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Fatigue Life Monitoring Program of RMAF MiG-29

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ABSTRACT

The Royal Malaysian Airforce (RMAF) operates one squadron of MiG-29 which were designed on Safe Life principle. RMAF conducts a fatigue life monitoring program to these airplanes. This activity is conducted based on the experience of having the fatigue life monitoring program to the RMAF F/A-18D. The fatigue life of RMAF MiG-29 is based on the wing-fuselage lug joint structure, and Low Cycle Fatigue (LCF) approach is adopted. The stress spectra of this component, is derived through mapping of g-spectra to the 1-g stress level of the lug. The g-history is obtained from the accelerator installed in the airplane, while the 1-g stress level is obtained by finite element modeling of the wing structure and lug joints. Rainflow cycle counting procedure was then applied. The fatigue characteristics (strain-life) of the lug material was obtained from the laboratory test, using the lug material sample, combined with the empirical formula of strain-life diagram. Notched effect is taken into account using Neuber theory. Mean stress effect is dealt with using Smith-Watson-Topper formula. Miner's rule is used to calculate the fatigue damage accumulation. A fatigue life prediction software for RMAF MiG-29 which incorporates the above concepts had been developed. Currently, this software is operational with the RMAF MiG-29, and is being used as part of its Aircraft Structural Integrity Program (ASIP). This paper reports on the development of the fatigue life monitoring strategy and software for the RMAF MiG-29.

Keywords*: ASI, Fatigue Life Monitoring, MiG-29*

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Introduction

The Royal Malaysian Airforce (RMAF) operates one squadron of MiG-29 which were designed on Safe Life principle. A fatigue life monitoring program is being conducted by RMAF to these airplanes. RMAF is also conducting fatigue life monitoring to its HAWK and F/A-18 fleets. The development of the fatigue life monitoring strategy and software for the RMAF MiG-29 is reported in this paper.

Fatigue actually is defined by failure of metal or other material under repeated or otherwise varying load which never reaches a level sufficient to cause failure in a single application. Component of machinery, vehicles and structures are frequently subjected to repeated loading that may lead to their failure due to fatigue. Fatigue behaviors have been studied for almost 150 years. Over that period many great researchers like Poncelet, Wohler, and Bauschinger have conducted research in fatigue. Despite 150 years of fatigue research, unintended fatigue failures still occurs and the research work on that never ended until now.

The traditional total life method makes no differentiation between crack initiation and crack growth. Since the development of the total life method, fatigue has been re-defined as a process of initiating a crack followed by an investigation of how that crack propagates through the structure (Figure 1). This paper deals only with the crack initiation (Safe-Life) portion, which is adopted in the fatigue design of MiG-29.

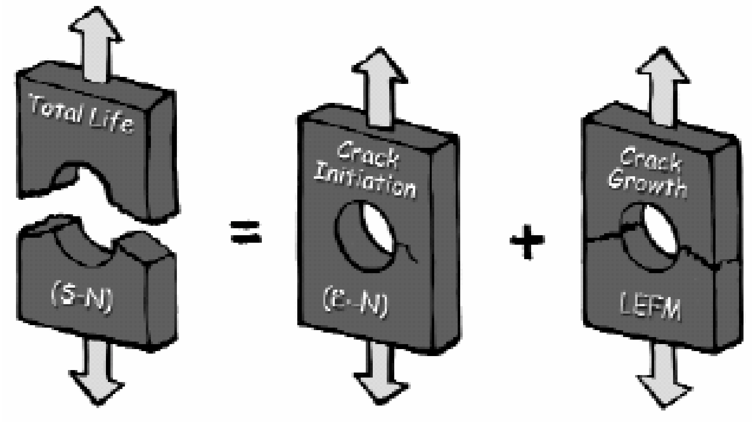

Figure 1: Three Main Fatigue Analysis Methods

Safe Life is a concept with a fundamental objective of having a structure, which is not going to fail during the life it is designed for [1]. Safe Life concept is closely related to the fatigue of structure. While static loading is associated with high magnitude type of loading, fatigue failure is often related with low magnitude cyclic load. However, it is important to note that fatigue failure is not always due to the low magnitude of cyclic loading; there are cases of high fatigue loading encountered during service. The fatigue problem, which is associated with high magnitude fatigue loading, is called Low Cycle Fatigue (LCF), while the low magnitude fatigue loading is called High Cycle Fatigue (HCF).

