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Validation of the multiaxial racetrack amplitude filter

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ABSTRACT

Amplitude filters are a most important tool in practical fatigue analyses to manage their computational cost when, as usual, the measured load history is noisy, oversampled, too long, and/or contains too many non-damaging low-amplitude cycles or events. To reduce the calculation burden, such filters should not only eliminate noise and remove redundant oversampled data from the measured signal, but also neglect small amplitudes that do not cause fatigue damage. The veteran racetrack filter can perform all such tasks efficiently, however it is limited to uniaxial load histories. Multiaxial filtering techniques have been proposed in the past, however they fail to identify the most damaging events in several non-proportional histories, in addition to losing information on the load path shape. In this work, a new, fast, and efficient multiaxial version of the traditional racetrack filter is proposed to solve these issues, synchronously filtering complex loading histories while preserving all their significant reversals and equivalent ranges, and their load path shape as well, a most important feature for multiaxial fatigue analyses. Six and three-dimensional versions of the filter are proposed, respectively for invariant-based and critical-plane damage calculation approaches. The method allows not only the proper filtering of stress/strain histories at a given material point, but also of any history of multi-dimensional quantities such as forces, moments, and/or displacements acting at different points of a structure. The filter efficiency is evaluated from tension–torsion experiments in 316L stainless steel tubular specimens with challenging non-proportional path shapes.

1. Introduction

Most service strain or load histories measured in practice have non-damaging low-amplitude events and non-negligible noise levels that introduce many irrelevant peak and valley events in the signal, which should not be considered in fatigue analyses. In fact, under real field conditions, these irrelevant events can be several orders of magnitude more frequent than the actual damaging events contained in the measured signal, a major practical problem when such signals must be used for structural integrity evaluations.

Frequency filters that can remove high-frequency noise are not appropriate for fatigue calculations, because they distort the signal and usually change the values of the load peaks and valleys, which are the main responsible for fatigue damage in rate-independent problems, where viscous effects can be ignored in the material behavior. Therefore, instead of frequency filters, *amplitude* filters are required instead in these cases to remove noise while preserving the values and the order of the significant peaks and valleys of the strain or load history, regardless of time or frequency associated with them.

Load input filters have been proposed in the past to eliminate some of such undesirable events, since they much increase the numeric burden in fatigue analyses. In fact, they may even eventually render such analyses impracticable. However, so far there is no filtering procedure that can be considered a really appropriate tool to solve such important problems in practical fatigue damage calculations under multiaxial variable amplitude loading (VAL) conditions. This paper aims to help solving this situation, generalizing the racetrack idea that has been successfully used to solve uniaxial problems since the 1970's [1].

Uniaxial amplitude filters can be directly implemented in the cycle counting algorithm, usually based on the rainflow method [2–4]. The implementation of such an amplitude filter is rather simple if applied to the output of the cycle counting method, since it only requires the elimination of the counted amplitudes below a certain non-damaging threshold level, with or without considering mean/maximum stress effects.

However, the main advantage of such amplitude filters is to significantly decrease computational time, removing from the load

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history noise and redundant data, as well as irrelevant non-damaging events, *before* counting them. In other words, they can only be useful in practice if the filtering process is efficiently performed *before* analyzing the fatigue damage caused by the load history. This is especially true for multiaxial VAL fatigue calculations based on the critical plane approach [5], which need rainflow counts of every projected history from every candidate plane. From the computational point of view such critical plane routines are intrinsically expensive, but nevertheless they are needed when modeling multiaxial fatigue damage in materials that tend to initiate a single dominant crack at critical points, like most metallic alloys.

In addition, the original rainflow procedure can only be started after the entire load history is known, increasing even more the computational cost as well as computer memory requirements, which can be quite significant for very long histories. Computational cost can be dramatically reduced with ‘‘real-time” rainflow algorithms, such as the pioneer Martin–Topper–Sinclair’s 1971 method [6], which essentially reproduces in real time the uniaxial rainflow algorithm as the load events are provided or measured. Several other ‘‘real-time” rainflow implementations have been proposed [7–11], which in essence are very similar to the original one [12]. In all of them, an amplitude filter could be easily included in the output step of the algorithm; but to decrease computational cost when dealing with real signals, in practice this filter should be applied *before* counting cycles, as discussed above.

The racetrack filter, originally proposed in [1] for uniaxial histories, can do that. It aims to eliminate from VAL histories small amplitude load events that do not induce fatigue damage, before applying any cycle counting method. In this way, the resulting condensed histories can accelerate both experiments and computations, focusing only on the few significant events that cause most or all of the damage. This filter has been successfully applied for managing practical uniaxial load histories, especially those measured by strain gages in actual field conditions, and is a well-proven tool capable of removing noise and most non-damaging events from real signals. Notice that this filter is only based on the signal amplitude, without including mean/maximum stress effects. Therefore, it is common practice in histories with tensile mean stresses to choose filter amplitudes significantly lower than the fatigue limit under zero stress ratio ($R = 0$).

