Experimental assessment of test tailoring methods for single-axis and multi-axis accelerated tests

Andrea Tosini[1], Emiliano Mucchi[2] and Giorgio Dalpiaz[3]

Engineering Department in Ferrara (ENDIF), University of Ferrara, Italy

E-mail: [1]andrea.tosini@unife.it, [2]emiliano.mucchi@unife.it, [3]giorgio.dalpiaz@unife.it

1. Extended abstract

During their operational life, industrial products are subjected to variable conditions of the surrounding environment: heat, humidity and vibrations may affect negatively the desired durability. The capability to withstand to such adverse conditions must be considered already in the early stages of design and its assessment is commonly performed through testing on prototypes. In order to accelerate the development process, it is common practice to shorten the test duration by subjecting the device under test to more severe conditions than those expected during normal usage. In the field of dynamic testing this has historically been realized by means of hydraulic and electrodynamic shakers, able to replicate on the tested item several types of excitations in a wide range of frequencies and forces. In particular, the Gaussian random excitation has been widely adopted for mechanical and electronic devices due its resemblance to the vibrations actually measurable in normal operational conditions [1]. In the view of performing even more realistic tests, in recent years gained increasing attention the practice of test tailoring, a method to synthesize the test vibration from the measured excitations of the environment where the component will operate. A crucial aspect of the method is represented by the so called *inverse power law* (eq.1), a formula that relates the desired test duration T_1 and the expected life of the component T_2 with the ratio between excitations energy content, respectively measured in the operational environment ($\ddot{x}_{RMS,2}$) and applied by the shaker ($\ddot{x}_{RMS,1}$). The exponent b is usually suggested by standards as a function of the severity of the environment surrounding the component.

$$\frac{T_1}{T_2} = \left(\frac{\ddot{x}_{RMS,2}}{\ddot{x}_{RMS,1}}\right)^b \tag{1}$$

The method, however, presents some drawbacks: first of all is based on a drastic simplification of the dynamics of the object under test as a single degree of freedom system, secondly, it does not consider the possible coexistence of excitations in multiple directions. In order to overcome these limitations, standards suggest to adjust the exponent b with correction factors inferred from engineering experience [2]. In addition, in order to simulate the multiaxiality of excitations, they suggest to perform an accelerated test for each Cartesian direction of the component. This last recommendation is motivated by the fact that the majority of electrodynamic shakers are single-axis machines: nowadays multiaxial shakers are still a rarity in the research panorama. Unfortunately, some researches proved how this approach not only is time consuming, but also may lead to failures not observable under normal usage conditions [3].

This proposed research fits into the context of accelerated testing by means of a multiaxial electrodynamic shaker available at the University of Ferrara, in Italy (fig.1). An experimental campaign has been performed using a machine able to excite in three directions simultaneously, allowing to compare the effect of simultaneous excitations and degree of correlation between the axes on the time to failure predicted by the inverse power law. The tests have been performed on cantilever beam specimens having a notch near the fixture zone and a lumped mass on the free end to precisely tune the resonant frequencies (fig.2). The excitation adopted has been a random vibration limited in frequency around the first bending modal shape, allowing to express the notch stress state as a function of the excitation by means of a single degree of freedom model. Since the geometry presented axial symmetry, the tests were performed exciting respectively only one axis or two axes along the symmetry planes, varying the levels of coherence.

