Maneuver-to-Maneuver Load Cycle Case Study

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ABSTRACT

In traditional fatigue evaluation methodologies, Ground-Air-Ground (GAG) cycles account for a significant portion of accumulated fatigue damage for many components. GAG cycles are typically conservative and thought to cover Maneuver-To-Maneuver (MTM) and Rotor-Start-and-Stop (RSS) cycles. Proper development and fielding of Condition Based Maintenance (CBM) systems require refined fatigue methodologies to appropriately account for MTM damage. This paper proposes use of damage based on the rainflow count of sequenced load pairs with CBM in place of adapting traditional GAG methodologies. The sequenced load pair method is illustrated using simplified data and demonstrated on more realistic notional flight test data. Use of sequenced load pairs is recommended for signals with significant low-frequency content.

INTRODUCTION

Helicopter component fatigue lives are determined by considering high-cycle fatigue damage during individual flight conditions and fatigue damage due to so-called Ground-Air-Ground (GAG) cycles (for example, see guidance contained in reference [1]). Quite often, the largest portion of calculated fatigue damage is due to GAG cycles. GAG cycles are intended to cover relatively low-frequency large-amplitude load cycles not present in any single flight condition, such as load cycles due to (1) Rotor Start and Stop (RSS) cycles and (2) load fluctuations between the various flight conditions encountered during performance of a mission. The authors assert that inclusion of the word “ground” within the description often leads to confusion. In fact, GAG damage during a given mission may not correlate to the number of landing events for every helicopter component, leading the authors to consider the alternate description “Maneuver to Maneuver” (MTM) load cycles.

This paper presents a case study of notional flight data to determine the strengths and weaknesses of the MTM (low cycle) scheme from the methodology in Figure 1, which is proposed for use with Fatigue Life Management (FLM) and Condition Based Maintenance (CBM) systems (see reference [2] for further information on implementation of CBM systems). Resulting MTM load cycles are compared to rainflow cycle counts of the reconstructed time history for the flight. Notional loads will be analyzed for main rotor mast torque and main rotor mast bending as examples of substantiating parameters with and without low frequency content, respectively.

This study will assist rotorcraft engineers in understanding the adequacy of fatigue methodologies and FLM related CBM systems in determining MTM damage.

TRADITIONAL GAG METHODOLOGIES

In order to account for MTM loads, the maximum and minimum loads measured in a flight load survey have traditionally been considered as the GAG load, and design usage spectra have been constructed with, for example, 6 GAGs per hour (see example contained Table 1 of reference [3]). Such a methodology is simple in its application and commonly believed to be conservative. In cases where 6 GAGs per hour have produced excessive fatigue damage, two alternatives to component redesign have arisen.

First, the developer may propose an alternate (average) GAG amplitude via some probabilistic or design usage spectrum based method to predict a population of GAG cycles likely to be encountered in service. For example, the maximum and/or minimum loads may be associated with load conditions which are not expected to occur often.

Second, the developer may propose an alternate frequency of GAG cycles based on reported field usage (usually landings). Although this proposal seems inherently reasonable at first consideration, it may not be appropriate for components where MTM loads are not driven by ground conditions or RSS load cycles. Consideration of RSS centrifugal loads should be supplemented with consideration of load fluctuations between flight conditions encountered during a mission.

A NEW CBM FRAMEWORK

As stated above, developers have often, on a case-by-case basis, refined conservative GAG calculations based on their understanding of GAG cycles encountered during actual usage. CBM systems provide a systematic mechanism for an improved understanding of load cycles.
CBM Damage Evaluation Methodology

- Develop Damage Tables for the configurations in the fatigue substantiation report. The fatigue damages are calculated using the following methodology. High Cycle Event damage will be calculated per occurrence basis for transient maneuvers and per unit time for steady state maneuvers.
  - High Cycle Fatigue Damage - Flight history data will be rainflow cycle counted. Max/min load cycle (GAG cycle within maneuver) will be considered as low cycle event, and will be excluded from the damage evaluation.
  - Low Cycle Fatigue Damage – Max/min load sequence will be established based on the sequence of events identified. The load sequence which accounts for maneuver-to-maneuver and GAG damage will be cycle counted and used to calculate low cycle fatigue damage.
  - The total fatigue damage is sum of high cycle and low cycle damage calculated.

