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An innovative modal approach for frequency domain stress recovery and fatigue damage evaluation

Claudio Braccesi, Filippo Cianetti *, Lorenzo Tomassini

University of Perugia, Department of Engineering, via G. Duranti, 93, Perugia 06125, Italy

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ABSTRACT

The aim of the present paper is to show and validate an innovative method, developed by authors to evaluate, in frequency domain, the fatigue damage of mechanical components modeled by modal approach and subjected to random dynamic loads. The authors, in particular, have theoretically demonstrated that the exact statistical properties (*spectral moments*) of the PSD functions matrix of stress tensor of the model are obtainable only from PSD functions matrix of its modal coordinates and from PSD functions matrix of inputs. To show the capabilities of this new approach and to verify the obtainable speeding up of the evaluation process two test cases are analyzed and discussed.

1. Introduction

The evolution, in last three decades, of the techniques of analysis and evaluation of fatigue damage in frequency domain of components subjected to random loads has brought this kind of approach to be an established feature in the scenario of fatigue design.

Even if the attention was addressed only to fatigue damage evaluation, starting from works of Whirsching [1] or Bendat [2], it is possible to notice a great progress in the approaches developed to evaluate load spectra or fatigue damage directly from the frequency domain representation of the components of stress state tensor, developed from theoretical, numerical or experimental point of view [3–24].

Whatever consolidated criteria is considered, it assumes to have a single stress power spectral density (PSD) function [2,25,26] as input (i.e. uniaxial stress state). To extend the capabilities of this kind of approach to multiaxial stress states, a lot of criteria were developed to adapt results and methods, designed for uniaxial stress conditions, to multiaxial ones, obtaining encouraging results [27–37].

Starting from a single stress PSD function, so called *direct* [3,8–10,13,22], *correction coefficients* [1,7,11,12,14], and *indirect* [21] criteria allow to obtain an evaluation of the load spectrum and of the cycles *probability density function* (pdf) or to, directly, assess the damage, by adopting a damage cumulation rule, such as the linear *Palmgren–Miner* one [38].

The aim of the present paper is to show and validate an innovative method, developed by authors to evaluate, in frequency domain, the fatigue damage of mechanical components modeled by modal approach and subjected to random dynamic loads.

In previous papers, the authors have focused their attention on the numerical evaluation of the stress state and of the associated fatigue damage of mechanical components subjected to random dynamic loads; this activity was developed starting from the hypotheses of mechanical systems modeled within a multibody code (MBS) and of component/s modeled by using modal approach [16–18,39,40]. From these hypotheses, the analysis of the dynamic behavior of the component, when performed in the frequency domain, was assumed to have the system representation expressed in a linearized form, as a state space system [2,25], having as inputs whatever loading condition and as outputs the modal coordinates of the component. The latter were associated with the corresponding mode shapes (i.e. stress mode shapes), previously obtained in the component mode synthesis process, carried out in any finite element analysis (FEA) environment. This utility is now implemented in all the major MBS codes, also thanks to the research activity of the authors themselves [16,39]. This hypothesis, apparently restrictive, allows to tackle the analysis of non-linear system too, in case of random load conditions [16], by always considering the linear behavior of the component (modal approach). In a previous work the authors have shown that it is possible to successfully deal with these conditions and, therefore, to well recover the

* Corresponding author. Tel.: +39 075 5853728; fax: +39 075 5853703.
E-mail address: filippo.cianetti@unipg.it (F. Cianetti).

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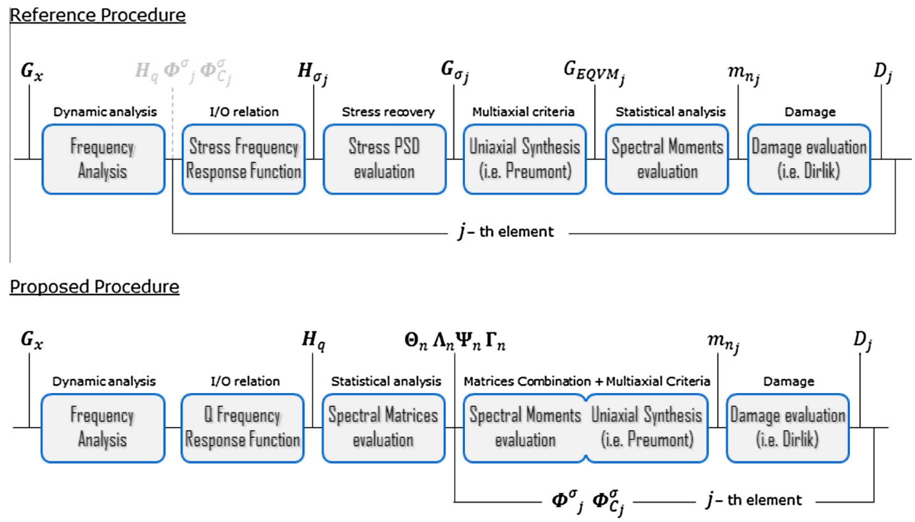

Fig. 1. Comparison between flow charts of reference and proposed procedure.

