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Sine-Sweep qualification test for engine components: The choice of simulation technique

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Abstract

Most of mechanical components, especially those belonging to aerospace sector, vehicles and, in particular, the automotive sector need an experimental qualification phase aimed to determine both their functionalities and their structural strength. Regarding the structural strength, the tests most commonly required by regulatory standards and typically performed belong to two categories, so similar as different: Sine-Sweep test and Random test. The present work is part of a consolidated research topic aimed to develop design techniques making them as much simpler and faster as possible in order to reduce product development times up to the virtual verification of test conditions. In particular, the present work is aimed to propose a frequency domain methodology for dynamic simulation and evaluation of the fatigue behavior for Sine-Sweep test, comparing it with the time domain technique that is considered as reference. The activity carried out in collaboration with a well-known automotive industry (HPE-COXA S.p.A.) verified these methodologies on a test case proposed by the company itself, i.e. the qualification of a set of supplying pipe of a high performance engine. The comparison between the time domain approach and the proposed approach in frequency domain certifies the extreme reliability of the latter as well as the advantages it offers to the designer in terms of computational times that results to be extremely reduced. The activity then created the prerequisites for the development of future research activities aimed to reduce calculation times as much as possible making such calculation tools of easily accessible to the industrial community.

Keywords: Virtual simulation, Qualification Test, Mechanical Vibration, Sine-Sweep

1. Introduction

Before being introduced in market mechanical components, from automotive to the aerospace sector, are necessarily tested through a series of qualification tests accurately designed to certify both their functionalities and their reliability MIL-STD-810F (2000), ECSS-E-10-03C (2012), PK (2010). Regarding the latter, one of the main tests generally performed is the vibration test MIL-STD-810F (2000). The reference standards, which differ according to

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the sector, require testing the component with a set-up (constraints and excitation) aimed to reproduce the actual operating conditions of the component. The types of tests and therefore the type of excitation performed to certify the structural strength of a component belong to three basic categories: Random, Sine on Random and Sine-Sweep MIL-STD-810F (2000), ECSS-E-10-03C (2012). These types of tests can be performed all or in part depending on the type of component and its function. Random vibration tests are generally those that best fit the real operating conditions of any component. Random excitation in fact allows exciting the component in a random way in a pre-designed range of frequencies simultaneously exciting all the natural frequencies of the system MIL-STD-810F (2000). The Sine-on-Random tests have been developed and imposed by the reference standards to simulate particular types of vibrations found, for example, on helicopters and crawler-type vehicles, in order to reproduce all those types of excitation in which there are at least one harmonic component (generated for example by an unbalanced rotating machine) superimposed on a random excitation Cornelis et al. (2017), Kim (2017). The Sine-Sweep test instead foresees to excite the system with a harmonic signal with time-varying frequency and amplitude according to a given law and with a predefined time length Maurizi et al. (2019). This type of test is imposed by reference standards in all those applications in which there are alternative motions of the components such as in automotive or aerospace sector. Sauther (2013), Wang et al. (2013), Wang et al. (2017). With the aim of avoiding an unexpected breakdown of the component during a qualification test, which would necessarily lead to reiterating the entire design phase with a considerable waste of time and money, it is clear how numerical simulation, allowing to perform virtual qualification tests, can be useful in any industrial sector. Whatever type of vibration test one wants to numerically simulate (Random, Sine on Random and Sine-Sweep) there are essentially two macroscopic approaches to be used: time domain approach and frequency domain approach Teixeira (2014). Although numerical simulation is therefore helpful in preventing unexpected breakdowns of mechanical components during qualification tests, its inclusion in the design process must be such that to not over-stretch the design phase time duration. As known from the available papers in literature Benasciutti and Tovo (2005), Zucca et al. (2018), frequency domain methods allows a reduction of calculation effort with respect to a time-domain approach maintaining, under certain hypotheses and conditions (i.e. Linearity of the system, Gaussianity of excitation and response Braccesi et al. (2018a), Cianetti et al. (2018b), Wolfsteiner (2017), Cianetti et al. (2017)), identical levels of reliability of results. On this base, it is therefore clear how the use of a frequency domain methods (due to its quickness and reliability) allows to achieve this goal. Although literature is full of numerical techniques, developed in the frequency domain, for the evaluation of fatigue strength for random and sine on random tests Mršnik et al. (2013), Dirlik (1985), Cianetti et al. (2018a), Han et al. (2019), for Sine-Sweep tests is not the same Kos et al. (2015). In this context, inspired from an industrial problem related to the automotive sector, the present work is aimed to develop a frequency domain calculation methodology, already outlined by the authors Braccesi et al. (2015) in a previous work, for Sine-Sweep tests trying to arrange it in a simple and robust manner, thus addressing all those industrial contexts in which it is necessary to simulate Sine-Sweep test. The proposed method starts with Sine-Sweep signal generation from an imposed frequency spectrum and from the possibility of post-processing the time-history recovering the initial frequency spectrum. At the same time, the proposed methodology has as objective the calculation, under dynamic conditions, of stress state and of the load spectrum entirely in frequency domain, solving, at the same time, the possible related problem of multi-axial stress state. The proposed approach, developed and presented in next pages, is compared with the time domain approach (considered as a reference in this activity) with the intent of evaluating its effectiveness both in terms of results (Damage) and in terms of calculation times. The test case, used to compare the results, is a set of feeding pipes of a high-performance engine supplied by the well-known automotive company HPE-COXA S.p.A. The results obtained from this comparison certainly certify the validity of the frequency domain proposed approach (both in terms of results and calculation times) demonstrating, once again, that frequency domain can be the reference domain in structural dynamics.

