

About the role of uncertainty assessment in environmental testing

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Abstract – A short review is carried out about the uncertainty issues and requirements in environmental testing. Aspects concerning standards and operating procedures are considered and discussed, including considerations about test benches specifications and data analysis. Particular attention is paid on vibration tests and effects of different parameters. Some considerations are also presented considering the effect of data accuracy on reliability predictions.

I. INTRODUCTION

Environmental testing plays a fundamental role in the reliability assessment of many engineering fields, like mechanical, electronic and material engineering.

Many issues are of interest, depending on a very large number of aspects, mainly referring to the aim of testing, to the typology and to the complexity of the items to be tested and to the quantities to be taken into account. In fact, a very huge amount of literature has been developed [1], [2], [3] and also many standards exist [4], [5], in the technical and military field.

Even though a comprehensive analysis is impossible to do from a practical point of view, some general considerations arise.

As a general rule, environmental testing is expected to demonstrate the adequacy of specimens to resist to specified loads (depending on cases, static/dynamic load, temperature/humidity/vibration as the quantity of interest and so on) without unacceptable degradation of its functional and/or structural integrity, when subjected to the specified test requirements. Different experimental approaches are available, which depend on the specific application. Test requirements are set in order to represent real loads and the accumulated stress effects, so that the resulting mechanical/electrical/thermal weaknesses and degradation in the specified performance could be identified.

This information, in conjunction with the relevant specification, makes possible to assess if the specimens could be accepted or refused.

Another approach, that is very studied too, is to carry on environmental testing, in particular taking into account vibration solicitations, to support models and procedures, aiming to evaluate the mechanical fatigue effects; often

the results of this study could be useful for estimation of Residual Fatigue Life (RFL).

As an example, in [6] a methodology is proposed to define residual fatigue life of simple mechanical components. A very integrated approach is described, including experimental analysis, theoretical mechanical models and probabilistic considerations. The first step of this methodology is to probabilistically assess in an experimental way the current state of damage (*damage mechanism, damage location and characteristic/equivalent damage sizes/extents*), also depending on the previous history and on the material characteristics.

A Bayesian probabilistic inference scheme allows us to drive the integration of current state of damage, seen in terms of its probability density function (PDF), and the PDF of the damage evaluation model parameters.

A further step of the approach includes the hazard models of the operational loads, in order to estimate the propagation of defects at the inspected damage locations: the representation of these models is obviously in terms of their PDF; it could be modified in updated propagation models by the information of measurements on defects. Finally, local and global performance limit-states are considered for definition of Residual Fatigue Life.

If the given approaches are compared, at first glance it seems that a complete and coherent probabilistic point of view is considered only when that it is strictly needed, according, for instance, to reliability and prognostic considerations. In fact, most of the results connected to environmental testing are in terms of pass/no pass, according to predefined thresholds.

Anyway, many aspects are described in terms of PDF of parameters in the environmental testing on the whole: as the example, we can consider the statistical behaviour of the random driving signal, [7], [8] (also taking into account the actions to optimize the dynamic behaviour of the driving/actuating devices: e.g. clipping, [9], phase management, [10], [11], mixing of different type of solicitations, [2], ...); furthermore, the real output PDF is difficult to predict, even though the input PDF is known, due to the system effect (which are often also not linear). If the possibility of carrying on accelerated tests (HALT) is considered, the above problems are emphasized [12].

Therefore, the need of defining the problems, including

their probabilistic information is fundamental and affects the capability of validating the information deriving from data and which will be the basis for decision making.

In other terms, this scenario will affect the quality of information deriving from measurements, i.e. their uncertainty and its propagation throughout the process of arriving to the final decision, including the confidence level of actions.

Environmental testing requires merging data of different type, of different meaning and quality in a way that the uncertainty propagation remain under control; this goal is not so easy to achieve, due to the lack of a consolidated approach, able to manage uncertainty throughout the whole process of such a kind [13].

In this paper, some aspects will be discussed concerning uncertainty evaluation in environmental testing applications, taking into account some existing tools in uncertainty management, the needs which should be satisfied in environmental testing and the possibility of integrating uncertainty considerations and its evaluation into environmental testing processes.

