When Do I Need to Change a Part? – Lifetime Analysis of Dynamic Helicopter Components

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1 Introduction

Numerous examples from the past show that a failure of a single part of an aircraft can lead to a catastrophic event. Therefore aircraft and all their dynamically loaded parts are required to have a finite Service Life Limit (SLL). This paper gives a brief overview of a calculation method used to determine lifetimes of dynamic helicopter components (fatigue evaluation) using linear damage accumulation. It is based on the Certification Specification for Large Rotorcraft CS-29 of the European Union Aviation Safety Agency [1].

The requirements for the fatigue evaluation of parts are shown in articles 29.307, 29.571 and 29.573 of [1] and apply to significantly loaded parts. These parts are called Principal Structural Elements (PSE) and must include "rotors, rotor drive systems between the engines and rotor hubs, controls, fuselage, fixed and movable control surfaces, engine and transmission mountings, landing gear, and their related primary attachments" [1, CS29.571(d)]. Lifetimes below the SLL of the aircraft have to be published in Chapter 4 of the Aircraft Maintenance Manual (AMM) as required by [1, A29.4]. Figure 1 shows a possible approach to calculate lifetimes which will be explained in the following chapters.

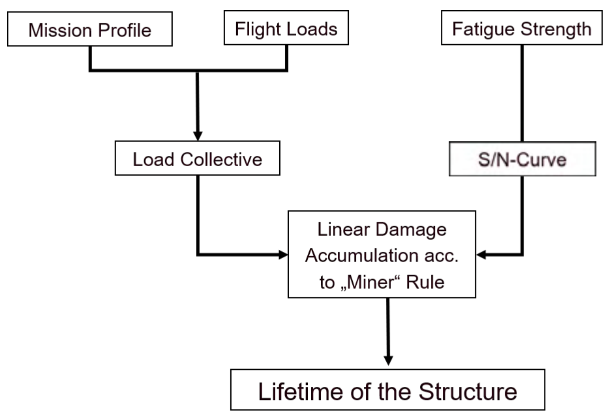

Fig. 1 : General approach to lifetime calculation of dynamically loaded helicopter parts using linear damage accumulation

2 Strength of a Part

2.1 Destructive Testing

Article CS29.571(e)(6) states that the fatigue evaluation has to be "supported by test evidence" [1]. Therefore destructive testing is the main method used to determine the fatigue strength of a part. Depending on the complexity of the part, the necessary tests can vary from (aged) material tests over subcomponent tests to full-scale (pre-damaged) component tests as described in [2].

Usually components are subjected to constant amplitude dynamic loading similar to loads experienced during normal flight. During the test, changes in stiffness and the growth of damages are documented. At the end of a test, a residual strength test is performed which "must show that the remaining structure, after damage growth, is able to withstand design limit loads without failure" [1, CS29.571(f)].

2.2 Creation of S/N-Curves

Based on several component tests as well as material values, S/N-curves can be established. They show the endurance strength of a part based on the number of amplitude load cycles until failure. In a first step a curve is fitted to the test points. This curve is called mean curve, as it represents a survival probability of 50%. Based on the scatter of the points and the severity of a failure of this part (for structural parts often catastrophic [2]), a load reduction factor is calculated for the curve. The reduced curve is called safe curve.

3 Loading of the Part

3.1 Mission Profile

During design of an helicopter a mission profile is established. It is usually based on past experience as well as customer surveys. According to [1, CS29.571(e)(2)] the mission profile has to cover all critical conditions as well as all other maneuvers the helicopter is able to do. In addition, the time share of each maneuver of the complete profile is defined.

3.2 Flight Loads

Based on the mission profile load classification flights are conducted. The helicopter is equipped with flight test instrumentation and all relevant strains, vibrations, temperatures, etc. are recorded by sensors for each flight maneuver.

By using rainflow counting [3] the number of load cycles as well as their mean and amplitude values are extracted from the time data of each flight maneuver. A typical rainflow matrix is shown in Figure 2. The horizontal axis shows the mean load classes, the vertical axis the amplitude load classes. Each field contains the number of load cycles for the given mean and amplitude load combination.

