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Fatigue Design 2019

Adapted Locati method used for accelerated fatigue test under random vibrations

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Abstract

Fatigue experiments are very important for the study of structural fatigue damage. As we all know, fatigue experiments usually consume a lot of resources and time, slowing down the research progress. The Locati method, which is applied to the frequency domain analysis method of random vibration fatigue, replaces the traditional up-down method and accelerates the progress of the fatigue experiment. This method can effectively improve efficiency and reduce test time and test piece consumption under the premise of ensuring accuracy. It is based on the material S-N curve, after one step-load fatigue test, combined with the FEM, the cumulative damage of the structure under random vibration load is quickly determined, and the life analysis is completed. The specimen was made by AISI304 and designed to make the fatigue damage of the second-order bending mode more significant. The random vibration acceleration defined by the Power Spectral Density method is used as a load and applied on the specimens through the shaker. In this process, the material properties of the structure will be optimally fitted according to the experimental results, so that the finite element model is as close as possible to the real structure for fatigue calculation. Finally, an experiment will be used to verify the accuracy of this method. The method has now been validated under Gaussian distributed signals.

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1. Introduction

In random vibration fatigue experiments, the results are usually different from theoretical calculations. The fatigue property of the material plays an important role in the results. In addition, the thermal effects of the process and the involvement of stress can affect the fatigue properties of the material. In the process of fatigue damage calculation, re-evaluating the fatigue performance of the specimen is also one of the keys to ensuring the accuracy of life prediction. (PU.Nwachukwu & L.Oluwole, 2017) Fatigue limit can be determined using the Up-and-Down method (also known as Staircase) (Lin, Lee, & Lu, 2001). It usually requires testing a large number of specimens to obtain reliable fatigue data (R.Serra & L.Khalij, 2016). Considering that a single experiment requires between 2 to 10 million cycles, the cost of the overall experiment cannot be ignored.

L.Locati proposed a method for quickly determining the fatigue limit when the fatigue properties of the material are known. This method uses several empirically to assumed S-N curves and step-load fatigue tests (L.Locati, 1955). It is based on experience to improve the efficiency of the experiment. Compared to the original method, the fixed frequency cyclic load is replaced by a random load around the second bending frequency range of the specimen using a vibration shaker, in order to make it suitable for random vibration fatigue experiments. This method aims to quickly determine the fatigue limit of the specimen. By experimental data, a finite element model is updated to be close to the real structure and used into fatigue calculation and future finite element simulations. According to the fatigue properties of the material, the actual relationship between stress and period is calculated by using the assumed S-N curve of the specimens and the results of the random vibration experiments which the determination of the initial load directly affects the efficiency and progress of the experiment. Then the damage calculation and life prediction are obtained and a new S-N curve is proposed. The acceleration-time (A-T) curve of the specimens is then established and the appropriate initial load can be directly selected for further experiments. In this way, the cost of the experiment (the number of test pieces and the test time) can be greatly reduced.

Nomenclature

N	Number of cycles
N_c	Turning point of the S-N curve
S	Stress range
C,m	The material constants are related to the stress ratio and the stress concentration factor
PSD	Power Spectral Density in g^2/Hz
PDF	Probability Distribution Function
$G(f)$	Input acceleration by frequency domain
$W(f)$	Response acceleration by frequency domain
$H(f)$	Frequency Response Function
L_c	Failure time
S_f	Fatigue limit stress

2. S-N curve

The S-N curve can be approximated as linear in double logarithmic coordinates. It is generally composed of three inclined parts and horizontal parts. The N_c is the turning point of the S-N curve (NE.Dowlings, 1993):

$$S^m \cdot N = C \quad (1)$$

When the stress ratio is -1, the material is subjected to alternating load, and the fatigue limit is represented by σ_{-1} .

For Equation 1, take the logarithm of the two sides and get the linear equation.

$$\log N = \log C - m \times \log S \quad (2)$$

Currently measuring the S-N curve is generally a set of specimens (take 6~10 piece), using the lifting method, at different levels, fatigue test, measuring the life of the fracture N_i , a series of test points and then connected by a smooth curve. The S-N curve of the material measured by this method is only 50% reliable. Moreover, this curve has a great walk in fatigue performance, and sometimes there are differences for the same batch of materials. After processing, the actual fatigue performance and curve performance of the structure is too different. If we use this curve to design the initial experimental load, it may occur, the initial load is too small, the time is wasted, and the initial load is too large to waste the specimen.

