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Structural Analysis of Ageing Pilatus P-3 Engine Mount

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Abstract

The Pilatus Trainer P-3 full scale fatigue test was performed in 1960 to validate a service life of 2’500 FH for the Swiss Air Force. The test showed minor damages after 5’000 FH which were all addressed in modifications for the whole fleet. During the military service life, no cracks were discovered. In 1975, a structural integrity study was done to assess the fatigue life of the fleet based on the Air Force usage. The Swiss fleet was cleared to 3’000 FH and 12’000 flights due to the less severe usage compared to the full scale fatigue test. The Swiss Air Force retired the P-3 fleet in 1995. The P-3 were sold as ¨oldtimers¨ to private people. In Switzerland, 17 aircraft received a civil registration by FOCA. The P-3 had between 3’000 and 3’400 FH during military usage. The current fleet leader has accumulated 4’270 FH. The P-3 full scale fatigue test demonstrated no fatale structural failure at 5’000 FH and 10’000 flights. Due to the high number of FH compared to the test, further investigations are needed to ensure the continuing safe operation of the civil registered P-3 airplanes. First, the available Nz spectrum from the military usage were analyzed and compared to the full scale fatigue test spectrum. Second, two Swiss operators were interviewed to understand the civil usage. The civil usage seems to be heavily depending on the operators, so a conservative engineering approach is necessary to ensure the structural integrity. An assessment was done with collecting all the data from the military usage and reviewing the available information. Some structural critical areas were identified after the first review. Most concern showed the engine mount which was never tested, and only limited static analysis was done in 1958 with no fatigue calculation. The engine mount is a tube structure with welded connection of steel material AISI / SAE 4130. A detailed FE model using ANSYS Workbench Platform was developed and 6 load cases based on EASA CS23 certification standard were applied. The mesh size was reduced to 1mm at the critical areas to model the welded structure. The static analysis was based on FKM criteria. The horizontal spin maneuver exceeds the tensile strength at two local positions. Based on the spectrum information from the test and the Nz exceedance data for the Swiss Air Force usage, a Rainflow Counting Matrix was developed. With the corresponding results for the Nz values, the spectrum could be converted to stresses at the critical locations based on principal stresses of the sub model FE data. For fatigue investigations the flying steady maneuver loads are contributing to the fatigue damage. In the first approach MIL-HDK-5J stress life data was used for max min stress level to see if the fatigue life is in the area of durability life of 107 cycles. Further analysis was done using strain life fatigue analysis which showed at two locations a much shorter life. Inspections at every 100 FH were scheduled to ensure the safe operation under civil usage.

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Keywords: Structural Analysis; Fatigue, Structural Intregrity; Aircraft Engine Mount.

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1. Introduction

Up to 1958, no formal fatigue requirements exist. Only static strength considerations plus safety factors were expected to preclude fatigue damages. In 1954, two Comet I De Havilland plane crashed with approximately 1’000 pressure cycles which was well below the anticipated service life. In 1958, six Boeing B-47 bombers crashed. To exchange information among experts and get more understanding to improve the fatigue design, the International Committee on Aeronautical Fatigue (ICAF) was founded

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in 1951. Already in 1952, Juerg Branger from the Swiss Federal Aircraft Factory (F+W Emmen) in Switzerland developed the so called fatigue history simulator. In 1959, the Pilatus P-3 military trainer was tested in the fatigue history simulator to demonstrate a service life of 2'500 flight hours (FH).

Today the fleet leaders of the Pilatus P-3 trainer under civil operation are close to the tested life of 5'000 FH (2 times the service life of 2'500 FH). The civil usage of these old planes may be quite different compared to the military usage. Nevertheless, the safe operation is a demand and has to be approved by experienced fatigue engineers. A further challenge is the documentation of past experience. In this paper, the procedure for the Pilatus P-3 will be discussed and a detailed structural analysis of the engine mount will be presented.

2. Pilatus P-3 Full Scale Fatigue Test

At the end of the fifties, the Swiss Air Force ordered the P-3 aircraft of the Pilatus Aircraft Ltd. for the training of their pilots in Stans, see Fig. 1. A simple Nz loads spectrum per 1'000 flight hours was set up, see cumulative Nz design spectrum from -3.5G up to 7.0G Fig. 2.