The fatigue life can be represented as the fatigue life expended (FLE). The value of FLE is between zero and one. FLE value below one means the component is safe. For example FLE equals to 0.5 can be interpreted as the component comes to half of its fatigue life. FLE equals to one means the component has come to the end of its life. In the case of FLE equal to one, either the aircraft goes to retirement or it can undergo a Service Life Extension Program (SLEP).

In the RMAF MiG-29 Fatigue Life Monitoring Program, the fatigue life is based on the wing-fuselage lug joint structure, and Low Cycle Fatigue (LCF) approach is adopted [2]. The stress spectra of this component, is derived through mapping of g-spectra to the 1-g stress level of the lug. The g-history is obtained from the accelerator installed in the airplane, while the 1-g stress level is obtained by finite element modeling of the wing structure and lug joints. Rainflow cycle counting procedure is then applied. The fatigue characteristics (strain-life) of the lug material was obtained from the laboratory test, using the lug material sample, combined with the empirical formula of strain-life diagram. Notched effect is taken into account using Neuber theory. Mean stress effect is dealt with using Smith-Watson-Topper formula. Miner’s rule is used to calculate the fatigue damage accumulation. A fatigue life prediction software for RMAF MiG-29, called *MiG-SLA* (MiG-Service Life Assessment), which incorporates the above concepts had been developed. Currently, this software is operational with the RMAF MiG-29, and is being used as part of its Aircraft Structural Integrity Program (ASIP).

MiG-29 Safe-life Analysis Procedure

The general procedure of the RMAF MiG-29 Safe-Life Analysis as used in the fatigue life monitoring program is modeled as in Figure 2.

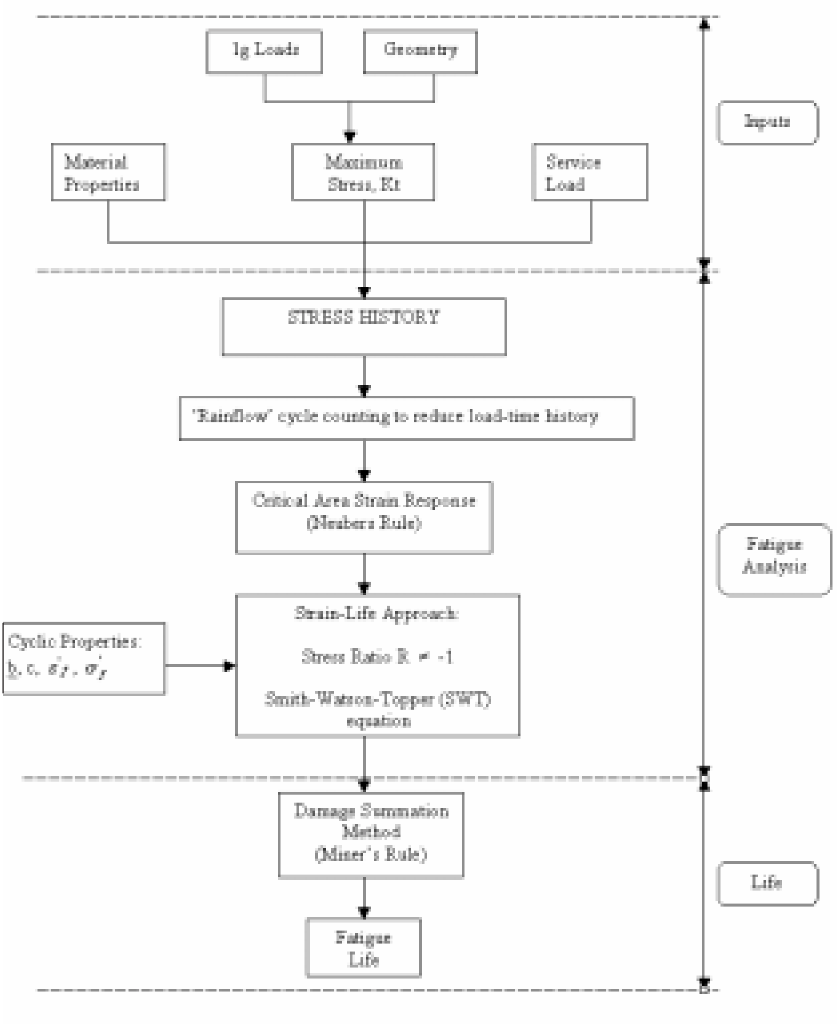

Figure 2: Life Prediction Flow Chart[2]

The crack initiation approach requires estimation of stress history. This needs input data of service load, lug maximum stress, and material properties. After the stress and strain at the critical location on the lug are estimated, ‘Rainflow’ cycle counting method is then used to reduce load time history into a number of events and sequence. When the load history is obtained, it is then multiplied with the stress obtained from the finite element analysis. This stress factor was a loading based on 1-g level flight. Then the strain-life methods that incorporate mean-stress effects are employed for predicting structural fatigue life. Following this, the linear damage hypothesis proposed by Palmgren and Miner is used to accumulate the fatigue damage.