2. Theory Background

2.1. Sine-Sweep signal generation

A Sine-Sweep signal is a deterministic process defined by a sinusoidal function with time-varying frequency as shown in Eq. 1

$$x(t) = A sin(2\pi f(t)t) \tag{1}$$

In Eq. 1 A is the frequency-varying amplitude and $f(t)$ is the frequency of the Sine-Sweep. Both the Amplitude A and the frequency range are generally defined by standards in terms of frequency Spectrum $S_{inp}(\omega)$ Lalanne (2014). Technical standards in general, defined also the the Sweep-Rate, *i.e*. the dependency of frequency over time. A Sine-Sweep can be defined by whichever dependency of frequency over time even if the most common lows are linear, logarithmic and inverse-logarithmic. In this paper only the logarithmic variation is considered. The dependency of frequency over time, in logarithmic case, is shown in Eq. 2.

$$f_{spec}(t) = f_{min} 2^{R(t-t_0)} \tag{2}$$

where R is the speed of the sweep, defined in units of *octave per minute*. By integrating Eq. 2 it is possible to obtain the frequency $f(t)$ of the Sine-Sweep as shown in Eq. 3.

$$f(t) = \frac{1}{t}\int_{t_0}^{t} f_{spec}(t) = f_{min}\frac{-1+2^{Rt}}{Rtln(2)} \tag{3}$$

If the generation of Sine-Sweep signals starting from imposed frequency spectrum is fundamental in this type of tests, the backward transition, i.e. the recovery of a frequency spectrum from a time history is necessary as well. Although this step could be intuitive and simple, relying on robust algorithms such the FFT, some precautions are necessary. In fact, the FFT returns the frequency spectrum of the signal, keeping constant the energy of the processes in both domains (time-frequency) but some differences in amplitude between the spectrum and the time-history may be noticed. To obviate this problem it is necessary to carry out a signal window operation in which each window has a number of points depending on the frequency of the process in that time interval. At this time the FFT of each window gives a peak, characteristic of a sine at a constant frequency from which, extrapolating the maximum amplitude and the associated frequency it is possible to recover the frequency spectrum of the time process.

