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THE IMPACT OF DYNAMIC LOADS ON TRANSMISSION SHAFTS OF THE CIVIL AIRCRAFT

ABSTRACT

The research presented in the thesis focused on impact the stochastic and the combined stochastic and deterministic loading scenario on the aircraft units. The aim of the research was to create general methods for vibration damage estimation under these loading scenarios and demonstrate it on the exemplary transmission shaft of civil aircraft.

The initial research focused on study of the legacy techniques and using of the commercial software for vibration damage estimation in the aerospace industry. In the thesis introduced methods for signal statistic and Rainflow Cycle Counting (RCC) in frequency domain. The main attention has been paid to the Dirlik method, the Narrow Band method, the Steinberg method and the Lalanne method, as these methods are commonly used in commercial software's for aerospace application (also in the Collins Aerospace Company).

The next step was creating programming tools to implement current state of knowledge used for vibration damage estimation in frequency domain – as the research assumed developing the extension of current methods. Algorithms for vibration damage estimation have been created with implementation of aforementioned methods for RCC in frequency domain. Created algorithms have been correlated against MSC CAE Fatigue software and were the base for further research. Additionally, during this phasis observed that the Lalanne method gives different damage results especially for narrow band signals comparing to the Narrow Band and the Dirlik methods. During this stage of research proposed modification the Lalanne method. Proposed modification of the Probability Density Function equation resulting in obtaining damage results close to the Dirlik method.

To extend the current state of knowledge proposed made the research on the time representations of the stochastic signals with using the IFFT (Inverse Fast Fourier Transformation) and the Monte Carlo methods – by analogy to the research made by Dirlik during developing his method. The research assumption was to retrieve the time domain PSD (Power Spectral Density) response from the PSD response derived for considered sample in the frequency domain with using aforementioned methods. At this stage of research built the programming tools, which allows to implement IFFT and Monte Carlo methods to PSD response function obtaining for considered sample with using linear dynamic approach in Abaqus environment (using the mode superposition method). Additionally created the algorithm for RCC in time domain to allow fatigue analysis in time domain.

Tools created in previous step have been then used for the research of the signal statistic parameters in the time and frequency domains. The research based on frequency domain PSD responses artificially created for research purposed and to retrieve the time domain PSD responses with using the IFFT and the Monte Carlo methods. The research results show that using current stage of knowledge, signal statistic parameters in the frequency domain (upward zero crossing, number of peaks, irregular factor) do not match to the same parameters in the time domain, especially for wide band and white noise signals. Aforementioned parameters are crucial in terms of vibration damage estimation, therefore proposed the modification of integration spectral moments. Proposed modification in integration the 1^{st}, the 2^{nd} and the 4^{th} spectral moments allows to match all mentioned parameters between time and frequency domain. Additionally in this phase of the research proposed modification Narrow Band method to make this method general, which can be used for narrow band , wide band and white noise signals (current state of knowledge allow to not conservative damage analysis only for narrow band signal, for other signals type this method gives very conservative damage values). It has been proposed to replace the number of peaks in spectrum with the number of upward zero crossing in the equation for estimation actual number of cycles in each stress range bins. All proposed modifications allow to obtain convergent damage values for the Dirlik method, the Narrow Band method and the Lalanne method, which is close the Dirlik original method. Proposed modification allows to precise damage estimation with using the Lalanne method and the Narrow Band method for all signals type with using much less empirical consideration than used in the Dirlik method.

During the research observed that the damage value quoted by Dirlik method is the mean value of damage, when consider larger population of samples – damage variate around the mean value, when analyses different time series representations of the considered one representation of frequency domain PSD response. This revelation is important in terms of accuracy the legacy methods – which are not able to provide the information about the damage distribution, therefore it is not possible to estimate the safe value of the damage (e.g., for which 99.73% of population have lower damage value). Research results allow to select three the best fitted distribution types: Normal, Exponentiated Weibull and Generalized Extreme Value distributions, which can be used for description variability of the damage. Additional observation was variation of the damage depend on block size (N) used in IFFT – frequency resolution used during the testing to retrieve the time series signal from the PSD curve. It has been observed that lower frequency resolution resulting in higher damage variability, which stabilize at $\log_2(N)$ equal to 20. Therefore, to not undertest aircraft units during the real testing for the stochastic loading, proposed to meet the inequality (damage for which 0.13% of population have higher damage value estimated for test frequency resolution need to be higher than damage for which 99.73% of population have no higher damage for frequency resolution for which $\log_2(N)$ is equal to 20). To meet this condition, it is proposed to modify the PSD input curve to envelop the original PSD requirement.

The next stage of the research focused on combined stochastic and deterministic dynamic loading requirement used in the civil and the military aircrafts. As the first step created the programming tool, which introduced the current state of knowledge and made the benchmark with the MSC CAE Fatigue software. The legacy methods assumes that vibration damage estimation under combined stochastic and deterministic loading is conducted in the frequency domain (superposition of two signal is conducted in the frequency domain). The thesis provides the proof that using this approach resulting in high conservative results of the damage. The new novel method has been proposed – analysis the damage under this load scenario with using combined time and frequency domains. For new proposed method assumes (the same as for legacy method) using linear dynamic approach to obtain the PSD response function (correlated against test results) and then switch to the time domain – retrieving PSD response in time domain using the IFFT and the Monte Carlo methods. The deterministic part of loading e.g., sine sweep take into account the frequency domain PSD response – using the connection between the time and the frequency (based on the sweep equation). The next step is to superimpose time representation of the stochastic signal and the deterministic signal in the time domain and provide RCC and damage estimation in time domain. The new method gives much less conservative damage result. For this load scenario per analogy to the pure stochastic loading acting, it is needed to derive the damage distribution as the damage variate around the mean value. As the best fitting distribution selected three aforementioned distributions used for only stochastic loading scenario (Normal, Exponentiated Weibull and Generalized Extreme Value distributions). The new proposed method allows to precise damage estimation for combined stochastic and deterministic loading and additionally allows to take into account test parameters e.g., stochastic signal clipping, the frequency resolution used during real testing.

The last stage of the thesis is implementation created or modified methods for analysis impact of dynamic loading on the civil aircraft exemplary transmission shaft. As the input for the fatigue analysis used transmission shaft, for which conducted vibration testing. The test results have been used for correlation the Abaqus FEM model, which used for the fatigue consideration. In the thesis included demonstrational fatigue analysis for stochastic loading and combined stochastic and deterministic loading with using developed methods.

The considerations presented in the thesis allowed for the development of a more robust technique for vibration damage estimation under random loading and combined random and deterministic harmonic loading, which has been adopted in the Collins Aerospace Company, and which will be the basis for creation of in-house software.

The thesis points at further development plan which will take into account strain life method with e.g., the Morrow mean stress correction and the critical plane approach. Additionally in the further research using considered methods for orthotropic materials will be considered.

Research results presented in the thesis have been introduced in two scientific articles which have been published in two international papers. Additionally, research results have been presented in monograph and conference paper. Research results have been also presented and discussed at four international conferences.