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Cumulative Fatigue Analysis and Life Cycle Determination of a Component

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ABSTRACT
When a component is repeatedly loaded the resulting effect is known as fatigue. In this paper we calculate life of a component subjected to cumulative fatigue loading. In many cases the weight penalty cannot be tolerated by using fatigue limit as allowable stress. Most structural components and parts are influenced by irregular fluctuating stresses in which the maximum and minimum stresses are continuously varying. Thus necessity is to use a fatigue theory which will analyze the damage as a result of varying magnitudes of stress cycles. The paper depicts analysis of fatigue life of a component under cumulative fatigue loading using palmgren miner's rule.

Keywords
High cycle stress, low cycle stress, residual crack growth, cumulative fatigue damage, damage tolerance.

1. INTRODUCTION
Of the many cumulative damage theories published the one most widely used is suggested by Palmgren and Miner. According to their theory the fatigue damage incurred at a given stress level is proportional to the number of cycles applied at that stress level divided by the total number of cycles required to cause failure of the component at that stress level. This damage is referred to as cycle ratio or cumulative damage ratio. If repeated loads are applied continuously at the same level till the failure point is reached the cycle ratio will correspond to 1.

2. Fatigue Load in Aero Structures
Striations are result of fatigue which start in grains of a metallic material which then results in a crack that at a certain size can be identifies by various testing techniques. The main characteristic for a fatigue life of a component is the number of cycles at a defined load. Fatigue and damage tolerance are one of the dominant factors throughout various the airframe design methods. These factors can only be satisfied when resulting stress distribution, loading conditions and material properties are properly known. The most common example of varying load in aero structures is load acting on wings of an aircraft. During different maneuvering conditions and adverse wind conditions like gust the wing experiences varying lift force which results in striations of material and hence weakens the components of the wing.

3. Stress Nomenclature
- Stress range: stress range is defined as the difference of maximum and minimum stress. i.e. used and best known is

  Stress range = $\sigma_{max} - \sigma_{min}$
- Alternating stress: alternating stress is defined as the half of stress range. i.e.

  Alternating stress = $(\sigma_{max} - \sigma_{min}) / 2$
- Mean stress: mean stress is defined as the average of maximum stress and minimum stress. i.e.

  Mean stress = $(\sigma_{max} + \sigma_{mi}) / 2$
- Stress ratio: stress ratio is defined as the ratio of minimum stress to maximum stress. i.e.

  Stress ratio = $\sigma_{min} / \sigma_{max}$
- Stress amplitude: stress amplitude is defined as the ratio of alternating stress to maximum stress. i.e.

Stress amplitude = σ_a / σ_{max}

(Refer to figure 3 for diagrammatic representation of stress nomenclature.)

4. Miner's Rule
4.1 Description
In 1945, M. A. Miner gave a rule that was first proposed by A. Palmgren in 1924. The rule is known as Miner's rule or the Palmgren-Miner linear damage hypothesis which states that where there are *k* different stress magnitudes in a spectrum, S_i $(1 \le i \le k)$, each contributing $n_i(S_i)$ cycles, then if $N_i(S_i)$ is the number of cycles to failure of a constant stress reversal S_i, failure occurs when :

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

C is experimentally found to be between 0.7 and 2.2. Usually for aircraft design purposes, C is assumed to be 1

4.2 Limitations
Though Miner's rule is very useful in approximations in many circumstances, it has several major limitations which are described as :

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- Probabilistic nature of fatigue cannot be recognized, and there is no other approach to relate life predicted by the rule with the characteristics of a probability distribution. Design curves are often used by analysts in order to calculate number of cycles to failure (N).
- In many cases cycles of low stress followed by high stress cause more cumulative damage than would be predicted by the rule. Hence it can be easily concluded that it does not consider the effect of an overload or high stress, which can result in compressive residual stress which may retard crack growth in a structure member.

5. Cumulative Fatigue Damage

Fatigue damage increases with applied load cycles in a cumulative manner. Cumulative fatigue damage analysis plays a key role in life prediction of components and structures subjected to field load histories.

As a result of palmgren and miner's concept many damage models have been developed for life cycle determination of a component under various fatigue loads.

Various theories used in cumulative fatigue damage analysis are:

- Linear damage rules
- Nonlinear damage curve and two stage linearization approaches
- Life curve modification methods
- Approaches based on crack growth concepts
- Continuum damage mechanics models
- Energy based theories

6. Cumulative Fatigue Analysis and Life Cycle Determination

Calculation of fatigue life of a component using Miner's rule can be done in the following steps:

(Note: these values of mean and alternating stress are arbitrary)

Step1: Mean stress, alternating stress and number of cycles for the component are given as:

Mean Stress	Alternating Stress	Number of cycles (n)
14.0	12	90
	9	120
8.0	2.5	50
	8.1	70
	7.9	130
9.5	3.5	70
	7.5	180
	6.3	150

Step2: With the aid of given input data we calculate the maximum and minimum stress levels corresponding to various alternating stresses.