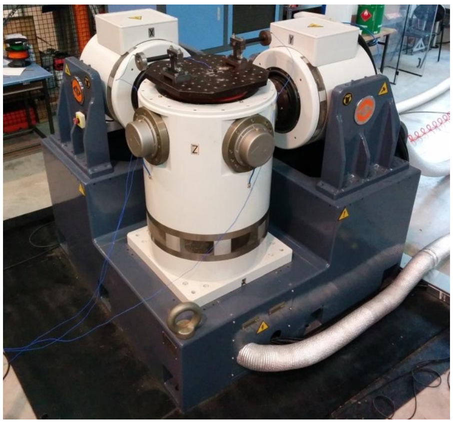

Figure 1. Triaxial shaker

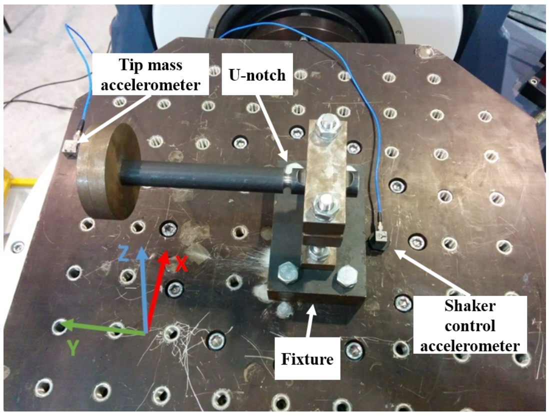

Figure 2. Experimental setup

All the tests were repeated with three different RMS acceleration levels, corresponding to values of 0.5, 0.55 and 0.6 gRMS, for a total of 95 tests: 39 tests were conducted with single axis excitation (13 tests for each excitation level) and 56 with biaxial excitation, using the same levels of the monoaxial tests and two distinct degrees of correlation between axes (9 tests for each excitation level and degree of correlation). Single-axis and multi-axis tests were performed with different objectives in mind: the single-axis tests had the aim to assess the limits of the formulation of the inverse power law in terms of accuracy of the predicted testing time, while the tests with biaxial excitation aimed to investigate the feasibility of the same law in more realistic scenarios.

1.1. Single-axis tests

All the performed tests evidenced a natural frequency drop imputable to the crack propagation in the notched area: it is a phenomenon that affects the stress state making it non-stationary, despite the stationarity of the excitation. This observation is important for the correct application of the inverse power law since the formula is based on the assumption of stress stationarity. This allows to consider each test divisible into two parts: a first part where the stress in the notch can be considered stationary (corresponding to a negligible resonant frequency drop) and a second part, where the damage accumulation invalidates this assumption. The effect of stress non-stationarity is evident comparing durations for tests considered only in their stationary part or in their completeness: the regression line that approximate in a least squares sense stress RMS and number of cycles has different slope value (fig.3 and fig.4), meaning a different exponent in the inverse power law. Even little differences may have detrimental effects on the predicted durability since the affected value appears as exponent in the formula.

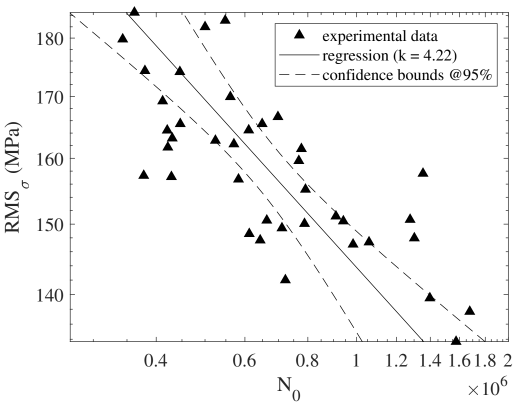

Figure 3. Regression line for tests in non-stationary conditions

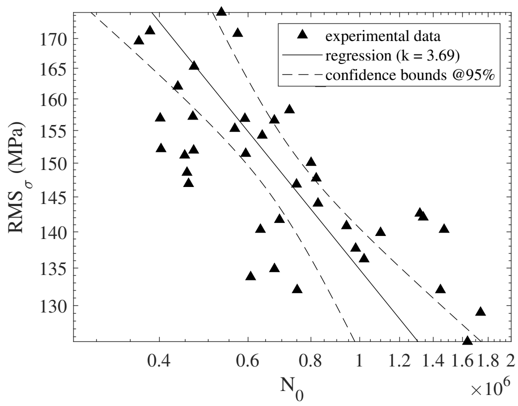

Figure 4. Regression line for tests in stationary conditions

1.2. Biaxial tests

The bi-axis tests permitted the investigation of the feasibility of the inverse power law when applied in multi-axis excitation scenarios. In order to obtain results comparable to those obtained from previous experiments, these tests were performed using the same excitation spectra but along two specimen symmetry planes simultaneously. The tests were performed adopting two very different degrees of correlation in order to assess its influence on the predicted test duration. The coherence was set to the values 0.98 and 0.05, respectively for tests hereafter named *high coherence* and *low coherence tests*, maintaining constant the value in all the excitation bandwidth.

Fig.5 shows the linear regression for tests considered in their complete duration, taking into account also the time in which the natural frequency decays to the 80% of its initial value (non-stationary conditions). Otherwise, fig.6 reports the linear regression only for the time interval from the beginning to the achievement of 3% of natural frequency reduction (stationary conditions). The same comparison between non-stationary and stationary conditions has been done also for the tests with low coherence. Regression lines in fig.7 and fig.8 appear very different from the respective high coherence tests, being more steep in both conditions. The reason seems to be imputable to the different mechanism of crack nucleation and propagation as a consequence of the lower coherence level. The choice of the degree of correlation between excitations is an aspect still not always considered in industrial applications of accelerated testing, even though last revision of the military standard MIL-STD-810 [4] goes in the right direction, providing guidelines for setting cross-PSDs in multi-axis tests.

