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Utilizing virtual vibration tests to optimize physical endurance tests

Frédéric Kihm*

HBM-Prenscia Products Division, France

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Abstract. Physical tests are performed at various stages of the development cycle of a product, from prototype validation to product qualification. Although costly, there are growing demands for qualification tests like endurance vibration testing to be more representative of the real world. At the same time there are growing demands to assess the durability of these items based on FEA simulation.

In this paper, we will explain how to set up a CAE-based test and how to correlate the results with some physical measurements. Specific assumptions will be explained and some advantages of using virtual tests will be highlighted such as the reduction of the number of prototypes needed, investigations on failures, evaluation of the level of reliability via sensitivity analysis, evaluation of the margins are at the end of a successful test.

This presentation will therefore focus on explaining and showing how virtual tests can enrich the exploitation of physical tests.

Keywords: fatigue; endurance; shaker tests; FEA; modal analysis; mode shapes; virtual strain gages

1. Introduction

As the need to design mechanically efficient, sophisticated and reliable components increases, the demand for solutions to run smarter endurance tests and optimize designs under vibration excitations is also increasing. Prediction of product fatigue life through analytical means like CAE-based simulation is an important component of product development. The accuracy of Finite Element Analysis (FEA) fatigue life predictions can be improved through experimental tests. And experimental tests can be optimized based on FEA.

This paper introduces how CAE-based simulation can be used to design smarter tests. The paper first introduces qualification (physical) tests. The next chapter describes how the fatigue damage accumulation can be estimated from FEA. The third chapter explains how to validate the FE modelling, in order to use it with greater confidence in “what-if” scenarios. The last chapter gathers and describes example applications of an FEA-based simulation to make smarter environmental qualification tests.

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*Corresponding author, E-mail: Frederic.kihm@hbmprenscia.com

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2. Environmental tests

Environmental testing is a form of vibration testing, where a test article is subjected to vibration of a specified form and amplitude for a period of time, in order to assess its operational integrity. Shaker tests are typically performed to qualify the endurance of a product.

The objective of product testing is to check that the test article is qualified for its expected service life. In order to replicate the same failure mechanism as in real conditions, the test specification must be representative of the service loads. In practice, vibration test requirements are often specified by industry standards such as MIL-STD-810G (2008), RCA/DO-160 Revision G (2010), etc. or synthesized from measurements under real operational conditions using a test tailoring approach (Halfpenny and Kihm 2006). The test profile must incorporate at least the same damage content as the original data, but will also require considerably shorter test times.

Often, long term operational loads are stochastic in nature, with a given distribution of energy across various frequencies. For random vibration tests, the input excitation is defined as a vibration profile called Power Spectral Density (PSD). An example PSD is illustrated in Fig. 1.

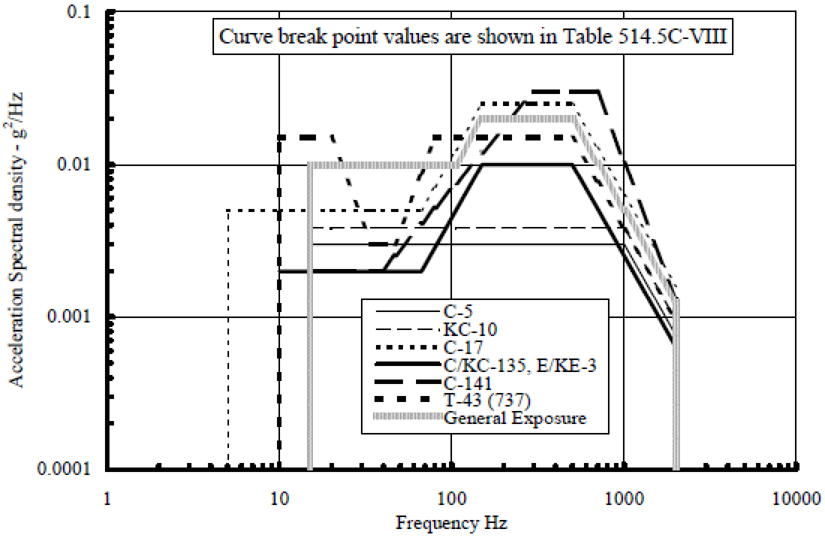

FIGURE 514.5C-6. Jet aircraft cargo vibration exposure.

