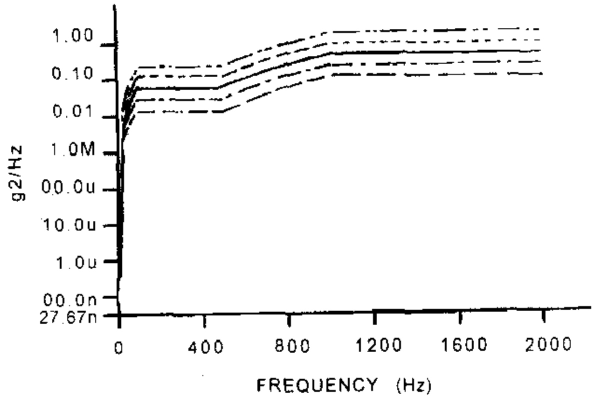

Figure 11. Vibration specifications

3. CONCLUSION

Adopting the scientific tailoring procedure, the vibration specifications as shown in Fig. 11 worked out to be 22 g in all the three axes were brought down. The earlier specifications were grossly over testing the units, thereby reducing their useful life. Since each axis has a different spectrum as can be seen in flight data also, it is logical to use different specifications for different axes. Thus the final specifications are formulated and used for testing the different sections of an aerospace vehicle.

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