3. Random processes and spectrum analysis

Generally, a zero-mean, standard deviation of 1, Gaussian random distributed load is used to perform a random vibration fatigue experiment, usually expressed as $G(f)$. The process is characterized in the frequency domain by one side with its power spectral density $W_G(f)$, the spectrum parameter could be obtained. The moments of each step are calculated as follows (DE.Newland, 1993).

$$W_G(f) = G(f)H^2(f) \quad (3)$$

$$M_j = \int_0^{\infty} f^j W_G(f) df \quad j = 0, 1, 2, \dots, n \quad (4)$$

Then the according to equation (4), the time domain property of $W_G(f)$ could be obtained

$$M_0 = \sigma_G^2, M_2 = \sigma_G^2 \text{ and } M_4 = \sigma_G^2 \quad (5)$$

After the expected number of upward crossing zero E_0 and the peak rate E_p for $W_G(f)$ could be obtained, as follows

$$E_0 = \sqrt{\frac{M_2}{M_0}} \quad E_p = \sqrt{\frac{M_4}{M_2}} \quad (6)$$

Further, the spectral and irregular factor γ_j bandwidth parameter ε_j could be obtained. The bandwidth parameter when $j=2$ is usually used.

$$\gamma_2 = \frac{E_0}{E_p} = \frac{M_2}{\sqrt{M_0 M_4}} \quad (7)$$

$$\varepsilon_2 = \sqrt{1 - \gamma_2^2}, \quad \gamma \in (0, 1) \quad (8)$$

When ε_2 is greater than 0.3, the vibration is a broadband random vibration, and when ε_2 is less than 0.3, the vibration is a narrowband random vibration. When ε_2 is close to 1, the vibration process approaches white noise.

4. Theory of Fatigue Analysis

What is now commonly used for fatigue calculations is the fatigue damage linear accumulation principle from Miner in 1945 (MA.Minor, 1945).

$$D = \sum \frac{n_i}{N_i} = \frac{1}{C} \sum n_i S_i^m \tag{9}$$

Where n_i is the number of cycles in the stress amplitude S_i , which was obtained by rain flow counting. N_i is the cycles of fatigue failure limit corresponding S-N curve at the same stress amplitude. When $D=1$, it means structural failure.

When calculating the random vibration fatigue of the probability density function (PDF) as $p(S)$, the number of cycles of duration T in $(S_1, S_1 + \Delta S)$, can be denoted as follows:

$$n_i = E_p \cdot T \cdot p(\Delta S) \cdot \Delta S \tag{10}$$

$$D = \frac{E_p \cdot T}{C} \int_0^\infty S^m \cdot p(S) dS \tag{11}$$

In past studies, scholars used many different statistical models to approximate the distribution of the cycles of specifying stress range during random vibration. There are 8 models that are discussed in the study and verify the actual effect, which is necessary because its effect directly affects the accuracy of life prediction.

Bendat proposes a narrow-band signal with as the bandwidth decreases, the probability density function of the peak tends to Rayleigh distribution (EL.Crow, JS.Bendat, & AG.Piersol, 1966). This will be able to easily find the fatigue life, σ_{RMS} is the root mean square of stress in specifying the frequency range

Narrowband approximation of a broadband process can be approximated by narrowband for a wideband process. Many scholars propose a correction factor to correct the fatigue life of a narrowband to obtain a broadband distribution of fatigue life (G.Chaudhury, 1986). The bimodal response spectrum approach considers bimodal spectral density as a superposition of two narrow-band random processes. The specific methods are Wirsching-light method, Ortiz and Chen method, Tovo-Benasciutti method and so on (H. Wirsching, 1980) (T.Dirlik, 1985) (D.Benasciutti, 2019) (D.Benasciutti, A.Cristofori, & R.Tovo, 2013).

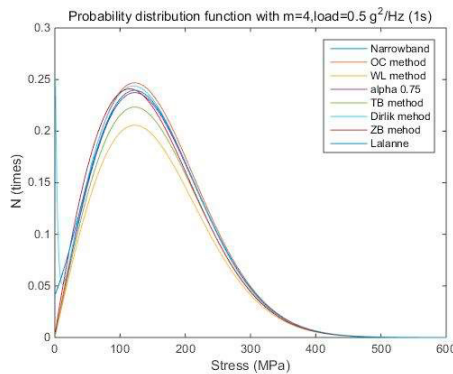


Fig. 1. The probability distribution function of response stress cycles

As shown in the figure 1, the curve of Dirlik using the gamma equation is considered to be the most suitable.