The needs connected to the merging of these actions, to realize connectivity and interoperability among all the operators involved in the supply chain will also be discussed.

Vibration testing will be considered as a representative example of problems that should be faced and the way of generalizing the results is also discussed.

II. METHODOLOGY AND RESULTS

A “global” methodology aiming at realizing a rigorous, complete and integrated approach for the uncertainty management in environmental testing of every type is, of course, very difficult to realize and it is out of the scope of this paper.

The following considerations want to show, in a preliminary way, how some results of an environmental test could be re-interpreted and enriched by means of some metrological considerations.

The scenario, among many possible cases, is a vibration test of a component, whose mechanical compliance with a pre-defined vibration load should be guaranteed with a set level of confidence.

The most suitable vibration solicitation, according to the standard indication, is broadband random [5].

In the case we want to discuss, the component is accepted if the mechanical behavior after the test satisfies the requirements: that is, if the difference of one natural frequency, Δf , of the system, is less than a predefined difference, which indicates that a modification in mechanical performances occurred. The evaluation of the difference Δf of the component is made by means of modal analyses, before and after the test.

In the standard, the aim of recommendations is to achieve reliability of information given by the results of the tests and their reliability. In order to satisfy these requirements

some pre-requisite of uncertainty level should be guaranteed with reference to different aspects, only to cite the most relevant:

- the uncertainty of the shaker: that means the uncertainty of the effective motion law that the free motion actuator of the shaker realizes in correspondence of a given input electric signal;
- the uncertainty of the real motion law, which depends on the mechanical characteristics of the connecting devices and on the geometries of components;
- the dynamic effects on the mechanical coupling devices, making different the motion of the specimen at different points;
- the uncertainty of temperature and of the other environmental parameters, which are relevant to identify the test conditions;
- the uncertainty of the measuring devices like the three-axis accelerometer or thermometer [14].

The evaluation of these aspects is often difficult to realize. Furthermore, the uncertainty affects also the verification of the acceptance criterion!

In order to propose some actions able to insert organically the uncertainty management in the procedure of environmental testing, a sequence of steps could be useful:

- a) To identify the basic concepts and operations useful to take into account, preliminarily. These concepts are the basic knowledge useful to merge skill and experience of people involved in measurement uncertainty assessment and experts of environmental testing; they should be also the material useful to satisfy the requirements of standards and to guarantee the reliability of the acceptance criterion.
- b) To identify the most critical elements, from a physical point of view, that make variable the results even though they should remain unchanged;
- c) To identify the indicators to be considered for the prediction of the variability and to quantify them, modelling the system under test;
- d) To determine the variability range of the selected indicators, modelling the system under test;
- e) To characterize, if possible, this variability in terms of its PDF;
- f) To realize an algorithm able to merge all the possible variability causes, in order to predict and to assess the whole variability. A possible intermediate, but useful, result could be to use the tool in order to realize a comparative analysis, identifying the most critical contributions. This indication should move to improve these aspects, to reduce the variability of results.

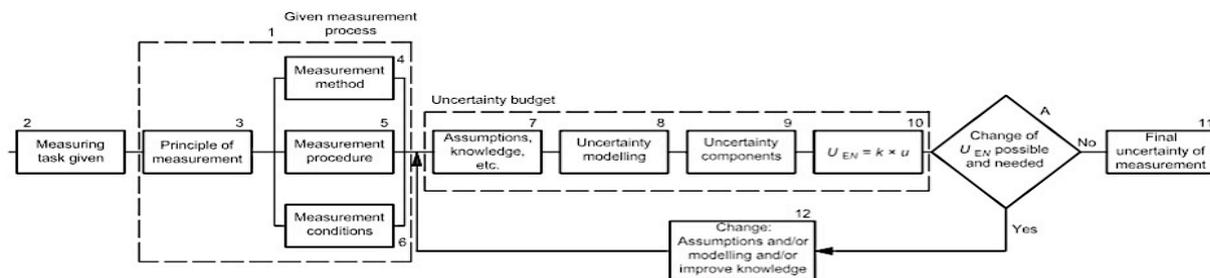


Fig. 1. PUMA: Procedure for Uncertainty Management [17].