Fig. 1 Example vibration profiles for an acceleration PSD from the military standard MIL STD 810

From the PSD profile, an excitation signal is generated to drive the shaker (Zhuge *et al.* 2010). The reproduced signal is meant to be random stationary and Gaussian.

Another type of vibration environment, often referred to as Sine-On-Random, is typically produced by rotating machinery. Examples of rotating machines are internal combustion engines, turbines, pumps, electric motors of generators. The generated vibration environment is typically made of harmonic tones superimposed on background noise. An example test specification for helicopter vibration from MIL-STD-810G (2008) involving sine-on-Random is given in Fig. 2, where f_1 is the rotor rotating frequency, f_2 the blade passing frequency and f_3, f_4 its harmonics.

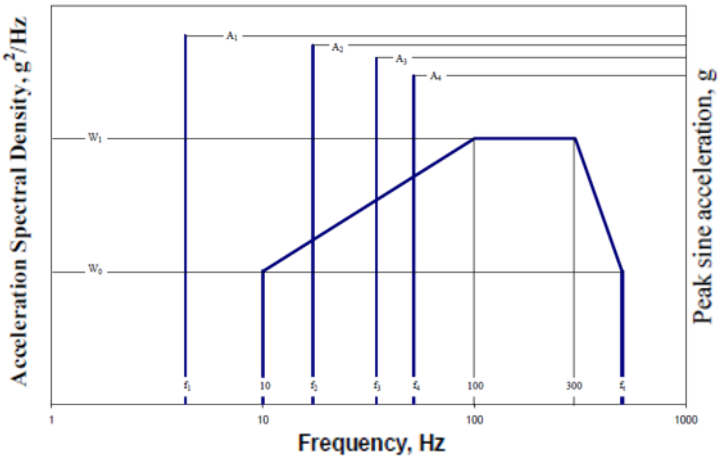

Fig. 2 Example test specification - Helicopter vibrations exposure - MIL STD 810G Figure 514.6C-8

Modern shaker controllers can also generate signals with high kurtosis. The kurtosis is defined as the fourth standardised statistical moment. Values of kurtosis greater than three indicate that a probability density function has heavier tails than a Gaussian distribution. Hence why the kurtosis is often used a metric to describe the "peakedness" or the "impulsiveness" of the data. A kurtosis value can be set up to make the test more representative of the expected vibration environment experienced during service life.

The generated drive signal has the same PSD and hence overall Root Mean Square (RMS) value, but is more impulsive compared to a stationary Gaussian signal. Fig. 3 shows the probability density functions of two excitation signals. The blue one corresponds to a Gaussian stationary signal, the red one to a non-Gaussian signal, where the kurtosis is set to 6.0. The horizontal axis represents the acceleration level of the input time series. Both excitation signals have the same RMS value.