In strain-life approach, fatigue resistance of metals can be characterized by a strain-life curve. The relationship between total strain amplitude, $\Delta\varepsilon / 2$, and reversal to failure $2N_f$, can be expressed through the following form [3, 4]:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f^{'}}{E}\left(2N_f\right)^b + \varepsilon_f^{'}\left(2N_f\right)^c \tag{1}$$

where $\sigma_f^{'}$ is the fatigue strength coefficient; b is the fatigue strength exponent; $\varepsilon_f^{'}$ is the fatigue ductility coefficient; c is the fatigue ductility exponent.

For a cyclic loading, stress-strain curve can be expressed through the following form:

$$\varepsilon_{total} = \frac{\sigma}{E} + \left[\frac{\sigma}{K^{'}}\right]^{1/n^{'}} \tag{2}$$

where K' is the cyclic strength coefficient and n' is cyclic strain hardening exponent (results of b divided by c).

When constructing a strain-time history from stress-time data, hysterisis loops have to be considered using cyclic stress-strain curve. Using Masing's Hypothesis, which assumes that the line describing a stress-strain hysteresis loop is geometrically similar to the cyclic stress-strain curve (Eqs. 2) but numerically twice its size [3], it is obtained,

$$\Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left[\frac{\Delta\sigma}{2K^{'}}\right]^{1/n^{'}} \tag{3}$$

Neuber's rule [4-6] is used to take into account the notch effect. The relation between the notch geometry and the stress-strain can be expressed through the following form:

$$\frac{(K_t\Delta\sigma)^2}{E} = \Delta\sigma\Delta\varepsilon \tag{4}$$

where K_t is the stress concentration factor of the wing lug structure. Equation (3) and (4) need to be solved sequentially, and as it requires the repeated try and error calculation to find the root of curve, Newton's iteration method is applied [7].

The strain-life equation need to be modified to account for mean stress effects. Smith, Watson and Topper (SWT) [8] have proposed an equation to represent the mean stress effects.

$$\sigma_{\max}\frac{\Delta\varepsilon}{2}=\frac{(\sigma_f^{'})^2}{E}\left(2N_f\right)^{2b}+\sigma_f^{'}\varepsilon_f^{'}\left(2N_f\right)^{b+c} \tag{5}$$

where $\sigma_{\max}=\frac{\Delta\sigma}{2}+\sigma_0$

Palmgren-Miner's cumulative damage summation rule [9,10] was proposed as a way to sum damage from different fatigue events or cycles, first by the Swedish engineer A. Palmgren and resurrected 20 years later by M. A. Miner:

$$\sum\frac{n}{N}=\frac{n_1}{N_1}+\frac{n_2}{N_2}+....+\frac{n_n}{N_n}=1.0 \tag{6}$$

where n is the number of cycles of a certain stress amplitude and is N the number of life of certain stress amplitude. The ratio of n/N representing the damage of the stress given.

Load History Development

The RMAF MiG-29 Load

In many air forces of advanced countries, there is a practice to fit a Flight Data Recorder (FDR) in their aircrafts to capture in-flight data including aircraft parameters and strain reading for the purpose of fatigue usage monitoring. The digital data captured are used as the loading history. In the case of the RMAF MiG-29 aircraft, the FDR fitted in the aircraft captures various data during flight, which include g-force history. At this stage a reliable method to collect and extract the related structural data was introduced. The available data for fatigue analysis is in g-history, Figure 3. What needed is to convert this loading spectrum from g-reading to strain form, and restructure the cycles event so that it is in the structured order.

For the purpose of converting the load spectrum form, finite element analysis was conducted. The main objective of the FEA is to find the lug stress at the symmetrical level flight of 1-g condition. This stress value is then multiplied to the loading history for every single peak and valley.