5. Locati method

The Locati method was proposed by L. Locati in 1955 to accelerate fatigue experiments and obtain fatigue property curves for materials fast (L.Locati, 1955). This method uses a step load to replace a very constant load, which greatly reduces the test time and also reduces the number of test pieces required.

With Locati method, it is possible to approximately estimate the fatigue limit when some fatigue parameters are known in advance, e.g. the slope of the S-N curve’s left branch. The Locati method is based on Miner law.

This method uses the gradual loading of the tested specimen. The initial stress value should not exceed the lowest expected value of fatigue limit. The fixed increment of the gradual load amplitude is assumed in the method. Similarly, the assumed number of cycles $n_i = \Delta N$ to be executed at individual levels is also fixed. Three curves are assumed based on the slope of the material S-N curve. At the bottom is the minimum estimate, the top is the maximum estimate, and the middle is the estimated mean. These three curves will have three intersections with the previous experimental plots.

Record the intersection point S and N , and calculate the damage caused by each load S_i ($i=1,2,3$) when the duration is N , and record it as D_i ($i=1,2,3$). The D-S curve is then plotted based on the S_i and D_i and S-N curve shapes. When $D=1$, through the curve, the fatigue limit of the structure S_f can be obtained.

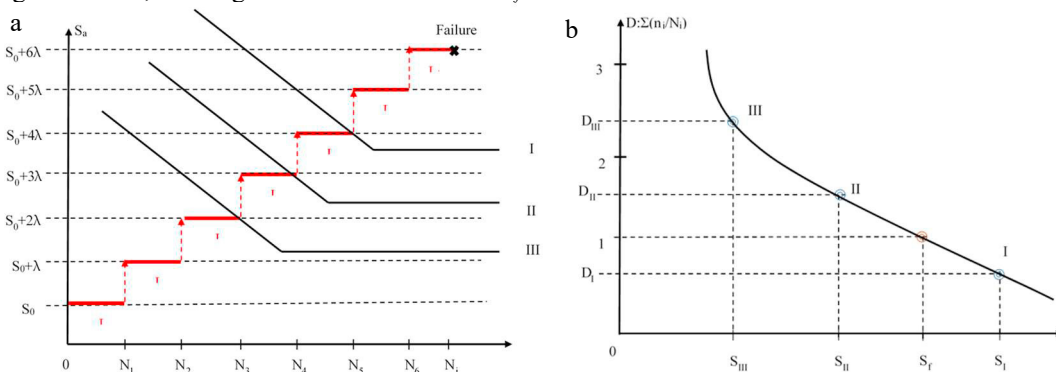


Fig. 2. (a) Step-stress applied in Locati method, (b) Damage-Stress curve based on step stress load

6. Experimental random vibration fatigue test

According to the adapted Locati method, before the simulation, one complete step load fatigue test should be performed, the life L_e was recorded and used into fatigue analysis. The fatigue experiment of random vibration is usually performed by a vibration shaker and a close loop control system. A specific input acceleration signal usually expressed by PSD within the specified frequency range.

In order to speed up the experiment and ensure the damage to appear in the observable position, the specimen is designed with two notches and the stress is concentrated at the notch position by changing the cross-sectional area, which means that the crack initiation and expansion area has been known. Through the CAE design, the length of the specimen is adjusted so that the displacement of the second bending mode is at the maximum position in the middle of the first notch.