2.2. Structural Dynamics

The equation of motion in modal coordinates q of $n-$degree of freedom system, subjected to a base motion ẍ is the following:

$$[I]\{\ddot{q}\} + [2\xi\omega_0]\{\dot{q}\} + [\omega_0^2]\{q\} = [\gamma]\{\ddot{x}\} \tag{4}$$

where $[I]$ is the identity matrix, $[2\xi\omega_0]$ is the diagonal matrix of damping with ξ the percentage damping, $\left[\omega_0^2\right]$ is the vector of natural frequencies and $[\gamma]$ is the matrix of modal participation factors. The integration of Eq. 4 can be simplified re-writing the equation of motion in a state-space form Ogata (2009), Cianetti et al. (2017). From the State-Space model and by the assessment of the input acceleration $\{\ddot{x}(t)\}$, the time-history of the modal coordinates $\{q(t)\}$ are easily obtainable.
From the State-Space model, it is moreover possible to define the Frequency Response Function (FRF) of the system. If modal coordinates in time domain are directly obtained from numerical integration, the spectra of modal coordinates must be computed as matrix product between the FRF of the system and the input Spectrum $S_{inp}(\omega)$ as shown in 5

$$\{S_q(\omega)\} = [H_{q/\ddot{x}}]\{S_{inp}\} \tag{5}$$

2.3. Stress recovery and fatigue damage evaluation in time domain: Reference Approach.

The reference approach, in time domain, for the stress recovery and damage evaluation follows the modal approach Cianetti (2012). The stress state $[\sigma_k(t)]$ of k^{th} element can be obtained by a linear combination between the modal coordinates $q(t)$ and the modal stress matrix $[\Phi_k^\sigma]$ as shown in 6.

$$[\sigma_k(t)] = [\Phi_k^\sigma]\{q(t)\} \tag{6}$$

If the stress state is uni-axial, the time history $[\sigma_k(t)]$ of the k^{th} element can be processed by a cycle counting algorithm (in this activity the rainflow counting method is used) obtaining, as output, the fatigue cycle n_i and the

associated mean and alternating stress component in the form $(n_i, \sigma_{m,i}, \sigma_{a,i})$. The mean and alternating stress can be synthesized to an alternating equivalent stress $\sigma_{alt,eqv}$ by the Goodman rule.
Introducing the material $S-N$ curve, defined in Eq. 7, it is possible to assess the number of cycle N to which the component can resist for a given value of alternating stress $\sigma_{alt,eqv}$.

$$S = aN^b \tag{7}$$

In Eq. 7 a and b are the interecept and the slope respectively. Once the load spectrum and the material $S-N$ curve are known, the fatigue damage can be obtained by the Palmgren-Miner Rules defined in Eq. 8 Fatemi and Yang (1998).

$$D = \sum_{i=1}^{n} \frac{n_i}{\left(\frac{\sigma_{a,i}}{a}\right)^{1/b}} \tag{8}$$

If the stress state is instead multi-axial, it is necessary to synthesize the stress state into a equivalent uni-axial one before using the rainflow counting algorithm and Palmgren-Miner rules. There are many approach in literature for the multi-axial synthesis Papadopoulos et al. (1997), Cristofori et al. (2011), Morettini et al. (2019). In this activity the criterion proposed by Braccesi et al. (2018b) is used. Once the multi-axial stress state has been reduced to a uni-axial one, the previously illustrated procedure can be used to estimate the fatigue damage.

3. Stress State recovery and fatigue damage evaluation in frequency domain: Proposed approach.

In frequency domain the matrix of stress spectra can be obtain by a matrix product between the spectra of modal coordinates $[S_q(\omega)]$ and the modal stress matrix $[\Phi_k^{\sigma}]$ as shown in 9.

$$[S_{\sigma,i}] = [\Phi_k^{\sigma}][S_q(\omega)] \tag{9}$$

To easily introduce the proposed cycle counting technique, firstly a uni-axial stress state is considered. Since Sine-Sweep are deterministic process, the number of cycle i to which the k^{th} element is subjected in a range of two succeeding frequencies, is given by the area underlying the frequency-time dependency $f_{spec}(t)$ in a time interval Δt as shown in Eq. 10.

