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Synthesis of Sine-on-Random vibration profiles for accelerated life tests based on fatigue damage spectrum equivalence

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ABSTRACT

In many real life environments, mechanical and electronic systems are subjected to vibrations that may induce dynamic loads and potentially lead to an early failure due to fatigue damage. Thus, qualification tests by means of shakers are advisable for the most critical components in order to verify their durability throughout the entire life cycle. Nowadays the trend is to tailor the qualification tests according to the specific application of the tested component, considering the measured field data as reference to set up the experimental campaign, for example through the so called "Mission Synthesis" methodology. One of the main issues is to define the excitation profiles for the tests, that must have, besides the (potentially scaled) frequency content, also the same damage potential of the field data despite being applied for a limited duration. With this target, the current procedures generally provide the test profile as a stationary random vibration specified by a Power Spectral Density (PSD). In certain applications this output may prove inadequate to represent the nature of the reference signal, and the procedure could result in an unrealistic qualification test. For instance when a rotating part is present in the system the component under analysis may be subjected to Sine-on-Random (SoR) vibrations, namely excitations composed of sinusoidal contributions superimposed to random vibrations. In this case, the synthesized test profile should preserve not only the induced fatigue damage but also the deterministic components of the environmental vibration. In this work, the potential advantages of a novel procedure to synthesize SoR profiles instead of PSDs for qualification tests are presented and supported by the results of an experimental campaign.

1. Introduction

Several systems may be subjected to vibrations during their operational life. These vibrations can induce fatigue damage, due to the repeated loading and unloading of the material, and the components must be designed to withstand the induced damage. Therefore, during the product development it may be necessary to validate the most critical components through durability tests in order to avoid the risk of failure. Standards were generally used in the past as guidelines to perform the laboratory tests (e.g. MIL-STD-810, GAM.EG 13, RTCA DO160 [1–3]), but in some cases their use may lead to oversized components and/or unrepresentative tests [4]. In the last decade, the Test Tailoring based on fatigue damage equivalence has been preferred to make the tests as representative as possible of the real application. With this approach, the real

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Nomenclature

A	(stress) intercept of the Wöhler curve (Basquin's law) [Pa]
a_{SoR_i}	Sine-on-Random ratio [–]
b	slope of the Wöhler curve (Basquin's law) [–]
d, D	fatigue damage [–]
f_n	SDOF-system natural frequency [Hz]
K	material constant relating the displacement to the stress [Pa/m]
M	number of sinusoids [–]
n, N	number of cycles at a certain stress level [–]
n_0^+	mean frequency of the SDOF-system response [Hz]
n_p^+	mean number of positive peaks per second of the SDOF-system response to PSD [s^{-1}]
$n_{p_{SoR}}^+$	mean number of positive peaks per second of the SDOF-system response to Sine-on-Random [s^{-1}]
Q	Q factor of the SDOF system [–]
r	irregularity factor of the SDOF-system response [–]
T	signal duration [s]
$\ddot{x}_a$	amplitude of the random component in the signal [$m\,s^{-2}$]
$\ddot{x}_s$	amplitude of the sinusoid in the signal [ms^{-2}]
z	SDOF-system relative displacement response [m]
z_a	SDOF-system response to the random contribution of the excitation [m]
z_s	SDOF-system response to the sinusoidal contribution of the excitation [m]
z_p	peak value of the SDOF-system relative displacement response [m]
ξ	damping ratio [–]
σ	stress [Pa]

environmental excitations that affect the analyzed system are measured and taken as reference to set up the qualification campaign. The problem is that usually the real vibrations cannot be used without a proper processing due to time and cost reasons (e.g. it is not possible to replicate the vibration for hundreds or thousands of hours). A solution can be to assess the fatigue damage potential of the environmental vibrations and then to synthesize a new profile with the same spectral content (potentially scaled) and the same amount of damage potential, but a limited duration. The most significant approach to Test Tailoring is probably the Mission Synthesis procedure introduced in some Standards [1,2] and formalized in the handbook authored by Lalanne [5], which is a milestone in this field. A frequency domain function called Fatigue Damage Spectrum (FDS) is computed to quantify the damage potential associated with the vibration that excites the analyzed system throughout its life cycle (focusing on the signal characteristics, instead of on the detailed, and often unknown, component properties). The output of the procedure is a synthesized profile with the same FDS but a limited duration, in order to obtain feasible qualification test specifications. The Mission Synthesis procedure proposed by Lalanne and implemented in several software solutions generates a Power Spectral Density (PSD) as test profile, and it is the standard in the industry (as an alternative, a purely deterministic synthesis in the form of a sine sweep is also possible). The synthesized excitation represents adequately the reference vibration when the latter is a random process with a Gaussian distribution of its values (as it is well represented by a PSD). However in a number of cases the field data do not follow a Gaussian distribution so that the synthesized PSD, though it preserves the FDS, may not be sufficiently representative of the original excitation in terms of signal characteristics, and it could lead to an unrealistic or inaccurate qualification test. Thus, a rising interest has recently been addressed to fine-tune the procedure for the cases in which the measured vibration does not follow a Gaussian distribution [6–11]. In particular, in this work the Mission Synthesis procedure in case of Sine-on-Random (SoR) vibrations is investigated and its possible advantages are presented. In fact, if a rotating part is present in the system, deterministic sinusoidal components can be superimposed to the random vibration. Therefore, a synthesized PSD may be inadequate to represent all the features of the actual environment in laboratory tests, whereas a SoR specification which preserves the nature of the excitation (i.e. random process plus deterministic components) is believed to better reproduce the characteristics of the real environment. Here, an original algorithm to synthesize a SoR test profile targeting a certain FDS is proposed and its supposed superiority is experimentally investigated through durability tests performed on laboratory specimens.

The paper is organized as follows: Section 2 recalls the theoretical basics to compute the FDS of a certain vibration excitation and to synthesize a PSD starting from the FDS; Section 3 introduces the novel Mission Synthesis procedure for SoR vibrations; Section 4 presents the method validation by means of a numerical application and an experimental campaign and discusses the advantages of the proposed procedure. Finally, Section 5 reports some concluding remarks.

2. Background

The FDS-based equivalence method has originally been proposed in French military standards [1], with the purpose to evaluate and compare the fatigue damage potential of different dynamic excitations on certain components. The device