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# Defining Component Environments and Margin through Zemblanic Consideration of Function Spaces

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## ABSTRACT

Historically the qualification process for vehicles carrying vulnerable components has centered around the Shock Response Spectrum (SRS) and qualification consisted of devising a collection of tests whose collective SRS enveloped the qualification SRS. This involves selecting whatever tests are convenient that will envelope the qualification SRS over at least part of its spectrum; this selection is without any consideration of the details of structural response or the nature of anticipated failure of its components. It is asserted that this approach often leads to over-testing, however, as has been pointed out several times in the literature, this approach may not even be conservative.

Given the advances in computational and experimental technology in the last several decades, it would be appropriate to seek some strategy of test selection that does account for structural response and failure mechanism and that pushes against the vulnerabilities of that specific structure. A strategy for such a zemblanic[1] approach is presented.

**Keywords**: shock response spectra, function spaces, optimization, component failure, qualification testing

## INTRODUCTION

The qualification process is largely in thrall to its own history. A process that could be implemented in the 1960s (almost sixty years ago) is still largely in place for the usual reasons of technical and institutional inertia:

- It is a process with which practitioners have become very comfortable.
- The qualification documentation on a large number of currently deployed systems is heavily based on the legacy processes, which because of historical acceptance are rarely re-examined.
- Baseline environments data were collected and stored in a commensurate manner (SRS).
- Much of the current environmental procedures documents (such as MIL-STD-1540E and MIL-STD-810G) are built around the legacy process.
- Despite an acknowledgment of the limitations and non-rigorous character of the current system, no more physics-based approach has been proposed.

Given the restriction that almost all information on the excitation in the existing environments specification is in terms of SRS -- original acceleration data has been lost or discarded -- the challenge is to identify tests that more thoroughly interrogate the system at hand to gain confidence that it would survive any excitation consistent with the SRS. We refer to this search for the most severe test for the specific system at hand as zemblanic.

[1] Zemblanity is the opposite of serendipity, the faculty of making unhappy, unlucky and expected discoveries by design.

## PROBLEM DEVELOPMENT

Let us consider the case where the environment is characterized by a one-dimensional SRS. We note that the shock response spectrum is a nonlinear operator on acceleration histories. Say that $S_1(\omega)$ is the SRS of acceleration history $f_1(t)$:

$$S_1(\omega) = N\big(f_1(t)\big) \tag{1}$$

A feature of this nonlinearity is that there is no unique inverse to the SRS, in particular, there may be two distinct acceleration histories $f_1$ and $f_2$ such that

$$\|N(f_1) - N(f_2)\| = 0 \text{ but } \|f_1 - f_2\| = \epsilon > 0 \tag{2}$$

where $\| \bullet \|$ is an $L_2$ norm. If our concern were just reproducing the SRS in the frequency range of interest, we might use any of a multitude of experiments to gain confidence that our structure could survive environments characterized by the specified SRS. It turns out that the choice of test is critical. Consider a structure having a vulnerability at some location. This could be a thin ceramic layer chemically attached to its substrate. Excessive bending would cause this ceramic to break.

Consider multiple tests that all are enveloped by an environments' SRS and that generate nearly identical SRS in some frequency range of interest. We note that experience shows that the potential for damage from each may be quite different. This suggests the wisdom of searching for the most damaging type of experiment when doing serious qualification. Though the acceleration histories contemplated have similar SRSs in the specified frequency range, the responses that they elicit in the structure and the consequent damage could be quite different. Of course, in the frequency ranges of interest we look to the type of experiment that most severely tests our structure and we select the parameters of the experiment along the same lines. It makes sense for qualification to include consideration of alternative experiments for each frequency range of interest, choosing the ones that best test the structure at hand. However, each experiment has some physical constraints on its parameters - for instance shakers have limitations on stroke and acceleration as well some resonant frequency bands that must be avoided.