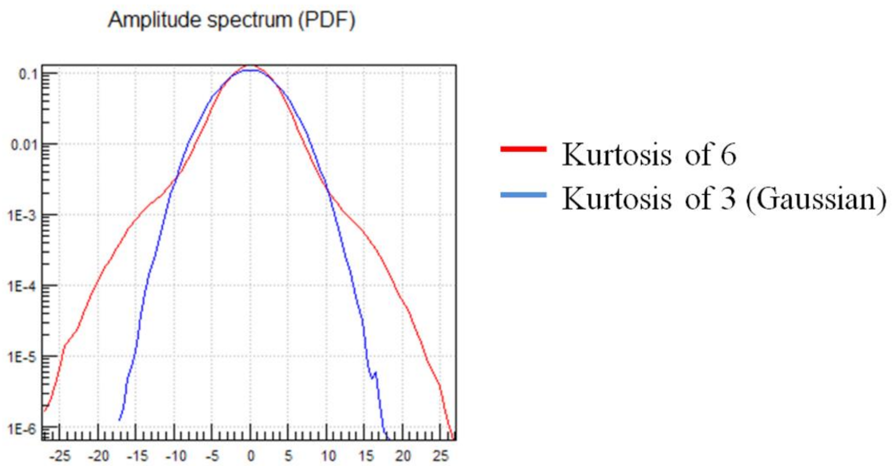

Fig. 3 Example distribution of excitation signals: Gaussian (blue) and with high kurtosis (red)

From Fig. 3, it is clear that the signal with high kurtosis exhibits higher amplitude levels than the Gaussian one. Tests with high kurtosis values can therefore be more representative of certain real non-Gaussian, impulsive environments. Another application of kurtosis control is the acceleration of a test. More impulses mean higher expected damage on the test article, so that the test duration can be reduced while reproducing the same overall damage.

Finally, deterministic loads are typically represented by time histories. Example deterministic test specifications include sine dwells, sine sweeps and Time Waveform Replication (TWR) (MIL-STD-810G (2008)). When used for simulating loads that are random in nature, the TWR doesn't capture the variability which can actually occur in the field since the waveform produced in the test is just one field measurement. Note also that it is seldom practical nor possible to conduct endurance tests using real measured data because of the volume of data necessary, the duration over which components must survive and inherent problems in achieving correlation between the actual test rig output and that desired (Steinwolf 2006).

No matter what vibration environment is to be reproduced on the test bench, engineers are required to reduce the test duration. There are two general types of accelerated environmental tests:

- Qualitative Accelerated Tests
- Quantitative Accelerated Life Tests

A qualitative accelerated validation or qualification test is performed to validate durability and reliability. Typically, qualitative tests are performed on small sample sizes with the specimens subjected to harsh environment(s), with the goal of no failures. They are used to validate the durability and reliability targets. However, no quantitative estimates (such R, BX, MTTF. etc.) are possible i.e. qualitative tests do not provide assessment of the reliability of the product.

Quantitative accelerated life testing, unlike qualitative testing, is designed to provide reliability information on the product, component or system, through data obtained during the accelerated test. In other words, it is used when one wants to estimate the reliability of a product by performing a test, but in much shorter amount of time. A quantitative accelerated life testing is therefore typically carried out until failure, so that failure times can be reported. It requires enough samples for performing statistical inferences with an acceptable degree of confidence.

The test acceleration is typically obtained through both usage rate acceleration and load amplification (or overstressing). The load amplification method simply scales the input time signal by an appropriate amount in order to reduce the test duration. Scaling the load will reduce the test duration exponentially. The scale factor is found by Eq. (1).

$$Scale = \left(\frac{realDuration}{TestDuration}\right)^{1/b} \tag{1}$$

where b is the slope of the Wöhler line.

Accelerated tests are extremely useful from an engineering point of view. If the test fails, the engineers will know it soon enough and they will have the means to remedy it. If a test is successful, the engineers may still have sufficient time in the project timeframe to push it further in order to assess the safety margins.

Considerable care is however required when using the load amplification method to ensure that loads are not scaled excessively thereby inducing local yield and altering the load path. A number of studies have actually reported longer component lives after scaling. This occurs when a plastic hinge is formed in the component which alters the load path away from the observed failure point.

Various types of vibration environments can be used to reproduce the loading conditions a component is likely to be subjected to during its service life. Such qualification tests are often accelerated and combined with a simultaneous temperature profile or other environmental loading conditions such as pressure, moisture, etc. Considerable care is however required to ensure the overstressed test does not lead to different failure mechanisms.