$$n_{i,k} = \int_{t_i}^{t_{i+1}} f_{spec}(t)dt \tag{10}$$

To make this procedure as more usable as possible, the integral of Eq. 10 can be computed by numerical integration. This method, although approximate, results to be as more precise as more the sampling frequency is high. If it true, the number of cycle in a time interval Δt can be computed as the product between the central frequency of two succeeding frequencies $f_c = \frac{f_i + f_{i+1}}{2}$ and the time interval Δt in which the succeeding frequencies are contained (Eq. 11).

$$n_{i,k} = \int_{t_i}^{t_{i+1}} f_{spec}(t)dt = f_{c,i}\Delta t_i \tag{11}$$

Concerning the amplitude linked to each counted cycle, since Sine-Sweep Signal are zero-mean process by definition, the amplitude of the stress spectrum for each central frequency $f_{c,i}$ supplies the alternating component $S^a_{k,i}$. The output of the procedure is a load spectrum, equivalent to that of time domain approach, in the form (n_i, S^a_i) to which applied the Palmgren-Miner rules Fatemi and Yang (1998). Figure 1 shows the proposed cycle counting procedure for Sine-Sweep process.

It is therefore clear how the proposed approach allows to obtain the load spectrum of each element of the component only if, in addition to the stress frequency spectrum, the frequency-time dependency $f_{spect}(t)$ is known. Even in case of experimental stress data, the function $f_{spect}(t)$ is a necessary parameter. Without it, the estimation of fatigue life is not possible. The proposed method can therefore be considered a "hybrid" method even if, as shown in the next, it is particularly reliable and rapid. Figure 2 briefly summarizes both the reference method (in time domain) generally used for estimating fatigue damage, and the proposed procedure in frequency domain.

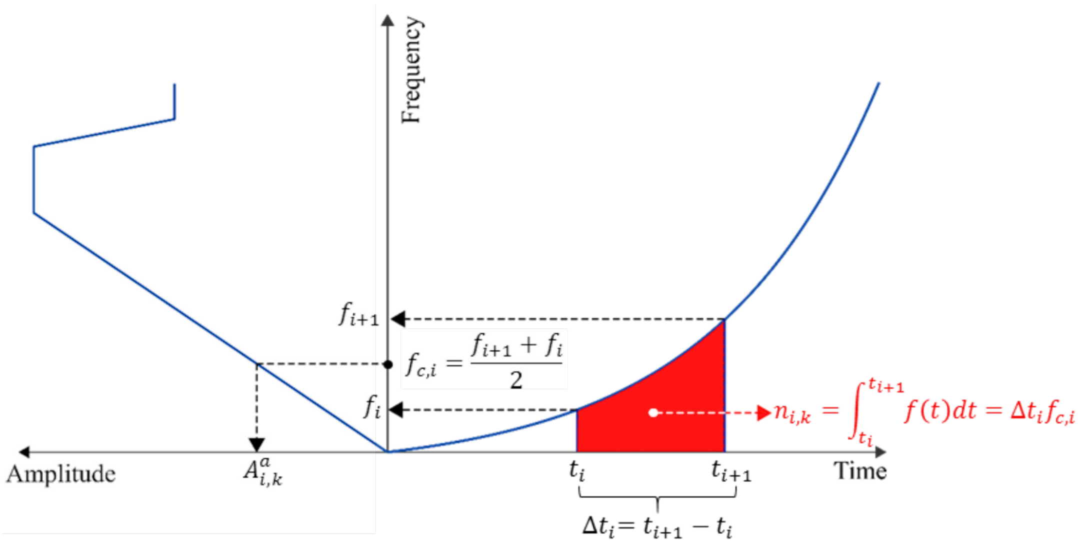

Fig. 1. Proposed load spectrum evaluation procedure for the k^{th}*element*

3.1. Multi-axial case

The load spectrum procedures proposed in previous section is referred to uni-axial case only. However, due to geometrical complexity, industrial component are often subjected to multi-axial stress state. To use the proposed procedure is therefore necessary a multi-axial synthesis. This can be done according to the following technique. Once the spectra of modal coordinates $S_q(\omega)$ and the modal stress matrix $[\Phi_k^{\sigma}]$ of the k^{th} element are known it is possible to evaluate a quadratic form of stress spectra matrix, as shown in Eq. 12