Mean Load Classes

Amplitude Load Classes	-1500 -1000	-1000 -500	-500 0	0 500	500 1000	1000 1500	1500 2000	2000 2500	2500 3000	3000 3500	3500 4000	4000 4500	4500 5000	5000 5500	5500 6000
0 300	2	22	82745	1329673	8307051	12317927	8147919	608900	38888	652	64	17	10	6	2
300 600	0	0	144	5048	394223	934379	84315	5130	84	15	9	4	0	0	0
600 900	0	0	0	590	93017	472562	133102	260	54	15	7	6	2	0	0
900 1200	0	0	0	47	3149	74085	35591	351	28	13	8	4	2	0	0
1200 1500	0	0	0	0	199	5203	1897	156	20	13	9	5	0	0	0
1500 1800	0	0	0	0	15	243	733	40	21	12	10	2	0	0	0
1800 2100	0	0	0	0	0	128	271	46	14	4	4	2	0	0	0
2100 2400	0	0	0	0	0	22	39	34	11	0	0	0	0	0	0
2400 2700	0	0	0	0	0	4	19	18	15	0	0	0	0	0	0
2700 3000	0	0	0	0	0	1	14	11	14	3	0	0	0	0	0
3000 3300	0	0	0	0	0	0	4	9	6	9	2	0	0	0	0
3300 3600	0	0	0	0	0	0	3	3	8	6	2	0	0	0	0
3600 3900	0	0	0	0	0	0	0	3	3	7	1	0	0	0	0
3900 4200	0	0	0	0	0	0	0	2	2	1	0	0	0	0	0
4200 4500	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0

Fig. 2 : Rainflow matrix of a measured load

3.3 Load Collective

In the load collective the rainflow matrices of all maneuvers are combined, weighted by their respective time shares. It is usually scaled to a fixed time basis (e.g. 1000 flight hours $[Fh]$). Each aircraft component has its own load collective.

4 Linear Damage Accumulation and Lifetime Calculation

To calculate the lifetime of a part, the cumulative damage method shown by Miner in [4] is used. Each field of the load collective represents the number of load cycles n_i for a specific mean and amplitude value combination. It is divided by the number of load cycles until failure N_i for these load combination, which is derived from the safe S/N-curve (Figure 3). This ratio is called damage. It is assumed that a part fails when the damage reaches 1. The time basis of the load collective (in this example 1000 Fh) is divided by the sum of all damages (equation 1), the result is the lifetime of the part.

$$L = \frac{1000\,Fh}{\sum \frac{n_i}{N_i}} \tag{1}$$

Alternatively this method can be used to for a damage tolerance evaluation by using crack growth tests and the resulting S/N-curves.

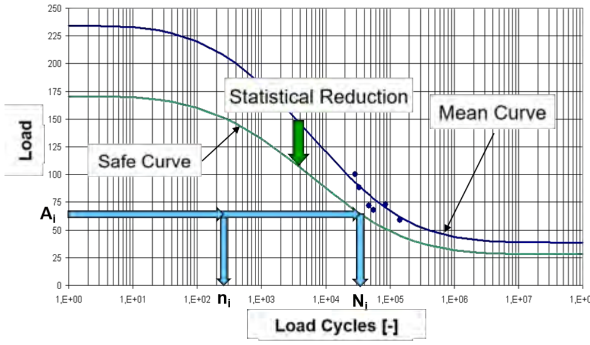

Fig. 3 : Linear damage accumulation based on a safe S/N-curve

5 Limits of this Method

One limit of this method is that Miner's rule does not account for the sequence in which high and low loads are applied to a part, which has influence on the fatigue strength. Cycles of low stress followed by cycles of high stress can cause more damage than what the rule predicts [5]. In addition the lifetime is highly dependent on the mission profile as well the flight data. It can be influenced by how specific test pilots fly.

6 Summary

This paper shows a method of how to calculate the lifetime of dynamically loaded helicopter components based on the rainflow counting method and linear damage accumulation.

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