3. Virtual vibration tests

The mechanical stress and the fatigue damage accumulated by the test article during the qualification test can be simulated using the Finite Element technique. A fatigue analysis can be performed from dynamic stress obtained from a forced frequency response analysis or a transient analysis. Fatigue damage can be calculated using frequency or time domain data (Halfpenny 2007). Results from the forced frequency response analysis serve as input to a spectral fatigue calculation, while results from the transient analysis serve as input to a fatigue analysis performed using time domain data and a rainflow cycle (Matsuishi and Endo 1968) counting scheme.

The forced frequency response analysis is performed by exciting the structure in physical degrees-of-freedom with a unitary sinusoidal base acceleration input over the frequency range of interest and the frequency response function (FRF) between the loading and the response is obtained. An example FRF for the absolute maximum principal stress (Pa/g) is shown in Fig. 4 for a specific node. Assuming a linear structural response, the response PSD G_{YY} can be calculated for any loading PSD G_{XX} as in Eq. (2)

$$G_{YY}(\omega) = |H(\omega)|^2 \cdot G_{XX}(\omega) \qquad (2)$$

where $H(\omega)$ represents the FRF.

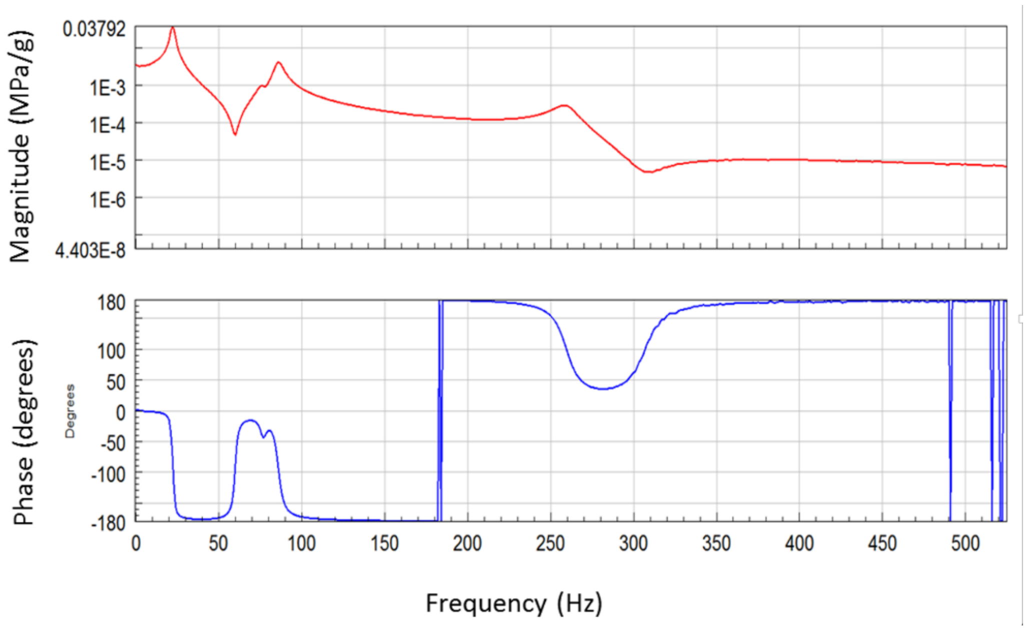

Fig. 4 Example Stress FRF obtained at a specific node

For the fatigue analysis, stress cycles are derived statistically from the stress response PSD. There are a number of expressions typically used to determine the probability density function (PDF) from a PSD of arbitrary bandwidth. Dirlik (1985) proposed an empirical closed form solution to estimate the PDF of stress range. Rice (1954) proposed a solution to estimate the PDF of stress peaks, which Lalanne (2002) used as a basis for determining the pdf of cycle stress range. Lalanne's formula is given in Eq. (3).

$$N(S) = \frac{1}{rms} \cdot \frac{\sqrt{1-\gamma^2}}{\sqrt{2\pi}} \cdot e^{\frac{-S^2}{2rms^2(1-\gamma^2)}} + \frac{S \cdot \gamma}{2rms} \cdot \left[1 + erf\left(\frac{S \cdot \gamma}{rms\sqrt{2(1-\gamma^2)}} \right) \right] \tag{3}$$

where γ is the irregularity factor determined and $erf(x)$ is error function.