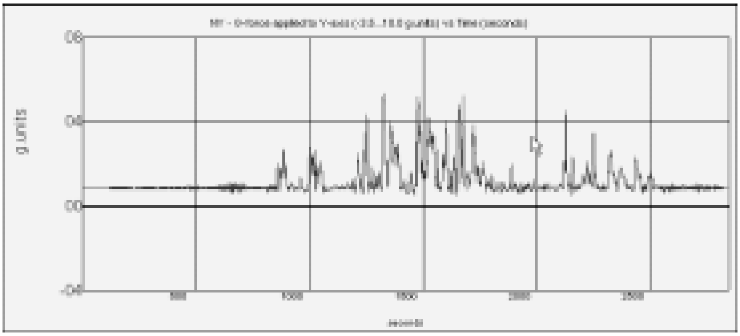

Figure 3: Example of g-history[2]

Cycle Counting

The rainflow method [11] has been used for cycle counting. Reducing the measured history into a series of cycles and half cycles consistent with basic material behavior is critical, and ‘Rainflow’ cycle counting is established herein as the soundest technique for achieving such reduction [11]. At this stage, it is also important to note that load truncated procedures need to be applied. In most of loading history, there is an existence of small number of ‘passed cycles’- cycles that do not cause any effect to the fatigue life. These cycles are removed from the load sequence. Fatigue life then can be predicted by combining the results of the cycle count with relevant basic data using the linear cumulative damage hypothesis.

Fatigue Material Properties

To determine the material characteristic of the lug, a specimen was prepared for material testing. Hardness test and chemical composition test were conducted [12]. It was found that the material was a titanium based alloy. In the strain-life analysis, the cyclic material data is needed. Here, approach proposed by Jun-Hyub Park and Ji-Ho Song [13] was used. Using extensive experimental strain-life curve data on 116 steels, 16 aluminium alloys and six titanium alloys, nearly all methods currently available for estimation of fatigue properties from simple tensile data are discussed in detail. They proposed that for the purpose of estimating the properties of titanium alloy, the uniform material law by Baumel and Seegar was considered the most accurate, and this approach was used in this project.

$$\frac{\Delta\varepsilon}{2} = 1.67\,\frac{\sigma_B}{E}\left(2N_f\right)^{-0.095} + 0.35\left(2N_f\right)^{-0.69} \qquad (7)$$

σ_B is the tensile yield strength.

Finite Element Analysis

The purpose of conducting the FEA is to get the maximum stress either at fuselage joint or wing lug joint based on the symmetrical level flight condition at 1-g. This stress will become the reference stress of other g-reading position in load spectrum.

Finite element analysis was performed on the MiG-29 Wing with the wing-fuselage lug joints regarded as wing supports [14]. The reaction forces at the support can be found and to be applied as external forces to the lugs of the wing and fuselage of the aircraft. The maximum value of stresses occurring at the lugs at 1-g flight condition were obtained. Figure 4 shows the finite element model of the wing [14], while the lug model is shown in Figure 5.

