Effects of multi-axis random vibration environments on fatigue-life and durability predictions

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Abstract

One of the main features of a product is its capability to withstand harsh environments that may compromise its durability over time. Therefore, screening laboratory tests are usually performed in the early stages of the product development process to predict the fatigue life beforehand. In this context, random vibration testing has become one of the most frequently employed procedures to ensure the durability and suitability of a product during its working life. Nowadays, the most performed tests are still single-axis shaker tests, due to cost of the equipment and for their reduced complexity compared to a multi-axial tests. However, real working environments almost always present a multi-axial loading condition. As a consequence, neglecting this aspect may lead to large errors in the estimation of the component durability and cause failures that can endanger equipment and people during the product lifetime. International standards propose to excite the unit under test with single-axis excitations along different directions sequentially, in order to mimic a multi-axial vibration environment by means of single-axis testing procedures. In this scenario, this work presents a testing campaign where sequential single-axis testing procedures are studied and compared with multi-axial vibration environments. Tests were run by taking advantage of the multi-axis shaker table available at the University of Ferrara, which is capable of exciting the unit under test along three independent translational degrees of freedom (DOFs). In particular, a cantilever beam is studied in order to assess the fatigue behaviour and the durability of the specimen under three different types of loading: 3 DOFs multi-axis uncorrelated vibration, a first sequential single-axis vibration and a second sequential single-axis vibration with inverted excitation sequence. Finally, the criticalities of the matter are analysed, exposing the inadequacy of single-axis testing to validate components subjected to multiaxial vibration environments.

1 Introduction

Nowadays, preliminary vibration testing is commonly performed by means of single-axis tests, mainly because of the reduced cost of the equipment and ease of implementation of the testing methodologies. While being easy to perform, single-axis tests have been proven to be not representative of multi axial vibration environments. Several works [1, 2, 3, 4] have shown how the dynamics of a specimen can be differently activated when the excitation environment is multi-axial rather than single-axial and that single-axis excitations are often incapable of reproducing a multi-axis vibration environment. In the recent past, several works have pointed out the benefits of multi-axis testing [5, 6, 7, 8], which allows to replicate operational conditions of real vibration environments. In this work, a testing campaign has been carried out to compare sequential single-axis to multi-axis testing. In particular, a relationship between the damage inflicted by multi-axis and single-axis loading is extracted, based on the different activation of the dynamics of the unit under test.

2 Experimental setup

The specimen chosen for the test campaign is a cantilever beam with two ”U” notches near the fixed end, depicted in Figure 1. The material chosen is the EN AW 6082 T6 aluminum alloy.

A lumped mass of about 0.47 kg is placed on the free end of the beam to tune its natural frequencies inside a convenient frequency range. During the test campaign the specimen was excited in order to activate

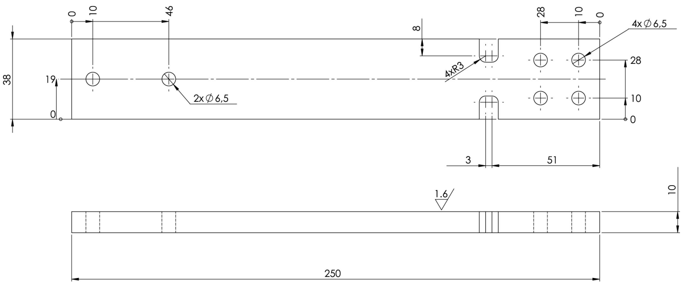

Figure 1: Geometry of the specimen used for the test campaign.

its first two modes at *55 Hz* and *117 Hz*, respectively. Two fixtures are employed to mount the specimen on the shaker table, namely *aligned* and *skewed* fixture. With the aligned fixture, each actuator is capable of activating only one mode of the specimen. On the other hand, the skewed fixture allows single-axis excitations to activate multiple-modes simultaneously. The use of the two fixtures is key in order to simulate multiple scenarios where the dynamic behaviour of the specimen is activated differently according to the type of vibration environment. A total of 84 specimens have been tested until complete rupture. The specimens are divided in 2 groups of 24 and 1 group of 36. Each group is tested with a different fixture or a different band of excitation. In each group 12 specimens are tested under tri-axial uncorrelated random vibration (3D) and 12 under sequential single-axis vibration (1D). In addition the 1D multi-mode test is repeated with inverted excitation sequence. One 1D sequence lasts for 12 minutes, 4 minutes per direction, and it is repeated until failure of the specimen. The tested configurations with the respective excitation profiles and test label are listed in Table 1.

ALIGNED FIXTURE

Test label	Specimens tested	Band	Level	X [g^2/Hz]	Y [g^2/Hz]	Z [g^2/Hz]
				[20 - 75] Hz	[20 - 75] Hz	[20 - 75] Hz
Single-mode (SM)	24	[20 - 75] Hz	LV 3	0.0737	0.0737	0.0737
			LV 2	0.0390	0.0390	0.0390
			LV 1	0.0184	0.0184	0.0184
				[20 - 150] Hz	[20 - 150] Hz	[20 - 150] Hz
Multi-mode (MM)	36	[20 - 150] Hz	LV 3	0.0473	0.0473	0.0473
			LV 2	0.0254	0.0254	0.0254
			LV 1	0.0152	0.0152	0.0152

SKEWED FIXTURE

Test label	Specimens tested	Band	Level	X [g^2/Hz]		Y [g^2/Hz]		Z [g^2/Hz]	
				[20 - 75] Hz	[76 - 150] Hz	[20 - 75] Hz	[76 - 150] Hz	[20 - 75] Hz	[76 - 150] Hz
Skewed (SK)	24	[20 - 150] Hz	LV 3	0.1105	0.0793	0.1105	0.0793	0.0508	0.1015
			LV 2	0.0554	0.0398	0.0554	0.0398	0.0254	0.0509
			LV 1	0.0278	0.0199	0.0278	0.0199	0.0128	0.0255

Table 1: Amplitude of the PSD profiles used.