Fig. 5 shows an example stress range histogram obtained using Lalanne's method.

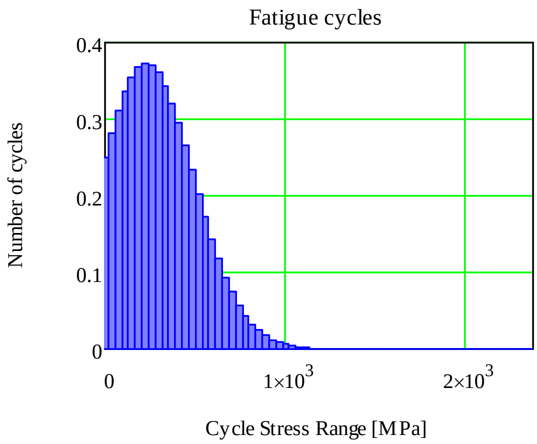

Fig. 5 Example Cycle stress range histogram using Lalanne approach

For Sine-On-Random excitations, another statistical approach exists to find a statistically derived, rainflow-like distribution of cycles corresponding to the stress PSD and sine tones (Kihm, Halfpenny and Ferguson 2015). Similarly, for random vibration environments with high kurtosis, a statistical approach was derived by the author (Kihm, Ferguson and Antoni 2015).

For the time domain approach, a modal transient analysis is performed to determine the modal response time histories for each loading condition. In the time domain, time histories of stresses are directly counted using a rainflow cycle counting technique (Matsuishi and Endo 1968). The damage from each cycle is then linearly summed using the Palmgren-Miner (Palmgren 1924, Miner 1945) damage accumulation law. The time domain approach is applicable to any type of signal, whether it be stochastic or deterministic. This approach, however, proves computationally intensive for stochastic loadings because long stress time histories are required to generate the tails of the stress range histogram in a statistically accurate manner. Poorly realized extremes can have a detrimental effect on the fatigue life estimate as the most damaging events are attributable to the high stress ranges in the tails. Convergence in damage estimates therefore improve with an increasing number of data points in a signal (Halfpenny 2007). In many practical cases, it is simply not possible to obtain the required duration of time signal for accurate rainflow counting. In these cases, especially, a frequency domain approach offers significantly more accurate fatigue life estimates under the aforementioned conditions.

Note that the application of other environmental loading conditions such as temperature profile or pressure car be accounted for in the CAE-based fatigue analysis. For instance, an elevated temperature can add thermal (quasi-static) stresses on the top of the mechanical (dynamic) stresses and can modify the material's fatigue properties (Halfpenny *et al.* 2015).

4. Test-CAE Correlation

Finite Element Analysis (FEA) fatigue life predictions are strongly dependent on a valid FE modelling. The accuracy of the fatigue predictions can be improved through experimental modal analysis and measured stress or strain responses.

It is therefore strongly recommended to validate the modal behavior of the FE model by comparing the analytical natural frequencies and mode shapes with those measured experimentally. This first check may lead the FE analyst to modify the boundary conditions, or to check the stiffness and mass characteristics of the model in order to obtain a better match. By doing so, any further dynamic analysis is done with a greater degree of confidence.

Fig. 6 illustrates an example mode shape comparison between test and FEA results for an exhaust muffler.

