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Using computer technique for developing method for vibration damage estimation under combined random and deterministic loading

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ABSTRACT: This paper is focused on developing a method for vibration damage estimation for military helicopters and fighter aircraft exposed to combined stochastic and deterministic loading. The first stage of the research focused on frequency domain damage prediction, for which algorithms based on superposition of spectral moments and Dirlik method of RCC in frequency domain were developed. The first phase of the research showed the legacy algorithm based on transfer function developed using FEM method in Abaqus environment is conservative. The second stage of research aims to develop a method which allows for a more robust damage estimation. For this purpose the Monte Carlo method for retrieving random signal in time domain from signal in frequency domain was used. To enable an assessment of a more complex loading scenario than just a random load a simultaneous sine wave or sine sweep was introduced. In order to obtain the system transfer function a 1g harmonic load response was recorded using FEM analysis. It was subsequently scaled linearly by the PSD input curve for random loading and sine wave or sine sweep function for deterministic loading to calculate the cumulative system response of the linear system. Developed novel method allows to precisely estimate vibration damage and can also be used for replication of test conditions.

KEYWORDS: vibration damage, random vibration, FEM, monte carlo method, frequency and time domain RCC algorithms

1. Introduction

RCC in frequency domain is commonly used for vibration damage estimation under stochastic loading of linear systems with synergy with FEM analysis. Precursor of RCC method in frequency domain was Bendat [1], who provided a method used for narrow band signals. Next milestone was the development of a RCC algorithm in the frequency domain made by Dirlik, using Monte Carlo method [2]. This approach is now considered one of the highest accuracy techniques used in commercial software [3-4] for assessment of damage under random loading.

The above methods have been developed for vibration damage estimation for purely stochastic loading. However they have been adopted for more general usage i.e. damage estimation under combined stochastic and deterministic loading [5], (e.g. simultaneous deterministic sine sweep and random load – see Fig. 1). This combination is required by USA Department of Defense Test Method Standard [6] or other specific requirement driven by military aircraft manufacturers.

The first stage of research introduced in this papers shows that using abovementioned method provides very conservative damage results. Second stage of research was the development of a novel method for precise damage estimation under combined loads. In this paper combined loads means simultaneous deterministic and stochastic loads.

The novel technique expands research done by Dirlik with considering frequency resolution, populational studies, combination stochastic and deterministic loading and additionally uses FEM for transfer function estimation.

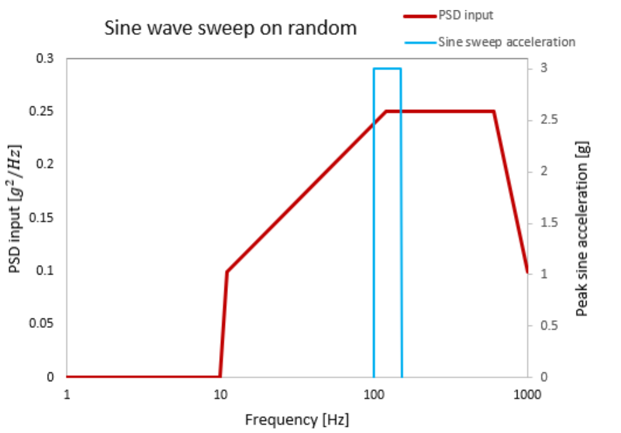

Fig. 1. Sine wave sweep simultaneous with random background

2. Frequency domain vibration damage estimation

Vibration damage assessment, based on transfer function of system, was derived using the mode superposition method in Abaqus environment. Derived transfer function H(f) is then multiplied by the PSD input G(f) defined for considered test duty and obtained PSD response function in frequency domain, see equation (1).

$$S(f) = H(f) \cdot G(f) \tag{1}$$

The PSD response function derived for each integration point of the discrete model is then the basis for usage of Dirlik method for RCC algorithm in frequency domain, as per [2, 5]. Damage was evaluated using the Miner rule

[7]. Damage results can then be presented on a discrete model using Abaqus [8] visualization module and author's scripts – see Fig. 2.