Mean stress	Alternating stress	Max. stress	Min. stress	Stress ratio
14.0	12	26.0	2	0.077
	9	23.0	5	0.217
8.0	2.5	10.5	5.5	0.524
	8.1	16.1	-0.1	-0.006
	7.9	15.9	0.1	0.0062
9.5	3.5	13.0	6	0.461
	7.5	17.0	2	0.117
	6.3	15.8	3.2	0.202

Step3: Arranging the maximum and minimum values of stress in descending order along with number of cycles:

S.NO	Maximum Stress	Number of cycles (n)	Minimum stress	Number of cycles (n)
1	26	90	6	70
2	23	120	5.5	50
3	17	180	5	120
4	16.1	70	3.2	150
5	15.9	130	2	90
6	15.8	150	2	180
7	13	70	0.1	130

8	10.5	50	-0.1	70

Step4: Calculating the fatigue life as per Miner's rule:

Mean Stress	Alternating stress	(n)	(N) cycles to failure
14	12	90	55000
	9	180	27000
8.0	2.5	50	-
	8.1	70	64000
	7.9	130	79000
9.5	3.5	70	-
	7.5	180	210000
	6	150	118000

Total number of cycles sustained n = 860

Total number of cycles to failure N = 553000

D*∑ (n/N) = 1

D*0.001555154 = 1

D= 643

7. Result and Discussion

Hence from the calculation we conclude that the component can sustain 643 cycles before failure.

8. Graphs and Figures

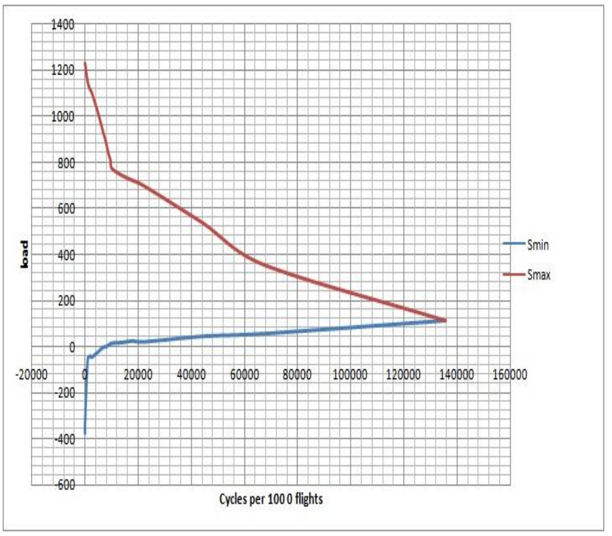

Figure 1: graph showing load vs. cycles per 1000 cycles.

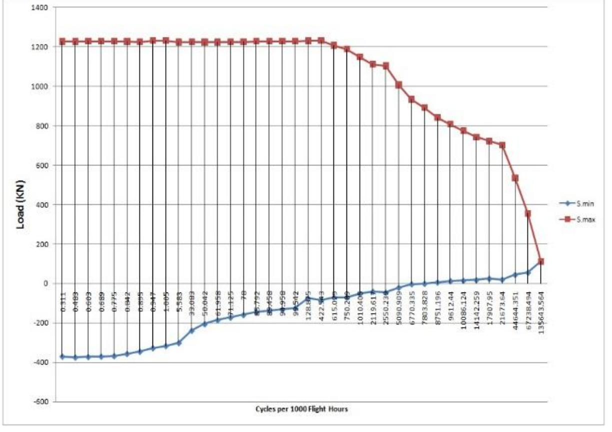

Figure 2: graph showing simplified load cycle for the above G.A.G cycle.

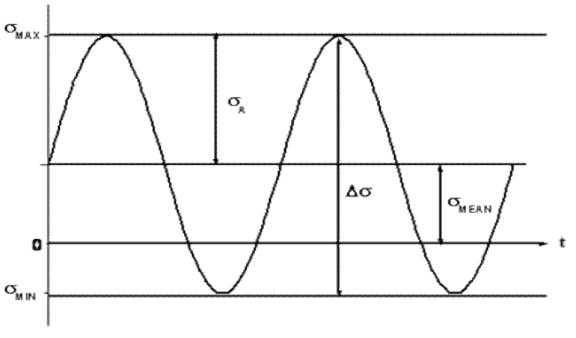

Figure 3: plot depicting stress nomenclature

9. Future Work

We wish to calculate the fatigue life and analyze the behavior of component under cumulative fatigue loadings using various other approaches like nonlinear damage curve and two stage linearization approaches, approaches based on crack growth concepts and energy based theories.

10. References

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