$$[S^*_{\sigma,k}(\omega)] = [\Phi_k^{\sigma}][S_q(\omega)][S_q(\omega)]^T[\Phi_k^{\sigma}]^T \tag{12}$$

where the apex T represents the transposed conjugate and the apex $*$ represents a quadratic form. The obtained matrix of spectra $[S^*_{\sigma,k}(\omega)]$ allows to exploit the matrix operation of the trace, that performed on the product between the stress spectra $[S^*_{\sigma,k}(\omega)]$ and the matrix $[Q]$ as shown in Eq. 13 allows to obtained a quadratic equivalent stress spectrum.

$$\{S^*_{\sigma,eqv,l}\} = trace\{[Q][S^*_{\sigma,k}(\omega]\} \tag{13}$$

In Eq. 13, matrix $[Q]$ is the definition of Von-Mises in frequency domain introduced by Preumont Pitoiset and Preumont (2000).
Since the obtained equivalent stress spectrum is quadratic, before to use the procedure previously introduced it is necessary to evaluate the magnitude as follow:

$$\{S_{\sigma,eqv,l}\} = \sqrt{\{S^*_{\sigma,eqv,l}\}} \tag{14}$$

Once the equivalent uni-axial stress spectrum $S_{\sigma,eqv,l}$ is known, it is possible to estimate the procedure introduced in Sec. 3 for the uni-axial case to estimate the fatigue damage.

4. Test Case

The activity conducted in collaboration with HPE Coxa S.p.A allowed to verify the proposed procedure on a industrial test case, i.e. the virtual qualification of a set of feeding pipes of an high performance engine (Fig. 3)

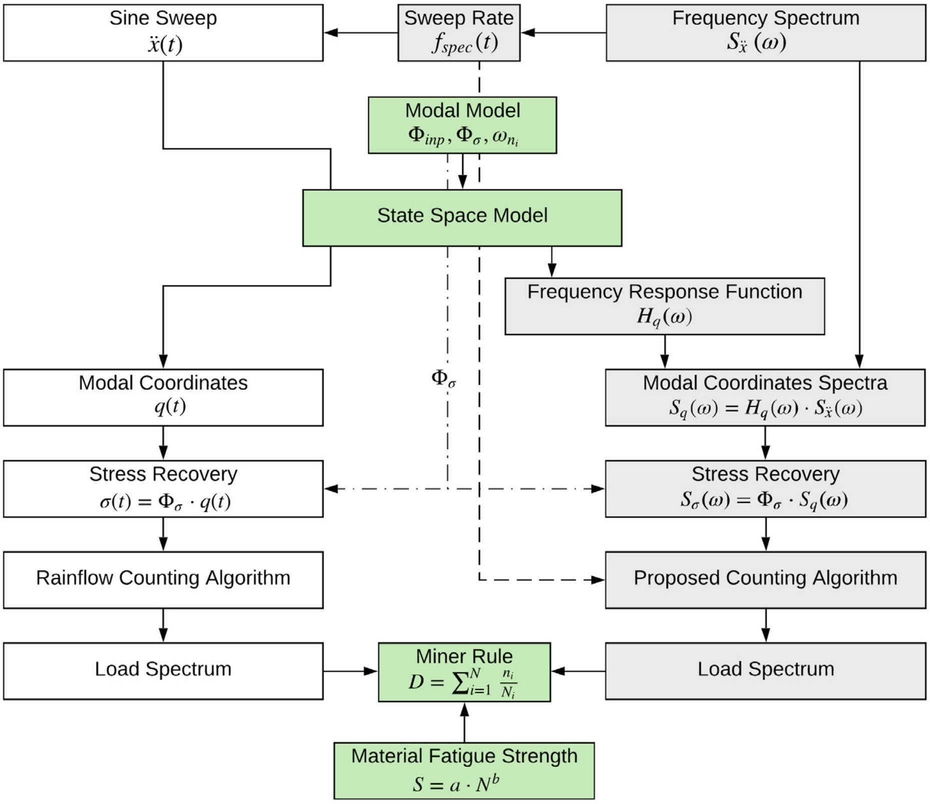

Fig. 2. Flowchart of the standard (white + green) and proposed (grey + green) procedure for fatigue damage evaluation for Sine-Sweep excitation

The system was modelled in ANSYS environment. The FE model was rigidly constrained at the fixture in order to make it a *Single Input Multi Output* system. From the modal analysis, natural frequencies, modal participation factors, displacement and stress modal matrix were extracted for modelling the system via state-space approach. The model foresees 1199882 SOLID187 elements e 879839 nodes. Tab 1 shows the materials for each components highlighted in Fig. 3.