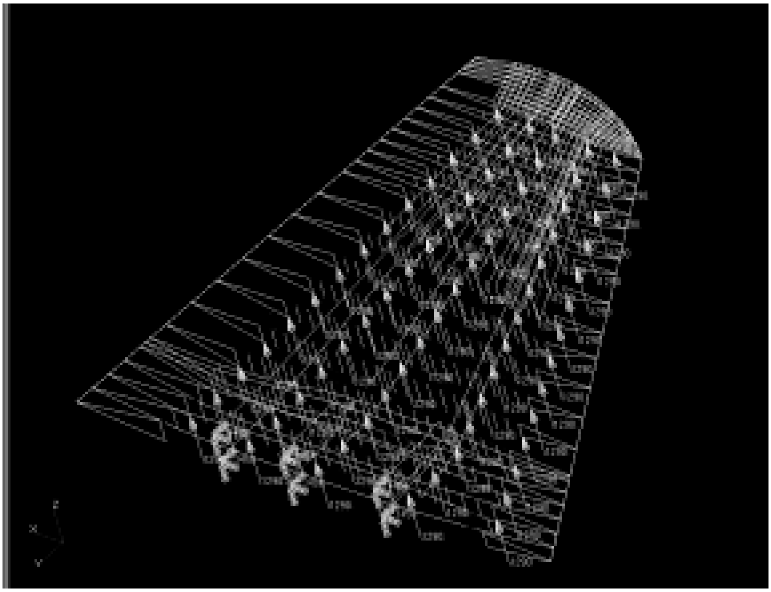

Figure 4: Model of the MiG-29 Wing

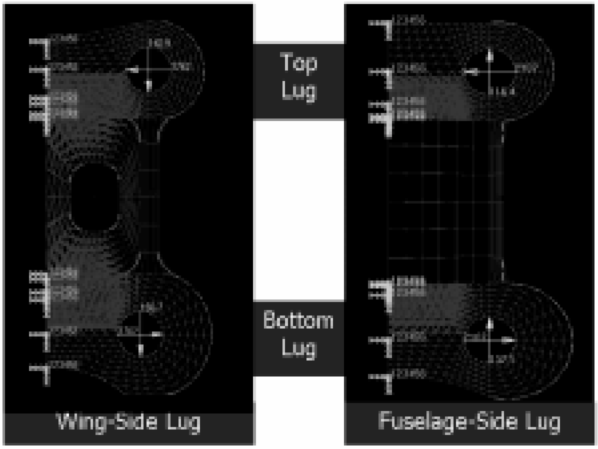

Figure 5: Wing and Fuselage Side Lug

Software Development

The software was developed in C^{++} language environment with flat file and binary database. In this way, it facilitates ease of installation in every RMAF base (it does not need the third party database and tools such as SQL, Oracle and Crystal Report). The software will read flight data from TOPAZ and can perform life prediction analysis. The software is able to find out the mission severity for each mission performed by the airplane. The fatigue index at any stage of operation can be obtained. Through its excellent graphical presentation, the software can display the mission profile for various flight data. Figure 6 below shows the interface of the software system. Currently the MiG-SLA has been in operation to conduct fatigue life monitoring to the RMAF MiG-29. The RMAF F/A-18 reporting format [15] is used as basis to produce the RMAF MiG-29 Fatigue Usage report. The data can then be used to assist the fatigue management of the RMAF MiG-29 squadron.

Conclusion

This paper has reported the development of fatigue life monitoring program of RMAF MiG-29. The fatigue life is based on the wing-fuselage lug joint structure, and Low Cycle Fatigue (LCF) approach is adopted. An

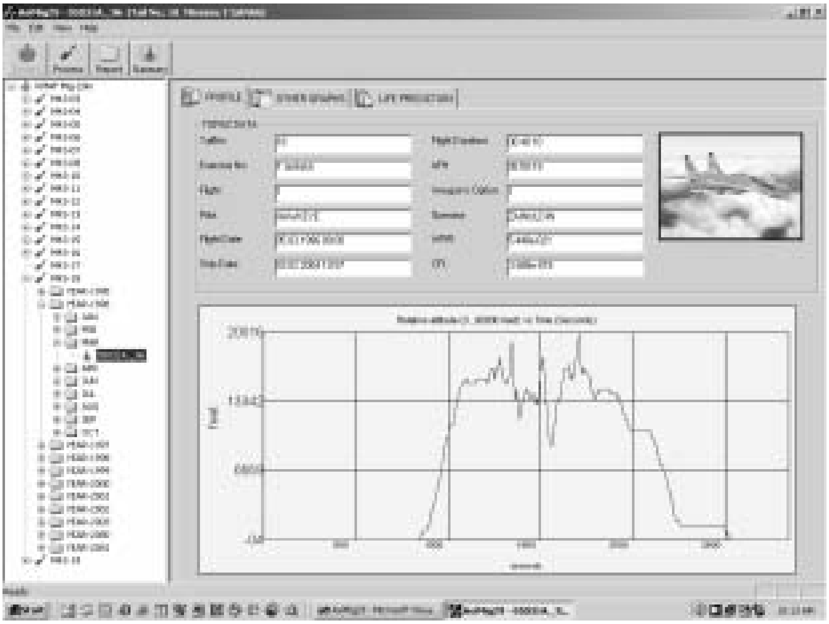

Figure 6: MiG-SLA Software Interface

algorithm for performing the fatigue safe life analysis was proposed. The fatigue characteristics (strain-life) of the lug material was obtained from the laboratory test, using the lug material sample, combined with the empirical formula of strain-life diagram. Notched effect is taken into account using Neuber theory. Mean stress effect is dealt with using Smith-Watson-Topper formula. Miner's rule is used to calculate the fatigue damage accumulation.

Loading spectrum development also was highlighted. The stress spectra of this component, is derived through mapping of g-spectra to the 1-g stress level of the lug. The g-history is obtained from the accelerator installed in the airplane, while the 1-g stress level is obtained by finite element modeling of the wing structure and lug joints. Rainflow cycle counting procedure is then applied.

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