A. Identification of the metrological basic concepts and operations

The main existing metrological approaches taken into account are listed below:

- Repeatability and reproducibility of results;
- PUMA, procedure for management of uncertainty (Fig. 1);
- Standard uncertainty evaluation (Type A and Type B) for direct and indirect measurements: equations from (1) to (7) in Annex I;
- Expanded uncertainty (confidence level and DOF): equation 8 in Annex I;
- Methods of Simulation of the Probability Density Function (PDF) for the output quantities of a system depending on the variability of inputs;
- Simplified model for evaluation of the variability range of parameter of interest (by numerical calculation and/or simplified formulas): equations (9) and (10) in Annex I;
- Conformity assessment (Fig. 2).

- Statistical behaviour of the random driving signal (also taking into account the actions to optimize the dynamic behaviour of the driving/actuating devices: e.g. clipping, phase management, ...); furthermore, the real output PDF is difficult to predict, even though the input PDF is known, due to the system effect (also non-linear)
- Specimen dynamic behaviour, taking into account also the installation on the test bench;
- Data processing approximations;
- The modality the solicitation is accelerated in case of accelerated tests; furthermore, the failure mechanism remains unchanged;
- Real mechanical characteristics of the inspected components;
- Measurement system uncertainty, that are usually required by the standard in terms of both sensitivity (calibration) and dynamic behaviour (response flat in the frequency range of interest, i.e. $\pm 5\%$);
- Temperature uncertainty: temperature variation due to the test and/or to the temperature estimation of the component to be tested in cases where temperature cycles are provided.

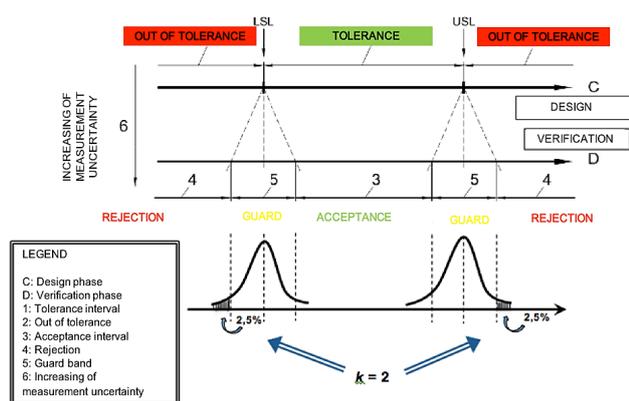


Fig. 2. Conformity assessment, adapted from [18]

B. Identification of the metrological basic concepts and operations Identification of the most critical aspects, affecting the variability of the quantity to be measured

The «true» difference of critical frequency before and after the test is affected by many contributions:

C. Identification and evaluation of the indicators for prediction's variability

If the relationship between the requested output, y , to be measured, and the quantities of interest can be hypothesized by the function $y = f(x_1, x_2, \dots, x_n)$, the indicators of interest are the ranges of variability of y_1, \dots, y_n , depending on variability of each input quantity, (x_1, x_2, \dots, x_n) .

D. Determination of the variability range for the indicators

The variability range of the selected indicators can be evaluated by numerical calculation, by probability simulation (Monte Carlo method [19]), by simplified methods.

Quantity x_i	Estimation of x_i	Standard uncertainty u_{x_i}	Distribution	Degrees of freedom	Coefficient of sensitivity	Uncertainty contribution s_i
x_1			rectangular	n_1		s_1
x_2			Gaussian	n_2		s_2
...			...			
x_n			...			
y			Gaussian (...)	n_y		s_y

$$s = \sqrt{\sum_i (s_i)^2}$$

Fig. 3. Uncertainty budget

E. Characterization of the variability (PDF)

Estimation of the most suitable Probability Density Function, able to represent the variability of data.

The aspects to be taken into account are:

- theoretical PDF of signals depending on standards or on the characterization of the application
- modifications of theoretical PDF depending on the operating solutions
- non-linearity
- correlations between of different PDF, associated to different indicators

F. Procedure to merge the contributions of different indicators

If the relationship between the requested output, to be measured, and the quantities of interest can be described by the function $f(x_1, x_2, \dots, x_n)$, the budget uncertainty method, could be useful (Fig. 3).