Table 1. Material used in FE model

Material [−]	Component [−]	Density $[Kg/m^3]$	Elastic Modulus $[MPa]$	Poisson Modulus [−]
Steel + Fuel	Supplying pipes	8133	$2 \cdot 10^5$	0.3
Aluminium	Fixture	2710	$7.1 \cdot 10^4$	0.3
Steel + Rubber	Mounting Bracket	7850	$2.6 \cdot 10^5$	0.3
Steel	Other components	7850	$2 \cdot 10^5$	0.3

The parameters necessary to design the $S-N$ curve for the Supplying pipes (object of analysis) shown in Fig. 3 are summarized in Tab.2. To be as more realistic as possible, the section after $2 \cdot 10^6$ *cycles* the Hybach hypothesis was used that foresees a slope equal to $1/3$ of the previous section.

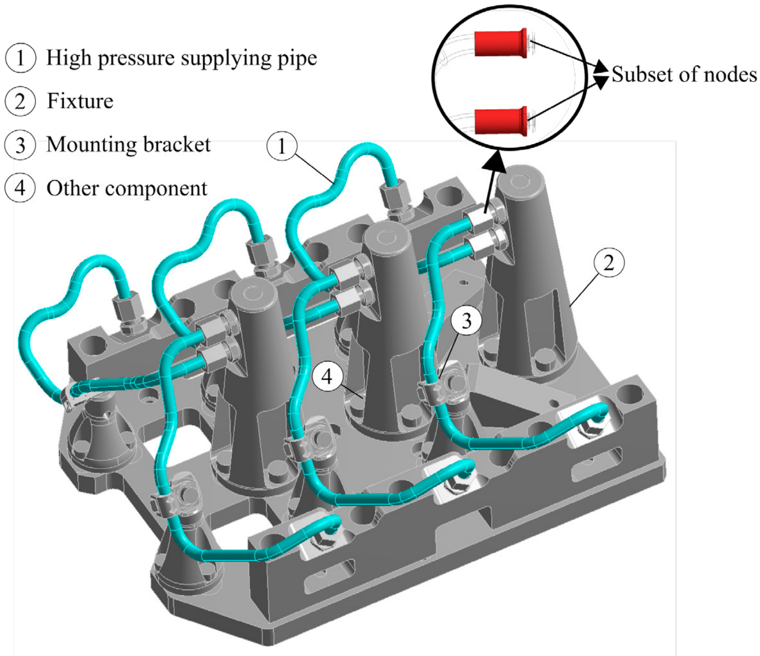

Fig. 3. Test Case. High pressure feeding pipe (blue). Subset of analyzed nodes (Red).

Table 2. Parameters of the $S-N$ curve of the feeding pipes

	from 10^3 to $2 \cdot 10^6$ cycles	from $2 \cdot 10^6$ to 10^9 *cycles*	
a	$1.7 \cdot 10^3$	$4.7 \cdot 10^2$	$[MPa]$
b	-0.13	-0.043	[−]

4.1. *The inputs*

The input frequency spectrum imposed by standards and used in following simulations is summarized by the parameters shown in Tab. 3.

Table 3. Parameters of the imposed frequency spectrum

Frequency $[Hz]$	Acceleration $[g]$	Velocity $[mm/s]$	Position $[mm]$
10	10	1.560	24.8405
700	70	0.156	0.0354
1500	70	0.072	0.0077
2000	40	0.031	0.0024
2500	40	0.024	0.0015
3000	25	0.013	0.0006

The speed of the Sweep imposed by the standard was equal to 1 $octave/min$. The time history of the Sine-Sweep was generated according to the equations shown in Sec. 2.1.