At this time, the 'fatigue history simulator' of F+W Emmen was ready for testing, and thus the P-3 was the first test item. After different preparations and some preliminary run, the real test began in August 1960. The requirements for fatigue history simulator can be expressed in 3 main tasks:

1. All applied load on the structure are controlled by a single command
2. The test facility must allow every loading history
3. The test facility must control itself automatically

The fatigue history applied on the simulator is an extract of the service history which contains every element which is significant for the fatigue life of the aircraft structure. The force are produced hydraulically and transmitted by mechanical means to the test specimen, whith jacks which are working in tension as well as in compression.

For the P-3 test, 24 different partial programs, based on V-G-H records (velocity, normal acceleration, altitude), describing take-off, climb, different types of flight, descent and landing, have been combined to generate 1'056 different flights, containing about 23'000 cycles per 250 FH (one spectrum block).

To set up the sequence of flight, the ballot box method has been used; it means that one flight after the other has been drawn randomly like in a raffle.

For this test, the rig the loads were applied through 19 hydraulic jacks, 16 for the wing in a lying position and 3 for the fuselage. The chord wise force application is different for the positive and the negative loads, matching the specific pressure distribution on the wing as well as on the fuselage. The load applying points have been located along each rib. No side loads were simulated at that time.

With this test rig, see Fig. 3 and its equipment within 24 hours, 72 real flying hours could be simulated. At that time, no strains and displacement were recorded during fatigue cycling.

Fig. 1. Pilatus P-3 trainer for Swiss Air Force

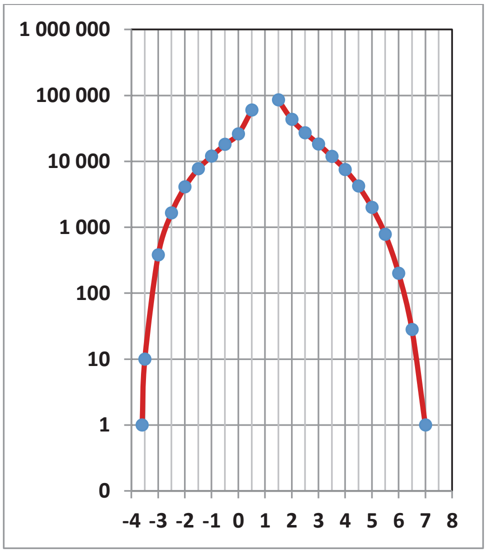


Fig. 2. Nz exceedance for P-3 design spectrum

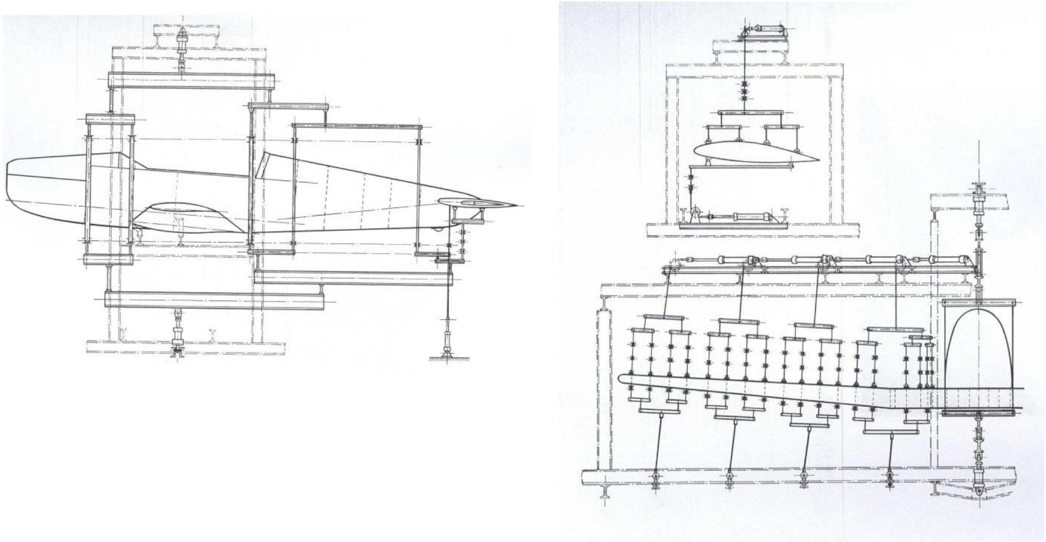


Fig. 3. Test rig for P-3 with all actuators acting in tension (wing actuators are lying horizontally)

For the full scale fatigue test, the last aircraft of the production has been selected. By the test start, the first aircraft had already 500 flying hours, and some loose rivets have been found due to static overloading but certainly not due to fatigue cycles. After 1’000 hours of fatigue testing, a fretting damage occurred. A repair has been done on the test article as well on the aircrafts of the whole fleet. After 2’500 test hours, the authority decided to extend the test up to 5’000 hours after a static overload test of 7G. At the end of 5’000 hours an ultimate test (factor of 1.5 on max service load 6G) up to 9G has been done. The specimen failed at 8G whilst the design ultimate load target was 9G.