## FORMULATION AS AN OPTIMIZATION PROBLEM

Generally, acceleration data for structures are recorded in a unidirectional manner: accelerations are measured in each of three directions and each of those three signals are recorded as independent SRSs. Each SRS is used to guide specifications for tests in that direction. Starting modestly, we address the question of test selection on the basis of a single SRS. The SRS is defined in such a way that

$$N\big(\alpha f_1(t)\big) = \alpha N\big(f_1(t)\big) \tag{3}$$

but in general

$$N\big(f_1(t) + f_2(t)\big) \neq N\big(f_1(t)\big) + N\big(f_2(t)\big) \tag{4}$$

Because of Eq. (3), one anticipates that acceleration histories associated with larger SRSs will be the more severe tests of a structure. On the other hand, from Eq. (2) we anticipate that there might be two acceleration histories $f_1$ and $f_2$ for which $N(f_1)=N(f_2)$ but such that $f_1$ causes damage to the structure and $f_2$ does not. In fact, one might anticipate that there exist acceleration histories $f_1$ and $f_2$ for which $N(f_1)<N(f_2)$ but such that $f_1$ causes damage to the structure and $f_2$ does not. This possibility was proven by Smallwood [1]. Given the non-uniqueness of acceleration histories that map to a given SRS, it is not sufficient merely to find accelerations that map to that SRS. Instead we shall attempt to find the tests consistent with the given SRS that most severely challenge the structure.

Let us assume a mapping from acceleration history to some failure measure of the component. For instance, this mapping could derive from a finite element model of the structure coupled with some failure metric such as peak von Mises stress, max curvature, or high-load, low-cycle fatigue criterion. This failure measure can be expressed as:

$$m = \mathcal{F}(f) \tag{5}$$

Also, we have some sets of tests $T_k$ and each test has a vector $\beta_k$ of test parameters in a regime of physically realizable parameters $B_k$, obtaining the acceleration history:

$$f_k(t) = T_k(t, \beta_k \in B_k) \tag{6}$$

For the given test, we might look for the optimal set of parameters to probe the durability of the structure:

$$m_k^*(\omega) = \max_{N(T_k(t,\beta_k \in B_k)) \leq SRS} \mathcal{F}\big(T_k(t, \beta_k \in B_k)\big) \tag{7}$$

If we have multiple tests available to us, the maximum damage possible from among these tests is

$$m^*(\omega) = \max_k m_k^*(\omega) \tag{8}$$

It should also be mentioned that additional constraints could be added to this optimization problem. Temporal moments, for example, as discussed by Cap and Smallwood, are a class of constraints for consideration.

Let us further consider multi-dimensional cases where we are given SRS information in each of two directions, but the character of the corresponding accelerations is not given. We know neither the imposed acceleration histories or the phase relationship between the two signals. We pose this issue again as an optimization problem. We consider tests $T_k$ that involve load in both the **i** and **j** directions

$$T_k(t, \beta_k) = f_{k,\beta_k}^x(t)\mathbf{i} + f_{k,\beta_k}^y(t)\mathbf{j} \tag{9}$$

The test to be specified is that experiment for which $N\left(f_{k,\beta_k}^x(t)\right) < SRS_1$ and $N\left(f_{k,\beta_k}^y(t)\right) < SRS_2$, but that most severely tests the vulnerabilities specific to that structure. We define

$$m_k^*(\omega) = \max_{N\left(f_{k,\beta_k}^x(t)\right) \leq SRS_1, N\left(f_{k,\beta_k}^y(t)\right) \leq SRS_2} \mathcal{F}\big(T_k(t, \beta_k \in B_k)\big) \tag{9}$$

The coupling between the *x* and *y* components of force is achieved through the physics and parameters of the experiment.

## DISCUSSION

Though the traditional methods of selecting and implementing qualification testing on the basis of reproducing SRS curves has been around for a very long time, so have its deficiencies. Because much if not most, of the environments information is stored as SRS, we are committed to employ it in our specification of qualification tests, but we are still free to look for the most intelligent and informed methods to select tests and test parameters. One approach is described conceptually here using an optimization formulation for selection and tailoring tests.

The approach outlined above will be demonstrated on the BARC structure introduced at IMAC XXXV. Means of expanding the method to consider multiple failure modes will be addressed, including the potential to devise failure mode-informed margin definition.

## REFERENCES


[1] Smallwood, D., "Enveloping the shock response spectrum (SRS) does not always produce a conservative test," *Journal of the IEST*, 49(1):48-52, 2006.

## BIOGRAPHY

Michael Starr received a PhD in Engineering Mechanics from UW-Madison. He is currently a Principal Member of Technical Staff at Sandia National Laboratories working on topics of fracture mechanics, contact, friction, energy dissipation, and the mechanics of jointed structures.