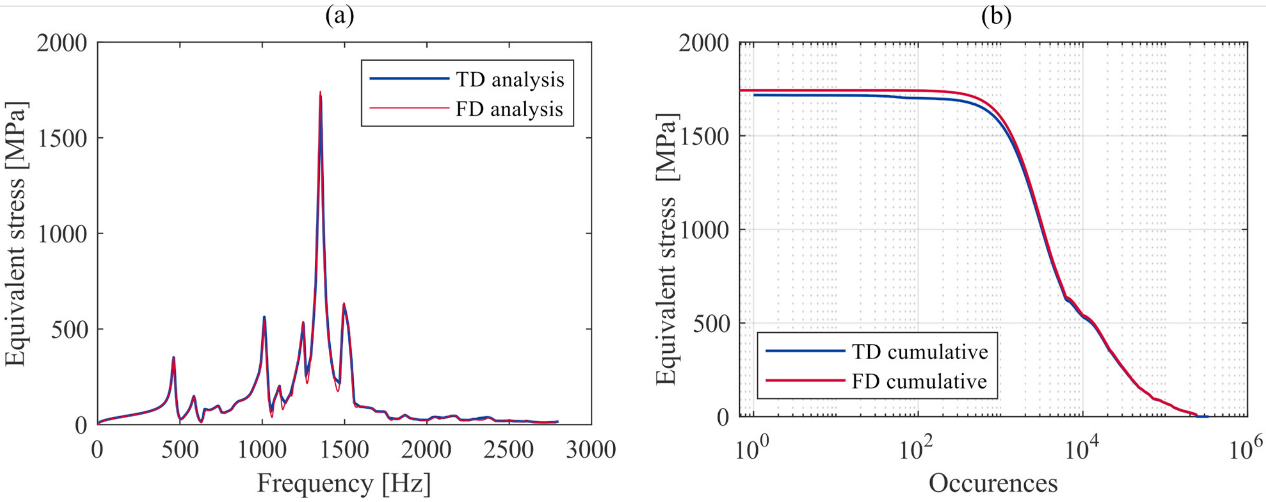

Fig. 4. (a) Comparison between frequency spectra obtained with the proposed approach (FD) and with the reference approach (TD) for node ID = 701. (b) Comparison between load cumulative obtained with the proposed approach (FD) and with the reference approach (TD) for node ID = 701.

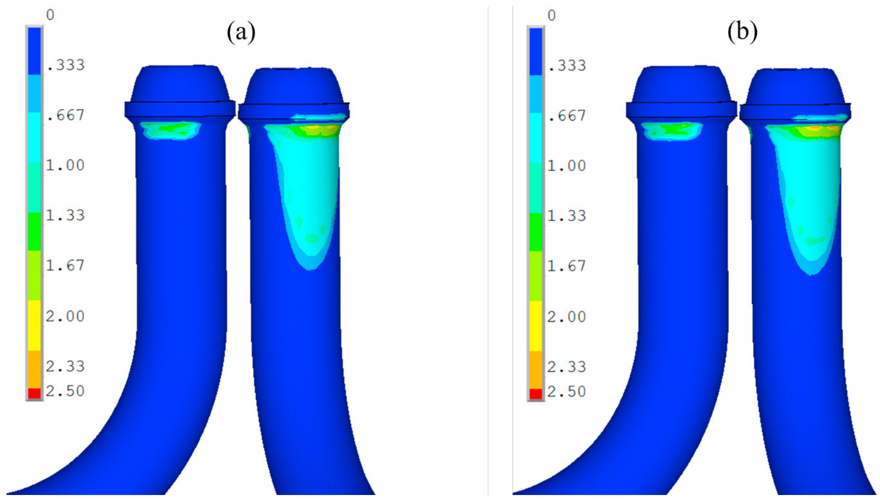

Fig. 5. Damage map for the set of analyzed nodes. (a) Reference Approach (Time Domain); (b) Proposed Approach (Frequency Domain)

