Random Vibration Fatigue Life Estimation of Power Controller

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Abstract: The power controller will be subjected to random external excitation loads during use. When subjected to high stress levels for a long time, the structure is prone to random fatigue failure, resulting in structural failure. Therefore, the prediction of the random vibration fatigue life of the power controller is very necessary. In this paper, Nastran software is used, Miner linear cumulative fatigue damage method combined with Gaussian three-interval method to calculate random fatigue of the structure. The final example shows the effectiveness of the method proposed in this paper.

Keywords: power controller; random fatigue failure; Miner linear accumulation; random fatigue calculation

Introduction
In the development of power controllers, static strength design is usually the main focus, but in actual engineering, structural damage is often caused by cumulative fatigue damage. Therefore, it is necessary to estimate the random vibration fatigue life of the power controller to ensure that the structure will not be destroyed by long-term high stress levels.

Based on the Miner linear cumulative fatigue damage theory, this paper adopts the power spectrum method [1~6] to estimate the random vibration fatigue life of the power controller by obtaining the dynamic stress response (PSD) and S-N curve of the structure under random loads.

1. Random vibration fatigue theory based on frequency domain method
According to the definition in [7], Miner’s linear cumulative fatigue damage law is:

\[ D = \sum D_i = \sum \frac{n_i}{N_i} \]  

(1)

In the formula, \( n_i, N_i \) are the number of cycles \( S_i \) of the stress level and the fatigue life of the structure under the stress level \( S_i \), respectively. When the total damage value \( D \) reaches 100%, the structure fails.

In time \( T \), the number of stress cycles in continuous state is:

\[ n_i = E(p)T \int_0^\infty P(S)ds \]  

(2)
Where \( E(p) \) is the expectation of the peak frequency of the random response signal; \( T \) is the action time of the random response, and \( \int_{0}^{\infty} P(S)ds \) is the probability density of the stress amplitude.

For constant stress amplitude, the logarithmic fatigue (S-N) curve is usually used to calculate the allowable number of cycles of fatigue failure of the structure:

\[
N(S_i) = C S_i^{-b}
\]  

(3)

Where \( N(S_i) \) is the maximum number of cycles corresponding to the stress amplitude, and \( C \) and \( b \) are material constants.

In the question, the three-interval method based on Gaussian distribution gives the probability density distribution of stress amplitude under random vibration [8~10]:

\[
P(-\sigma^-\sigma^+) = 68.3\% \\
P(-2\sigma^-2\sigma^+) = 95.4\% \\
P(-3\sigma^-3\sigma^+) = 99.73\% 
\]  

(4)

Therefore, the random vibration fatigue theory based on the frequency domain method uses the stress intensity spectral density (PSD) and the stress density distribution function to calculate the number of stress cycles of the structure under random vibration within the time \( T \). According to the Miner linear cumulative fatigue damage method, the fatigue life estimation method of the structure under random vibration is obtained.

2. Random vibration fatigue life estimation of power controller

Most of the vibrations encountered by the power controller during transportation and actual use are random vibrations. This random excitation is usually represented by the acceleration power spectrum, and the conditions are shown in Figure 1.

![Figure 1. Acceleration power spectrum](image)

Figure 1 shows the relationship between acceleration power spectral density and frequency, describing the vibration of the structure in a statistical sense. At any given moment, the amplitude of its vibration is uncertain, but by the statistics of its vibration amplitude given the characteristics, the
area under the curve is expressed as the root mean square acceleration.

In order to calculate the random vibration fatigue life of the structure, the harmonic response analysis of the structure is first performed to obtain the relationship between the structure response and the frequency, and then the random analysis module of MSC.Nastran is used to realize the random acceleration excitation analysis of the power controller by the modal superposition method. According to the random vibration analysis results, the Miner linear cumulative fatigue damage method and the Gaussian three-interval method are used to estimate the random vibration fatigue life of the power controller. Therefore, the specific process of obtaining the random fatigue life calculation of the power controller is as follows:

(1) According to the engineering analysis accuracy requirements, use the pre-processing software Patran to establish a finite element model of the power supply controller that can simulate the actual;

(2) In order to understand the dynamic characteristics of the power controller, perform modal analysis on the power controller, find the natural frequencies of the PSD load spectrum in the frequency domain, and prepare for the frequency response analysis;

(3) Considering the actual environmental conditions experienced by the power controller, apply boundary loads to the finite element model, select an appropriate structural damping ratio, and use the modal superposition method to analyze the harmonic response to obtain the relationship between structural response and frequency;

(4) Apply the random vibration analysis module in MSC.Nastran to realize the random acceleration excitation response analysis of the power controller;

(5) Obtain the probability density distribution of stress amplitude under random vibration according to the three-interval method of Gaussian distribution, and then obtain the number of stress cycles of the structure in time T;

(6) Estimate the random vibration fatigue life of the power controller based on the Miner linear cumulative fatigue damage method, and judge whether the structure fails within the vibration time T.