1.3. Concluding remarks

This paper deals with some issues that can arise in the dynamic testing practice and that can affect the time scaling law, discussing some weak points of the common adopted procedures that may produce inaccuracies in the assessed durability. The non-stationarity of the stress state caused by the propagation of cracks has been recognized as a factor capable to heavily influence the predicted time-to-failure, both in single and multi-axis excitation configurations. The hypothesis of stress stationarity, implicit in the inverse power law foundation, is in contrast with the experimental observations, due to mechanical fatigue accumulation. This discrepancy may have great influence on the predicted durability since the committed error reflects on a very delicate coefficient, that appears as exponent in the time scaling law.

From the perspective of performing tests even more realistic, it is reasonable that in the near future single-axis shakers will be superseded by multi-axis machines. It is thus crucial

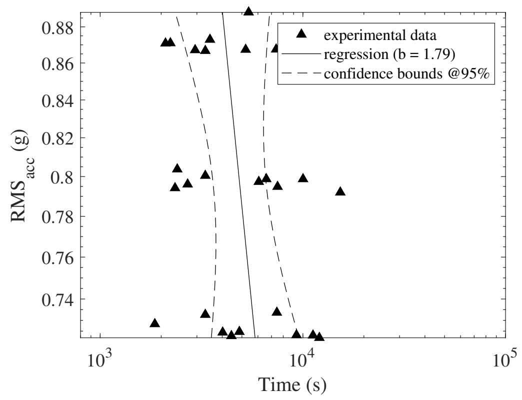

Figure 5. High coherence tests in non-stationary conditions

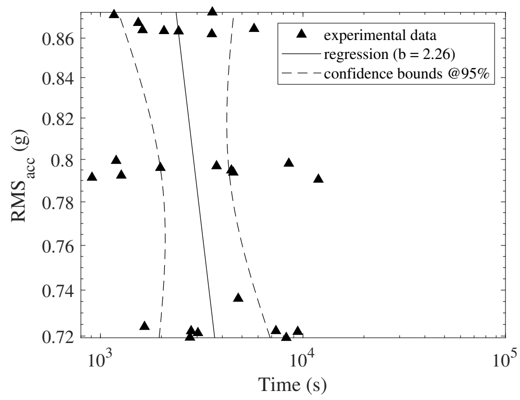

Figure 6. High coherence tests in stationary conditions

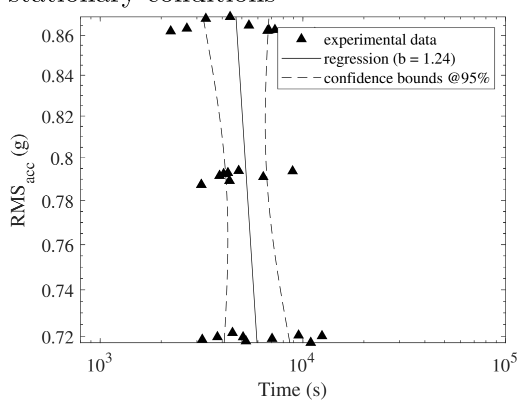

Figure 7. Low coherence tests in non-stationary conditions

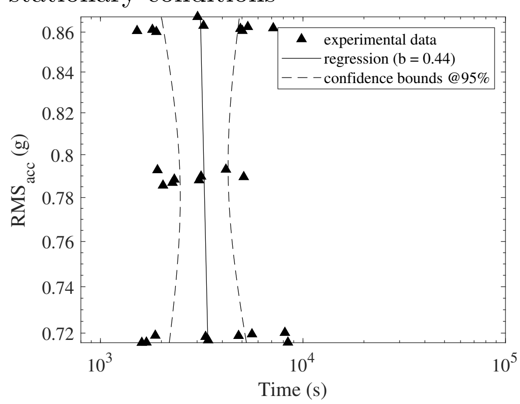

Figure 8. Low coherence tests in stationary conditions

to investigate the limitations of current testing practices and problems that may arise in multiaxial scenarios. The experimental campaign evidenced the influence of coherence between the excitations in different directions, in particular on the exponent of the inverse power law that appears to be substantially lower if compared with the corresponding monoaxial tests. This fact appears to be even more marked lowering the levels of coherence, meaning that the time necessary to reach the same damage level depends to a lesser extent on the excitation RMS values.

All the observations drawn have been obtained from machined ad-hoc specimens. However, it is plausible that the observed effects of stress non-stationarity and coherence keep validity also for mechanical components with much more complicated geometries and stress states.

References

[1] Ernst M, Habtour E, Dasgupta A, Pohland M, Robeson M and Paulus M 2014 *Journal of Electronic Packaging* **137** 1
[2] Lalanne C 2014 *Mechanical vibration and shock analysis* 3rd ed vol 5 (Wiley-ISTE)
[3] Whiteman W E and Berman M S 2001 *Journal of the IEST* **44** 20
[4] 2008 *MIL-STD-810G - Test Method Standard for Environmental Engineering Considerations and Laboratory Tests* (USA Department of Defence)