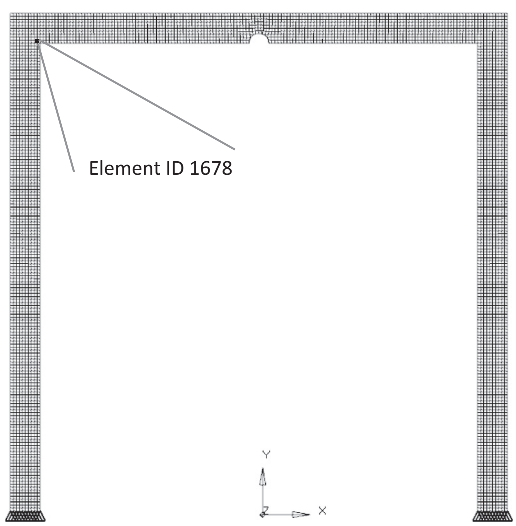

Fig. 2. Representation of FE model of test case no. 1 and of the most damageable element (ID = 1678).

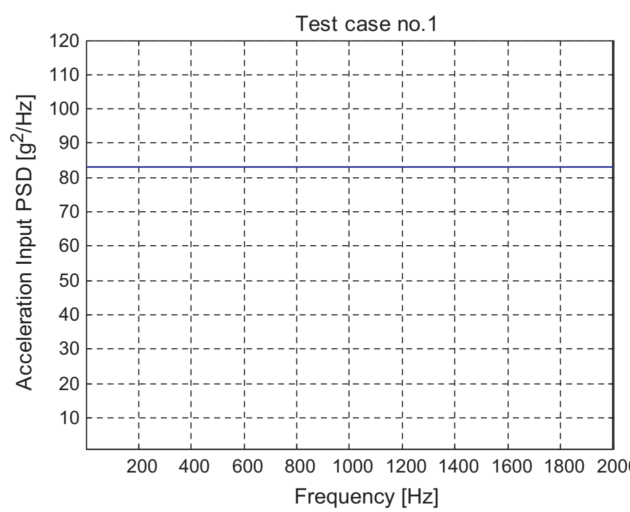

Fig. 3. PSD function of the acceleration input – test case no. 1.

matrix of power spectral density functions (PSDs) [16] of the stress tensor of a generic element of the FEA model, by combining time domain dynamic analysis with the previously cited one.

The *reference* frequency domain procedure to evaluate damage was and is a method that, by looping among all elements, reconstructs the power spectral density matrix of the stress tensor, a matrix 6 × 6, and then summarizes its content in a single power spectral density function [39,4,26,29–31], for example by using *Preumont*'s approach, that can be subjected to any frequency criterion. When the stress state satisfies the hypothesis of Gaussian stationary ergodic signal and is synthesized by a single signal, the literature shows a whole series of approaches that, starting from its power spectral density function (PSD) and the relative *spectral moments*, allow to directly obtain an estimation of the damage [3–24]. *Dirlik*'s one [3] is considered by authors as reference criterion, which, if compared to the other ones, shows a greater applicability to a wide range of PSDs [11,12,23]. A lot of approaches then try to adapt results and methods developed for uniaxial stress conditions to multiaxial stress states with encouraging results [27–31,33,35,36,37].

One of the aims that the research on fatigue arises is to provide the designer with tools that are able to understand the physical behavior of the phenomenon correctly without huge computational costs. The frequency domain stress state recovery (dynamic analysis step) and the use of the above approaches (results post-processing step) allow to reach this aim, especially if their use is oriented to the first stage of the mechanical system design process and, in particular, to the identification of components critical locations.

In order to speed up as much as possible the frequency domain method, the authors have undertaken a further research activity aimed to minimize calculation time and errors in the damage evaluation of flexible components by FEA or multibody (MBS/Flex) approach [39,18].

This paper demonstrates the capabilities of an innovative stress recovery and statistical content evaluation, especially for finite element analysis calculation environments (FEA). First of all the authors briefly describe the state of the art of performing dynamic numerical analysis in frequency domain. By addressing and illustrating the theoretical problems in using the modal approach, focusing on finite element analysis, a new dynamic simulation procedure, adoptable and easily implementable by FEA codes, is shown. The authors show the theoretical demonstration – of how the fatigue damage of all or of a subset of elements of the model