3. Calculation example

A power controller is subjected to various random excitations during transportation and use. In order to effectively judge whether random fatigue failure occurs, the power controller is fatigued according to the random fatigue life calculation method of the power controller. The main material of the power controller is aluminum alloy, the density of the material is $2.7 \times 10^3 \text{ kg/m}^3$, the modulus of elasticity is $70.6 \text{ GPa}$, the Poisson's ratio is 0.33, and the basic S-N curve is $S^N=1.5 \times 10^{13}$. According to the method in the previous section, a finite element model that can simulate the actual power supply controller is first established in Patran, as shown in Figure 2.

![Figure 2. Schematic diagram of structure](image)

The solid elements in the model mainly use 8-node hexahedral elements with high accuracy and high computational efficiency, and some complex solid elements use high-precision 10-node tetrahedral elements, and use plate elements to mesh the thin plate parts to improve simulation computational efficiency.

Then conduct modal analysis on the power controller to find the natural frequency of the power
controller structure. This article takes the modal with a natural frequency within 320Hz. There are 6 modes with a natural frequency within 320Hz. The average frequency of the power controller is 255Hz.

Figure 3 The second mode of the structure (151.12HZ)  Figure 4 The second mode of the structure (239.74HZ)

Figure 5 The third mode of the structure (261.49HZ)  Figure 6 The fourth mode of the structure (264.32HZ)

Figure 7 The fifth mode of the structure (300.48HZ)  Figure 8 The sixth mode of the structure (316.46HZ)

Through modal analysis, understand the dynamic characteristics of the power controller, consider the actual environmental conditions of the power controller, apply boundary loads to the finite element model, and select an appropriate structural damping ratio. Based on the modal superposition method, the random vibration analysis module in MSC.Nastran is used to analyze the random vibration of the structure. The root mean square stress cloud diagram of the structure under theory $3\sigma$ is shown in Figure 9. The maximum stress of the structure is 122Mpa.
Figure 9 The maximum root mean square stress cloud diagram of the structure unit Pa

According to the Miner cumulative damage theory, each stress cycle in the structure will use a part of the structural life. When the total cumulative damage reaches 100%, it means failure has occurred.

According to the basic S-N curve, the vibration times of the material under the corresponding stress are:

When the stress is \( \sigma = 7.401 \text{ MPa} \), 
\[ N_{1\sigma} = 2.22 \times 10^9 \]

When the stress is \( \sigma = 3.812 \text{ MPa} \), 
\[ N_{1\sigma} = 2.79 \times 10^9 \]

When the stress is \( \sigma = 1223 \text{ MPa} \), 
\[ N_{1\sigma} = 8.26 \times 10^8 \]

Using the Miner linear cumulative fatigue damage method, according to equations (1), (2) and (4), it is calculated that the power controller will be damaged within 690 hours.

4. Conclusion

This paper proposes a random vibration fatigue life calculation method for power controllers based on Miner’s linear cumulative fatigue damage theory, which can predict the damage of the structure due to cumulative fatigue damage.

In order to calculate the random vibration fatigue life of the power controller, Nastran is used to perform modal analysis on the structure to understand the dynamic characteristics of the power controller, and then the random vibration analysis module in Nastran is used to perform random vibration analysis on the structure. Use the Miner linear cumulative fatigue damage theory to calculate the random fatigue life of the structure according to the analysis results, predict the vibration time when the cumulative damage of the structure reaches 100%, and improve the reliability of power control.

The calculation example shows that the power controller will not fail within 690 hours under random excitation load. The finite element analysis of the power controller using Nastran simulation tools has important reference value for the random vibration analysis of the component structure in engineering practice. It can make the engineering designer think more deeply in the design stage, in order to improve the anti-vibration performance and service life of the structure.

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