4.2. Comparison between results obtained via time and proposed frequency domain approach

In this section the results obtained with the reference approach (time domain) and the proposed approach (frequency domain) are shown. Modelling the system in a state-space representation and by using the approach summarized in 2 the stress component are firstly obtained and secondly synthesized to an equivalent uni-axial stress state. After that, the rainflow counting and the proposed cycle counting algorithms were used to extract the fatigue cycles. Figure 4 shows a comparison between the equivalent uni-axial stress frequency spectra obtained with the proposed approach in frequency domain (FD) and that recovered from the reference approach (TD) for the node ID = 701 that results to be the most damaged node. As shown in Fig. 4, no differences can be noticed between the results obtained with reference and proposed approach. This aspect certifies the goodness of the proposed cycle counting algorithm. To better show the effectiveness of the frequency domain approach for Sine-Sweep test, Fig. 5 shows a damage map extended to the full set of analyzed nodes. Even if the obtained fatigue damage, with both approaches is higher than 2 and so higher than the fatigue limit, the shown analysis and results has the unique purpose to shows the goodness of the proposed frequency domain approach for the estimation of fatigue damage. To this aim, the shown results certify, without doubts, the effectiveness of the frequency domain approach. However, so high damage values are due to the not-consideration of notching profile in simulation. Notching profiles, generally used in qualification tests, are used to monitor and to reduce, if needed, the excitation level in certain crucial zone of the system. Although the obtained results are quite comfortable, what worth to note is the computational effort required from both approaches. To highlighted benefits arising by a frequency domain approach, computational time for each section of the simulation were recorded for both approaches in order to make firstly a phase-phase comparison and secondly a full-time comparison. It worth to note indeed that some simulation phases, as the evaluation of modal coordinates both in time and in frequency domain, are executed once at simulations while the stress recovery must be performed for each element. Tab.4 shows a comparison for each simulation phase for an individual node. As clear, the computational time are undoubtedly in favor of frequency domain. The ratio (evaluated over the total required time) is about 31 times.

Table 4. Comparison between computational time for each simulation phase with reference and proposed approach for the individual node. (apex [1] indicates once evaluation per simulation)

Reference approach (Time Domain)					
	$q(t)$	$\sigma(t)$	$\sigma_{eqv}(t)$	Load Spectrum	Total
Computational time [s]	78.8[1]	4.2	83.5	14.0	181.0
Proposed approach (Frequency domain)					
	$S_q(\omega)$	$S^*_\sigma(\omega)$	$S_{sigma,eqv}(\omega)$	Load Spectrum	Total
Computational time [s]	1.3[1]	0.04	2.96[1]+1.02	0.26[1]+0.24	5.8

Extending the required computational effort to the full set of 1678 analyzed nodes, the frequency domain approach requires about 2.7 h while a time domain approach needs about 54 h.

5. Conclusion

Numerical simulation can be a useful tool in all those industrial contexts where design components must overcome vibration qualification tests. Integrating numerical simulation in the design process allows to simulate the qualification tests reducing the risk of a possible non-expected breakdown of the component. The integration of a simulation phase within the design process however necessarily involves an increased of the design times. To this end, a numerical simulation carried out entirely in frequency domain allows the calculation times to be reduced, thus reaching the initial purpose. Although for Random and Sine on random analysis, several simulation techniques and procedures are available in the literature, for Sine-Sweep excitation is not the same. In this context, this work is aimed to propose a simulation procedure, simple and robust, entirely in frequency domain for Sine-Sweep tests. The proposed approach has been validated by comparing the results obtained with the reference approach (time domain) and those obtained with the proposed method (frequency domain) on an industrial test case (a set of feeding pipes of a high performance engine) proposed by HPE Coxa SpA. The obtained results show once again the advantages of using a frequency-domain approach. In fact, guaranteeing an excellent correspondence between results, the calculation times are reduced of about 31 times. This makes possible to state one more time that simulation technique, entirely developed in frequency domain, can be integrated into any design process being simple, reliable and inexpensive in terms of computational effort.

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