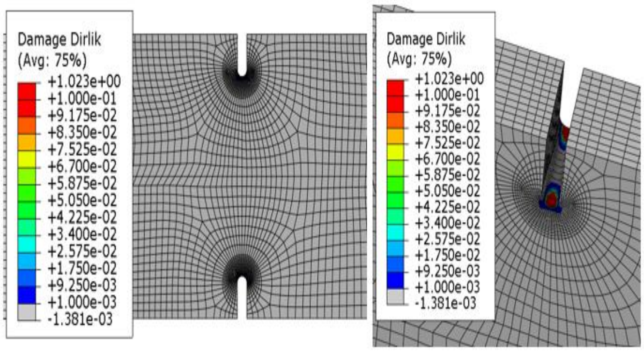

Fig. 2. Frequency domain vibration damage estimation using Dirlik method

Obtained damage values have been benchmarked against commercial software and the difference in results do not exceed 1%. This result is the basis for the stage one of the research – damage estimation for combined stochastic and deterministic loading in frequency domain.

3. Frequency domain vibration fatigue estimation under combined stochastic and deterministic loading

Methodology introduce in section 2 of this paper is the basis for damage estimation under combined loads. References [6-7] describe the idea for damage estimation based on superimposing of spectral moments generated by random and deterministic loads. The abovementioned approach was used.

Deterministic load amplitude is estimated by taking into account the system response (transfer function in considered sine wave or sine sweep incremental frequency $H(f_{SW})$) and can be called transfer function amplitude $Amp(H(f_{SW}))$, see equation (2).

$$Amp(H(f_{SW})) = \text{AmpSW} \cdot \sqrt{H(f_{SW})} \qquad (2)$$

Where AmpSW is amplitude of the input sine wave or sine sweep signal.

Damage value obtained by created algorithm has been benchmarked against damage value obtained using commercial software and obtained great correlation.

The abovementioned method proved to be highly conservative. Two loops of analysis under vibration loading were calculated. The 1st loop, based on algorithms for vibration damage estimation under deterministic loading (pure sine sweep), obtained damage value of 0.009 for critical integration point. The 2nd loop, based on algorithms for combined stochastic deterministic loading and a low level non-damaging random load (giving 0 damage after evaluation using the algorithm for pure random loading, peaking at 9MPa of 5 sigma stress). For the combined load scenario a damage of 0.58 was calculated for the same sine sweep as in the 1st loop (resulting in 0.009 of damage). The results above have shown legacy approach high conservativism and initialized the further research.

4. Combined frequency and time domains vibration damage estimation under combined stochastic and deterministic loading

Second stage of the study focused on developing a novel method for precise vibration damage estimation under combined loads. The idea is based on retrieving time series signal from the frequency domain PSD response as proposed by Dirlik [2] with using Monte Carlo method.

The sine sweep can be written as a function of time and frequency – see equation (3). Due to the coupling of the dependence of the sine sweep with the time and frequency domains, sine sweep function can be scaled by the transfer function H(f) to obtain a time series sweep with including the system response – see Fig. 3.

$$Frequency = f_1 + K \cdot Time \qquad (3)$$

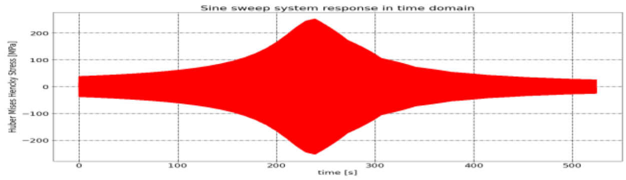

Fig. 3. Sine sweep system response in time domain

This signal, which consist of the stress value, can be now superimposed to random time series PSD resposne retrivied using Monte Carlo method (asuming linearity of system, with restiction that time sequence of retrived random signal match to time sequence of sine sweep). For superimposed signal RCC in time domain was used, SN curve introduced and damage for combined stochasitc deterministic input evaluated.

5. Summary and conclusion

Below the main points of the conclusion are presented:

1) pure frequency domain method for vibration damage estimation under combined loads is highly conservative,
2) novel developed method allows a precise vibration damage estimation for combined loading scenario,
3) new method allow for clipping of random signal within +/-3σ stress/acceleration for precisely test replication. Therefore additional conservatism can be removed,
4) proposed method can also take into account frequency resolution of controller used for testing. This parameter influence the damage variation as proved with research made for large population of samples.

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