- Fatigue Life Factors (or Damage Fraction Factors) will be evaluated for CBM tracked components to ensure the baseline reliability is maintained.
  - The life or damage fraction factors will vary depending on the conservatism in establishing S/N curve, number of loads collected to substantiate the top of scatter loads, and conservatism in design usage spectrum.

Figure 1. Proposed Condition Based Maintenance Fatigue Damage Evaluation Methodology
encountered during a mission. In the near term, all major helicopter platforms will incorporate CBM systems capable of providing helicopter fatigue engineers with a greater understanding of usage. However, fatigue methodologies should be updated to appropriately incorporate the resulting improved fidelity in usage knowledge. In particular, before GAG methodologies can be updated to allow for CBM credits per reference [2], MTM methodologies should be developed to allow for accurate accounting of both RSS load cycles and load fluctuations between the flight conditions encountered during a mission.

Modern Misinterpretations of GAG

As noted above, many understand the need for tracking GAG cycles in simple terms of landing events only. As a result, it is often proposed that GAG cycles be tracked based on simple use of a weight on wheels (or skid gear) sensor alone. The authors assert that such methods would not be appropriate for loads which exhibit significant fluctuations at relatively low frequencies during the course of a mission. Although weight on wheels sensors may prove useful for recognizing ground conditions, CBM systems promise complete regime recognition capabilities which enable a comprehensive understanding of MTM loads.

Digital Source Collector Capabilities

Digital Source Collector (DSC) systems are currently being developed with the capability to record the parametric flight data necessary for regime recognition. Although platform specific developmental work is necessary to provide regime recognition capabilities which are consistent with legacy flight load survey data used in the fatigue substantiation, such systems should be able to identify all flight regimes encountered during a particular flight and record the regime sequence of occurrences and durations for each transient and steady-state regime, respectively.

When coupled with legacy flight load survey data, the resulting DSC generated flight regime sequence has the potential to provide engineers with a greater understanding of load fluctuations between flight conditions encountered during a mission.

ALTERNATIVES TO TRADITIONAL GAG

Provided with a known regime sequence for a particular flight, one may consider using legacy flight load survey data to construct three MTM load summary trace candidates:
1. List the maximum and minimum load for each regime in the regime sequence, termed herein as “max-min load pairs”.
2. List the minimum and maximum load for each regime in the regime sequence, termed herein as “min-max load pairs”.
3. List the maximum and/or minimum load in the same sequence as they occur in the legacy flight load survey data for each regime in the regime sequence, termed herein as “sequenced load pairs”.

ILLUSTRATIVE EXAMPLE

Before examining more realistic flight loads, a simple example is used to illustrate the three MTM load summary trace candidates suggested above: max-min load pairs, min-max load pairs, and sequenced load pairs.

Consider the example time history trace shown in Figure 2, which is composed of ten equal-length regimes, each lasting exactly one unit in time. For simplicity, these loads are completely fictional and no units are displayed for the load or for time. Figure 2 also shows the maximum and minimum values for each regime.

Max-min load pairs are shown in Figure 3. As indicated by the name, the maximum and minimum values for each condition are paired and placed in the arbitrary order that such that the maximum load occurs first in each condition. Figure 4 compares the rainflow cycle count of the max-min load pairs to the rainflow cycle count of the time history trace. From Figure 4, it is evident that the rainflow count of the max-min load pairs contains two cycles with alternating values in the 200 to 250 range which are not contained in the original time history trace.

Similar results are shown in Figures 5 and 6 for the case of min-max load pairs where the maximum and minimum values for each condition are paired an placed in the arbitrary order such that the minimum load occurs first in each condition.

Closer inspection of Figures 3 and 5 reveals that the additional cycles are due to load conditions containing generally increasing or decreasing values. Arbitrary placement of the maximum or minimum value first adds an additional cycle to these conditions, which is not present in the time history trace.