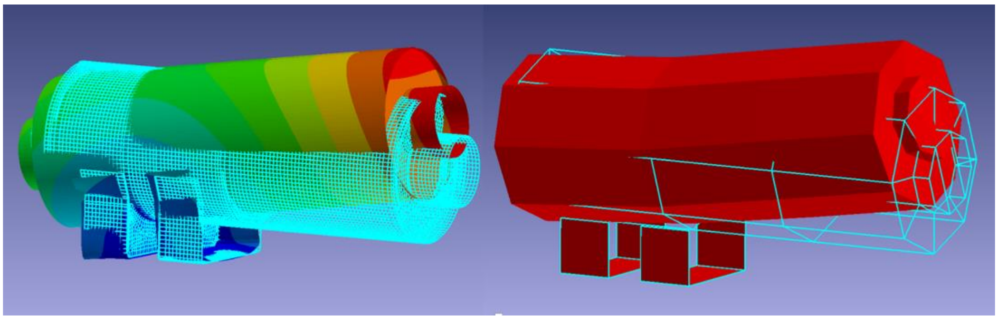

Fig. 6 Example comparison of the first mode shape between test and FEA results

The next objective is to compute the stress levels obtained when the structure is excited. A dynamic finite element analysis dependent on damping is required. The mass and stiffness govern the frequency at which resonance occurs, while damping controls the magnitude of the response. Damping is critical when investigating system dynamics as it governs the magnitude of the dynamic stress response and hence ultimately the component's durability. Assumed damping characteristics can lead to dramatic errors in the fatigue life prediction. Therefore, a modal test is necessary to properly quantify the damping and to improve the accuracy of the durability analysis. nCode VibeSys™ uses experimental modal analysis to extract the damping ratios for each mode from the Frequency Response Functions (FRF). To do so, the FRF is curve fitted and a mathematical model incorporating modal damping is found (Ewins 1995). Fig. 7 shows an example curve fit of an FRF.

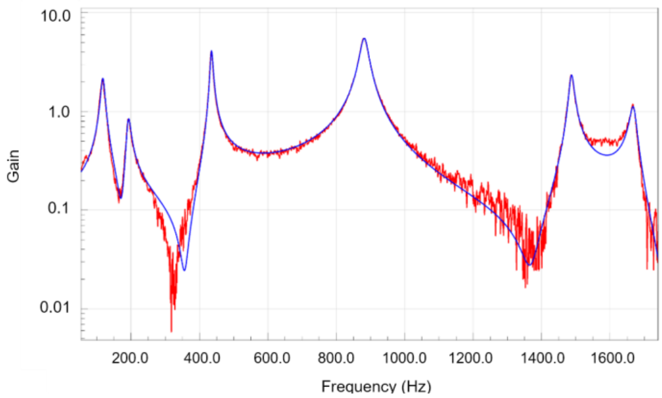

Fig. 7 Example curve fit of an FRF

The last step consists in validating the calculated mecanical stress when it results from the combination of multiaxial loads. If the model is loaded with simultaneous excitations, the calculated stresses are a combination of the stresses obtained from each of the simultaneously applied loads, just as they are in the real world.

In order to validate the stress results obtained analyticaly, one can use a “virtual strain gauge” to extract the FE-based results and correlate them with measured strain gauge data. If the model has been properly meshed and loaded, the predicted virtual stress or strain will correlate with the measured stress or strain. The degree of correlation can be obtained by comparing the actual and predicted stress values. Note that virtual strains can be recovered in the exact orientation of the gauge during the real strain measurement. Fig. 8 illustrates the use of virtual strain rosettes positioned on a meshed FE model.