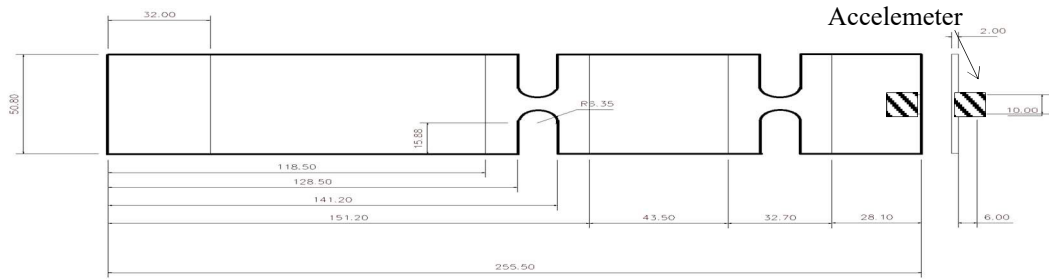


Fig. 3. Specimen geometry

The specimen is made of AISI304 and Young's modulus ($E=1.69 \times 10^{11}$ Pa), density ($\rho=8000 \text{ kg/m}^3$) and another property of material can be found from the material card. According to the measurement of the specimens, the actual quality can be obtained, the average of 5 specimens is 113.6g. After the actual material density can be calculated as 7942.22 kg/m^3 . It can be seen that there are subtle differences in the material properties of the universal material card. Specific analysis of each test piece is the key to ensuring an accurate test.

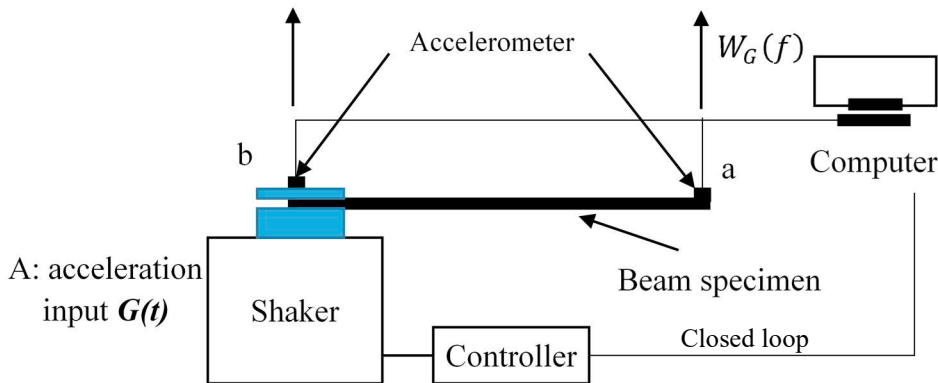


Fig. 4. Schematic diagram of the test

Through the modal analysis, the bending mode of the specimen under the clamping-free state can be obtained.

Table 1. Bending mode of the specimen by experiment

Mode	1	2	3
Natural frequency (Hz)	17.1	84.4	229.9

For Gaussian random vibration, PSD used to describe the level of acceleration. This time, the acceleration for a constant RMS value within the range of the second bending mode evaluation is selected. According to the modal analysis results, load frequency range choose 40-130 Hz (84.4 ± 45 Hz), so the bandwidth is 90Hz. For the initial load, choose $S_0=0.25 \text{ g}^2/\text{Hz}$, choose a step size of $\lambda=0.05 \text{ g}^2/\text{Hz}$ until its failure. Choose the load shape as follows according to the Fig.5.

Through PSD calculation, it could obtain the equivalent acceleration with unit g for all the level of the load as Table 2, it can be found that these two parameters are linearly related in the sample PSD (DE.Newland, 1993).

Table 2. PSD-gRMS table

PSD : g^2/Hz	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
gRMS : g	4.75	5.20	5.62	6.01	6.37	6.72	7.04	7.36	7.66

After one complete test, the specimen failed after a total of averaged 8.5 hours and the test was finished in load level of $0.65g^2/Hz$.

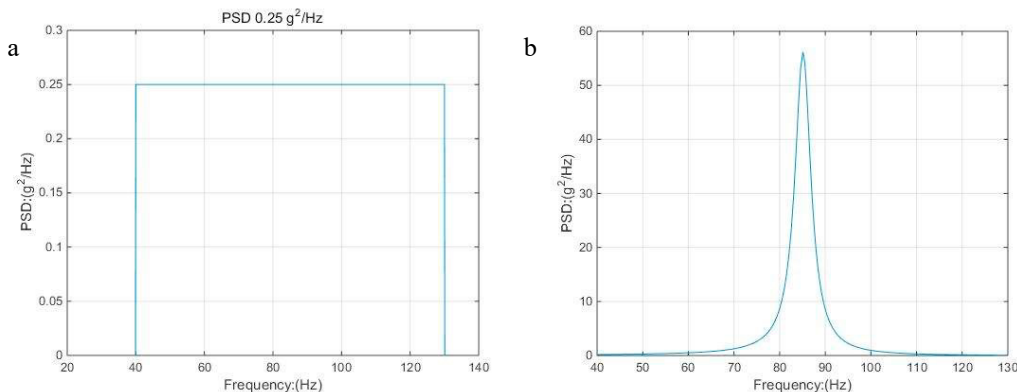


Fig. 5. PSD shape of the initial test (a) input acceleration, (b) response acceleration