![Figure 2. Simple Time History Trace for a Flight with 10 Regimes](image-url)
Figure 3. Max-Min Load Pairs

Figure 4. Rainflow Results for Max-min Load Pairs

Figure 5. Min-Max Load Pairs

Figure 6. Rainflow Results for Min-Max Load Pairs
Figure 7 illustrates the sequenced load pair method where the maximum and minimum values for each condition are paired and placed in the sequence in which they occur in the time history trace. Comparing Figure 7 to Figures 3 and 5, it is noted that no additional cycles appear to have been added to the original time history trace when using sequenced load pairs. As a result, Figure 8 demonstrates that all cycles above an alternating load of 100 are captured exactly using the sequenced load pair method. Cycles below an alternating load of 100 are most likely due to high cycle effects in the time history trace.

Finally, although the maximum MTM load cycle would traditionally be counted as the GAG cycle, three of the four MTM cycles in Figure 8 which are above an alternating load of 100 would be missed.

CASE STUDY USING NOTIONAL LOADS

Usage data for a particular 2 hour mission indicates 65 regimes. Mast torque and mast bending data (notionally from some flight load survey) are analyzed in Figures 9-12.

Due to flight condition bins inherent to the usage spectrum, Figure 9 is created from a sequence of discontinuous load traces. As a result, Figure 10 indicates use of sequenced load pairs is only slightly more accurate than use of max-min load pairs. When applied to a sequence of discontinuous load traces, the max-min load pair method does not add as many extraneous high-amplitude cycles as shown in Figure 4.

As was the case with the illustrative example, the low-frequency content included in the notional mast torque signal in Figure 9 is significant. Use of a MTM load pair method is particularly important for these signals when high cycle damage is calculated using peak stress counting (also known as rotor compressed cycle counting).

It is important to point out that for this flight, misuse of the traditional GAG methodology would count one GAG cycle. Nine of the ten most significant cycles could be omitted, depending on the methodology used to calculate high cycle damage. Again, this impact would be most significant in cases where high cycle damage is calculated using peak stress counting. It is noted that 12 GAG cycles in the 2 hour flight would account for these omissions.

Not all components experience loads with significant low-frequency content. However, in order to understand the impact of the MTM load cycle method, mast bending is included as part of the case study. For such load traces, high cycle (intra-maneuver) damage per the Figure 1 methodology would be adequate for calculating the total fatigue damage. Use of either rainflow counting or peak stress counting would adequately capture fatigue damage.

The mast bending signal shown in Figure 11 is approximately fully reversed (with near zero steady value). Figure 12 indicates that the steady loads predicted for such a signal by the sequenced load pairs appears to increase the scatter in steady values. Additionally, a significant number of (intra-maneuver) cycles are not predicted by the MTM load pair methods.

CONCLUSIONS

For load signals with low-frequency content, it has been demonstrated using realistic notional flight data that significant MTM load cycles are not adequately covered by an “accurate” tracking of traditional GAG cycles. In place of traditional GAG, new MTM methodologies have been developed and demonstrated. For continuous load traces, the sequenced load pair method accurately captures low-frequency load cycles when compared to a rainflow cycle count of the time history load trace.
Figure 9. Notional Mast Torque Time History Trace for a Flight with 65 Regimes

Figure 10. Comparison of Mast Torque Rainflow for a Flight with 65 Regimes
Figure 11. Notional Mast Bending Time History Trace for a Flight with 65 Regimes

Figure 12. Comparison of Mast Bending Rainflow for a Flight with 65 Regimes
RECOMMENDATIONS

Use of sequenced load pairs is recommended to track MTM loads per the methodology in Figure 1 for components in load environments with significant low-frequency content.

Additional work is recommended prior to application to cases of substantiating parameters that do not accurately capture RSS loads and cases of combined loads such as using von Mises stress. Other future work should include demonstration of the combined entire high/low cycle fatigue methodology in Figure 1 using signals similar to the mast bending and torque traces included in this case study.

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REFERENCES