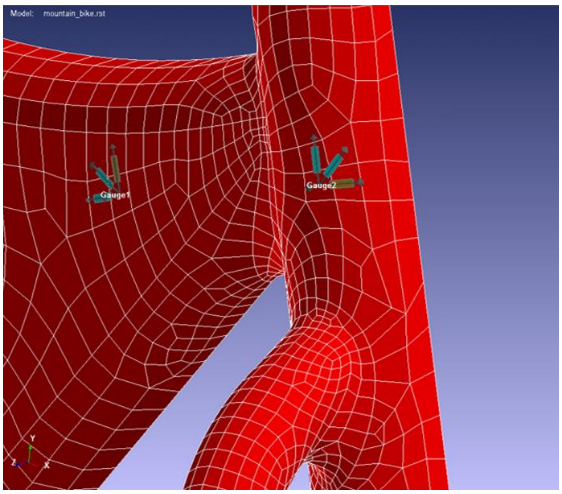

Fig. 8 Example use of virtual strain gages

The use of experimentally determined modal characteristics and measured stress or strain responses can improve dramatically the accuracy of the fatigue life estimation. The basic concepts introduced in this section can be summarized in the diagram in Fig. 9.

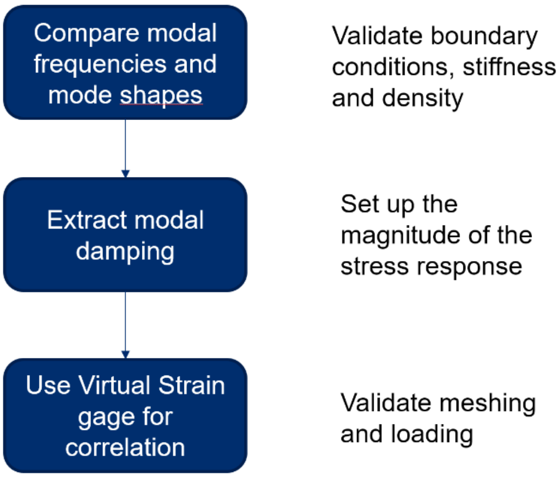

Fig. 9 Summary diagram for the validation of a dynamic FE model for stress and fatigue analysis

5. Virtual tests to help physical tests

Historically, durability simulations based on FEA is used to help optimize the design of a component. It allows sensitivity analysis to be performed in order to select the optimum material, geometry, process, etc. required to fulfil a target in terms of service life.

Test engineers want to accelerate a test whilst keeping the same failure mechanisms. Accelerating a physical test certainly helps reduce the time-to-market but it care is required when using this method to ensure that loads are not excessively scaled. A CAE-based fatigue analysis can help to check the failure modes have not been altered. For instance, one can check the increased stress does not exceed the yield strength or observe on the fatigue curve which endurance domain is activated.

CAE-based fatigue analysis can help understand why a test has failed prematurely. The numerical analysis will reveal whether the failure is due primarily to some geometrical singularity or to the material used being inadequate, etc. It will also provide means to remedy it by using sensitivity analysis and therefore finding a smoother geometry or more appropriate material respectively by simulating “what-if” games.

Now, in the other scenario of a successful test, a CAE-based fatigue analysis can be used to assess the safety margins. This is typically needed to ensure the component is not overdesigned.

Often only a few test articles are used in many cases for the qualification test. Safety factors can be used to account for variations in applied service loading and the fatigue strength of the component. In addition to the safety factor, another multiplying coefficient may be used to account for the limited number of durability tests to actually be undertaken and ensure a given reliability level within a given confidence level. A probabilistic fatigue analysis can be adopted to help assess the influence of the variability in the analysis properties (loading, material strength, surface finish, etc.). Several fatigue life estimates are therefore obtained and the engineer can observe the span of the fatigue lives and derive reliability metrics such as the B(x%) life for instance.

6. Conclusions

This paper discussed how experimental tests can be optimized based on FEA by evaluating "what-if" scenarios for instance. Similarly, it is well-known by designers that the accuracy of FEA-based fatigue life predictions can be improved through experimental tests.

Qualification (physical) tests were first introduced. The load amplification method to reduce a test duration was discussed and the risks over over-scaling the loads was underlined. A way to estimate fatigue life from FEA was then described. Once validated, a FE model can be used to make more efficient environmental qualification tests and extract more engineering information from them.

The validation of the FE modelling is however crucial for this application. The paper gives suggestions on how to validate and enhance the FE modelling based on experimental measured data.

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