7. Simulations

In order to perform virtual test for response analysis, a finite element model was built based on the material card and geometry (ALTAIR Hypermesh). After, the modal analysis was performed using Abaqus on this model. Through the comparison with the experimental results, the relevant parameters are updated to obtain a finite element model close to the experimental specimen responses. After validation and verification, the refined FE model is more closed to the real specimen.

For the harmonic analysis, the stress frequency response function (FRF) for the unit acceleration load (1g) is obtained in the specified frequency range. In the vibration fatigue analysis, one of the nodes with the highest stress in the second-order bending mode in the notch is selected for the evaluation index of the PSD response using ABS MAX principle stress.

Then, according to each level of the experiment loading, each amplitude stress under the load is defined. Further, the spectral coefficient of the PSD corresponding to the load can be calculated, and the damage value determined according to the previously mentioned distribution model. Comparing the eight previous methods by difference from the average value, the best method is selected.

According with the initial S-N curve of the material card, the limit value of the low-cycle fatigue portion is 1729 MPa, and the m value is 17.92. Obviously, these parameters are a bit high relative to the actual material. In fact, after 8.5 hours (as obtained experimentally), the damage calculation result is $0.035502 < 1$. When the slope of the original S-N curve is kept constant, different fatigue limit values are considered. When the ultimate strength value equal to 1421 MPa, after 8.5 hours, the damage value is 0.99 which obtained by interpolation calculation. Then the rest parameter of S-N curve calculated based on fatigue limit. Finally, the corrected S-N curve for the specimen is as shown in Fig.6.

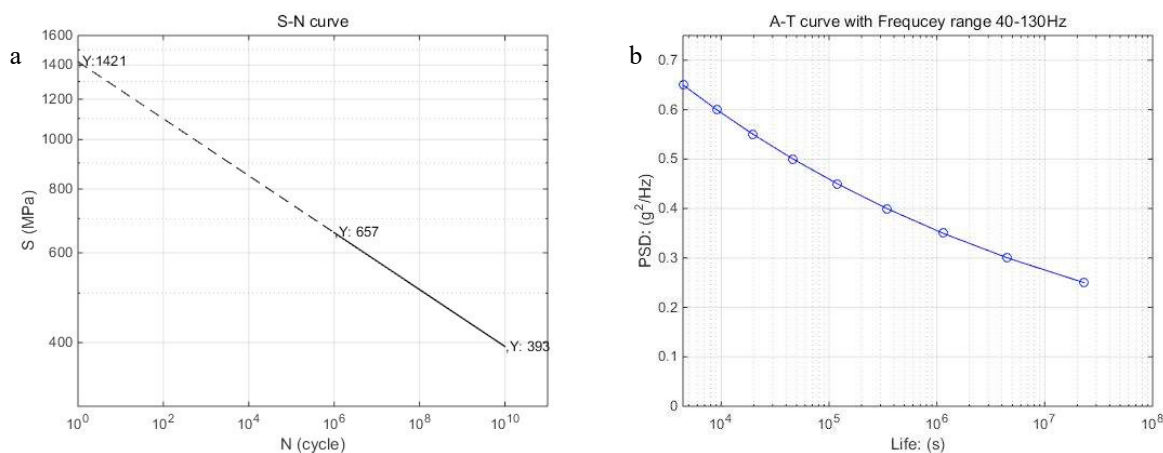


Fig. 6. (a) Corrected S-N curve of the specimen, (b) A-T curve of vibration test

According to the corrected S-N curve, the A-T curve of the specimen in the experimental frequency range could be determined. It is used as a reference to guide the relevant fatigue experiments of similar models and to specify the initial load and reference range of the experiment.

8. Conclusion

By using adapted Locati method, virtual test by the finite element simulations can be performed after one completed test, and the S-N curve of the specimen can be corrected. Obtaining an A-T curve for a specified PSD spectral shape based on the corrected S-N curve of the specimen could improve the accuracy and efficiency for similar experiments.

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