A tri-axial accelerometer (model PCB 356B20) is placed on the tip of the beam, to measure the acceleration on the free end of the specimen. The measured acceleration is then converted into stress at the notch of the specimen using a transfer function calculated via finite element analysis.

3 Results

The testing campaign provided the time to failures (TTFs) and the S-N curves, approximated by Basquin's Law [9], of the specimen in different test configurations. Therefore, the TTFs and the S-N curves are used to extract a relationship between 3D and 1D tests. The test configurations are compared with each other in order to analyse different scenarios in which the dynamics of the specimen is activated differently. The comparisons made are the following : $SM_{3D}vsSM_{1D}$, $MM_{3D}vsSM_{1D}$, $SK_{3D}vsSM_{1D}$, $MM_{3D}vsMM_{1D}$, $SK_{3D}vsMM_{1D}$, $MM_{3D}vsSK_{1D}$ and $SK_{3D}vsSK_{1D}$. In order to characterize the activation of the specimen dynamics, the spectral

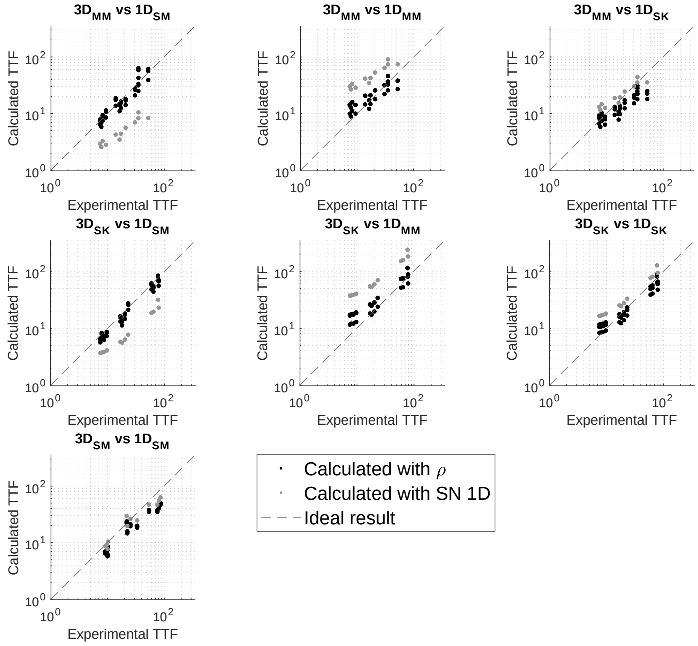

Figure 2: Experimental 3D TTF compared to the TTF calculated using the 1D S-N curve and the TTF calculated using ρ

moments of the stress *power spectral density* (PSD) are used. in particular χ is defined as follows:

$$\chi = \frac{\Sigma_{i=1}^{M}\left(\frac{\alpha_{2_{3D}}}{\alpha_{2_{1Di}}}\right)}{\Sigma_{i=1}^{M}\left(\frac{\omega_{1_{3D}}}{\omega_{1_{1Di}}}\right)} \tag{1}$$

in which M is the number of 1D excitations, α_2 and ω_1 are the bandwidth parameter and the mean frequency of the stress PSD, respectively [10]. Furthermore, it has been found that the the ratio between the damage inflicted by the 3D and the 1D excitations can be approximated by the following formulation:

$$\rho = \frac{D_{3D}}{D_{1D}} = \frac{a\chi + b}{\chi^2\left[\Sigma_{i=1}^{M}\left(n_{0_{1D_i}}^{+}\sigma_{RMS_{1Di}}^{k_{1D}}\right)\right] / \left(n_{0_{3D}}^{+}\sigma_{RMS_{3D}}^{k_{1D}}\right)} \tag{2}$$

in which, k_{1D} is the slope of the 1D S-N curve, n_0^+ is the number of zero up-crossing [10] and σ_{RMS} is the RMS stress value; a and b are fitting parameters; $a = 3.05$ and $b = 1.5$ are found minimizing the least square error between the experimental ρ and ρ calculated using Equation (2). The formulation of Equation (2) is applied to the specimens of the testing campaign, in order to obtain the 3D TTF starting from the 1D TTF. Figure 2 shows the the experimental 3D TTF compared to the TTF calculated using Equation (2) (black dots) and the TTF calculated using the S-N parameters of the 1D test (gray dots); the closer the dots to the *ideal result* line the better the result. The 3D TTFs calculated using ρ are always close to the experimental TTF, while the gray dots present large errors when multiple modes of the structure are activated. These results highlight that estimating the specimen durability under 3D vibrations using 1D tests can lead to large errors if multiple modes are contributing to the damaging of the specimen. On the other hand, the calculation of the 3D TTF using ρ always gives results close to the experimental TTF, indicating that taking into account the different activation of the specimen dynamics is key to have accurate results in terms of durability predictions.

4 Conclusions

In this work sequential single-axis and multi-axis testing are compared from a fatigue point of view. In particular, a relationship between the damage caused by single-axis and multi-axis vibration has been extracted from the experimental results of the testing campaign. The relationship takes into account the different activation of the specimen dynamics under different loading. The results highlight that taking into account the different activation of the modes of the specimen is key to correctly estimate the TTF under multi-axis vibration.

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