In this case, all the uncertainty contributions should be considered independent from a measurement point of view. As an example, some uncertainty contributions for resonance frequency have been estimated according to the above model with reference to the testing of a simple mechanical component;

- Frequency resolution: 0.02 %, distribution rectangular
- Test bench effect: 1.0 %, including geometry, temperature and mounting effects, by Montecarlo simulation [15], distribution normal
- Data processing, including excitation broad band/sensor uniformity and accuracy: 0.5% (experimental), distribution normal.

The level of confidence of measurement will drive the use of this information. In fact, the concept of the allowed maximum difference of characteristics of the specimen, before and after the test, is transformed into a conformity

interval, based on the requested level of risk of the decision. The expansion of the standard uncertainty will take into account the degrees of freedom of measurement. The acceptance interval for the frequency variation has to be reduced by twice the expanded uncertainty in frequency measurement, according to the above criteria.

Note that this approach is quite different, and specular, to the indication of some standard, [16], where uncertainty in frequency measurement is thought as the cause of an increase of the allowed frequency difference for acceptance.

The uncertainty budget could be used also for a preliminary comparison among uncertainty contributions: particular attention should be paid to the most relevant terms in order to avoid of having uncontrolled the aspects that mostly contribute to the whole variability. Often, this care is expected to significantly improve the overall accuracy with task of reduced effort.

III. CONCLUSIONS

Uncertainty evaluation, even though in a simplified procedure, is used as a tool to support and to validate the information deriving from measurements in environmental testing. Simple concepts and actions are individuated and described in order to significantly improve the physical meaning and reliability of results of vibration testing. According to this approach, the adequacy of specimens to resist to specified loads is analyzed in terms of conformity check to tolerances, to be satisfied taking into account the uncertainty of measurements. The merging of concepts of metrology and of environmental testing works as a first step to improve the integration of the probabilistic aspects included in tests and in the chosen indicators into an approach able to considering the causes of variability and to manage their effects. The ability of evaluating the confidence level of data and, therefore, the risk associated with decisions based on them will improve all the present methods with respect to the assessment of reliability of component and systems.

ANNEX I

Direct Measurements: Type A evaluation [20]:

$$\bar{Y} = \frac{1}{n} \sum_{k=1}^n Y_k \quad (1)$$

$$s(\bar{Y}) = \sqrt{\frac{\sum_{k=1}^n (Y_k - \bar{Y})^2}{n(n-1)}} \quad (2)$$

Direct Measurements: Type B evaluation [20]

$$u(Y) = \frac{u(Y)}{m} \quad (3)$$

$$u(Y) = \frac{u(Y)}{\bar{m}} \quad (4)$$

$$u(Y) = \frac{a}{\sqrt{3}} \quad (5)$$

Indirect Measurements: uncorrelated input quantities [20]

$$u_c(y) = \sqrt{\sum_{i=1}^N \left[\frac{\delta f}{\delta x_i} \cdot u(x_i) \right]^2} = \sqrt{\sum_{i=1}^N [c \cdot u(x_i)]^2} \quad (6)$$

Indirect Measurements: correlated input quantities [20]

$$u_c(y) = \sqrt{\sum_{i=1}^N \left[\frac{\delta f}{\delta x_i} \cdot u(x_i) \right]^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{\delta f}{\delta x_i} \cdot \frac{\delta f}{\delta x_j} u(x_i) \cdot u(x_j) \cdot r(x_i, x_j)} \quad (7)$$

Expanded uncertainty [20]

$$U = k \cdot u_c(y) \quad (8)$$

Partial derivatives [20]

$$\frac{\delta f}{\delta x_i} = \left. \frac{\delta f}{\delta X_i} \right|_{x_1, x_2, \dots, x_N} \quad (9)$$

Numerical calculation [20]

$$Z_i = \frac{1}{2} \{f[x_1, \dots, x_N + u(x_i), \dots, x_N] - f[x_1, \dots, x_N - u(x_i), \dots, x_N]\} \quad (10)$$

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