However, the original racetrack filter unfortunately cannot be used in multiaxial fatigue calculations, even though amplitude filters are much more needed in such cases to decrease their intrinsically high computational cost. In fact, to properly measure load signals, it is necessary to oversample the digitalized data at a rate high enough not to distort the signal (theoretically, at least at a sampling frequency twice as high as the highest significant spectral component of the signal, but usually at a much higher rate in practice) [13]. Moreover, signals measured under real field conditions are always contaminated by noise, which introduce hopefully small but usually many irrelevant peaks and valleys that can make fatigue analyses impractical if not properly removed beforehand. Hence, the usual case in practical applications is to deal with oversampled data and noisy measurements.

A simplistic approach to decrease the number of points in oversampled multiaxial data would be to apply a peak/valley filter to each and every component of the loading, to remove all data points that are not peaks or valleys of any of their stress or strain components. But this filtering practice *cannot* be safely used in non-proportional (NP) multiaxial histories, for two reasons: first, the path between two load reversals is needed to evaluate the path-equivalent stress or strain ranges associated with each rainflow count, e.g. using a convex enclosure method or the Moment of Inertia (MOI) method [14]. Equivalent stress or strain ranges end up underestimated if too many points in the load path are filtered out. Thus, some points along the path should not be eliminated from the load history, even if they do not constitute a load component reversal.

The second reason against using a simplistic non-reversal filter is because the reversal points obtained from a multiaxial rainflow algorithm do not necessarily occur at the reversal of one of the stress or strain components. For example, the relative von Mises strain, used in the Wang–Brown [15] and Modified Wang–Brown (MWB) [16] rainflow counts, may reach a peak value at a point that is neither a maximum nor a minimum of any strain component. But such most important points would be filtered out by a non-reversal filtering algorithm, resulting in non-conservative fatigue damage and life predictions.

One example of this simplistic filtering approach for multiaxial histories is the ‘‘Peaks Procedure” from [17], which filters out all events whose components are not peaks or valleys, potentially eliminating important load points that could have the highest von Mises stresses or strains in the load history, even though each individual component was not maximized. In addition, this procedure would store each and every event that constitutes a peak or valley from any single component, which for noisy measurements could result in no events at all being filtered out, even if the unavoidable noise had very low amplitudes.

An appropriate multiaxial amplitude filter should thus consider not only peaks and valleys, but also how a measured multiaxial loading path deviates from its course, evaluated by some metric such as the von Mises stress or strain. This fundamental feature is needed to avoid filtering out important counting points from multiaxial rainflow algorithms or significant paths that could affect the calculation of an equivalent stress or strain range, since all stress or strain components contribute altogether for the reversals that can be eliminated. Finally, once the original VAL history is condensed into a smoother history by discarding small amplitude ranges that cause negligible fatigue damage [18], as well as the unavoidable noise e.g. from actual strain measurements, the calculation effort can be much decreased without compromising its accuracy. Such filters are an almost indispensable tool for practical fatigue analyses.

In the next section, the uniaxial racetrack algorithm is reviewed, along with a physical peg-slot analogy that will be useful for the multiaxial generalization proposed in this work.

2. Uniaxial racetrack filter

Fig. 1 illustrates the uniaxial racetrack filter [1,19], condensing the original history from Fig. 1(a) into the history in Fig. 1(d), eliminating amplitudes smaller than a user-specified value r. Originally inspired by slalom ski races, this amplitude filter idea is to draw a *racetrack* of width $2r$ bounded by upper and lower *fences* that have the same profile as the original history, see Fig. 1(b). Every time a *driver* racing in this racetrack needs to change its direction a reversal point is identified, as seen in Fig. 1(c) where the driver needs to change twice its direction near points B and E, but not in points C and D (which are filtered out), because there is no need to avoid the fences associated with them.

Narrow tracks almost keep all the original reversals, while wider ones filter out most of the original loading history. As exemplified in Fig. 1, the condensed (by the racetrack amplitude filter) history does not change the order of the load events, an essential feature to account for plasticity memory effects.

Besides the driver (or perhaps slalom skier) analogy, the racetrack problem can also be regarded as a problem involving a small round peg P oscillating inside the slotted hole of a bar whose center is the point O, see Fig. 2, with total range $2r$. Initially, the peg and slot centers are aligned with point A, see Fig. 2(a). In the figures,