Despite very careful inspections before this ultimate load test, the fatigue damage that leads to failure was not remarked before. Finally one of the hydraulic mechanics found a damage in a hidden corner by chance. It was termed as a classic example of a fatigue failure. The failure occurred by shear in a web plate of the main spar in both outer wings, at the attachment to the inner wing. A check of the stress calculation of this part showed that the web and the riveting did not reach the ultimate factor of 1.5. On all service aircraft the allowed limit was thus reduced temporary to 5G, and it was possible to strengthen it by a redesign for the whole fleet before an accident occurred.

The P-3 full scale fatigue test showed minor damages which were all addressed in modifications for the whole fleet. During the military service life, no cracks were discovered during inspections (intervals of 100 FH, 200 FH or once a year) and no special incidence for structural damages was reported. In 1975, a structural integrity study was done to assess the fatigue life of the fleet. The Swiss fleet was cleared to 3’000 FH and 12’000 flights due to the less severe usage compared to the full scale fatigue test.

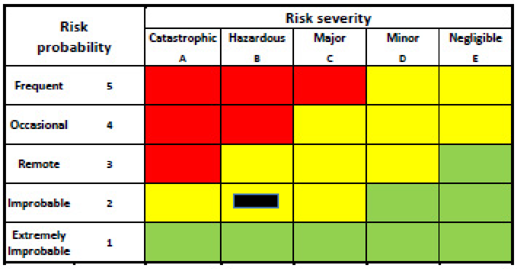
The Swiss Air Force retired the P-3 fleet in 1995. The P-3 were sold as ¨oldtimers¨ to private people. In Switzerland, 17 aircraft received a civil registration by the Swiss Federal Office of Airworthiness) FOCA. The military service schedule was converted for civil usage. The P-3 had between 3’000 and 3’400 FH during military usage.

The current fleet leader has accumulated 4’270 FH whereas another plane has done less FH but reached already 4’872 landings. The P-3 full scale fatigue test demonstrated no fata failure at 5’000 FH and 10’000 landings. This means that the P-3 showed a safe life of 2’500 FH and 5’000 landings. According to the structural integrity study of 1975, the fleet leader exceeded the cleared limit of 3’000 FH. Therefore, further investigations are needed to ensure the continuing safe operation of the civil registered P-3 airplanes.

3. Assessment for Civil Usage

First, the available Nz spectrum from the military usage were analyzed and compared to the full scale fatigue test spectrum. Second, two Swiss operators were interviewed to understand the civil usage. As a result, we can conclude that the P-3 are no more flying spins and do not exceed 5G’s. Most flights are within 1 to 2G. During special displays, the P-3 flyers of Airolo still fly loopings with higher G but 5G seems to be the real limit. This information is very limited for making engineering analysis concerning the remaining life of civil usage. The civil usage may be heavily depending on the operators.

Nevertheless, an assessment was done, collecting all the data from the military usage and reviewing this information. The risk matrix of International Civil Aviation Organization (ICAO) was used to rank the status of the P-3 structure regarding safe operation. In general the structure of the P-3 has hazardous risk severity with improbable risk probability ranking 2B, see Fig. 4 graphic.



Risk probability		Risk severity				
		Catastrophic A	Hazardous B	Major C	Minor D	Negligible E
Frequent	5	🟥	🟥	🟥	🟨	🟨
Occasional	4	🟥	🟥	🟨	🟨	🟨
Remote	3	🟥	🟨	🟨	🟨	🟩
Improbable	2	🟨	🟨 ■	🟨	🟩	🟩
Extremely Improbable	1	🟩	🟩	🟩	🟩	🟩

Fig. 4. Result of ICAO risk matrix for P-3, and critical areas of P-3 structure.

The critical areas were found to be:

- engine mount fairing; not tested
- landing gears; not tested
- vertical tail; not tested
- connection between inner and outer wing; high loads transfer, bolts were already replaced in service

No service failures or cracks were reported and documented. After the changes due to residual static test in the fleet, no modifications were done. In a review with the FOCA, it was decided to do a static analysis and fatigue investigation on the engine mount (priority 1). These fairings were never tested but are safety critical. A crack could lead to fatal failure which must be avoided under all circumstances.

4. Structural Analysis of Engine Mount

For loads selection the EASA standard CS23 was applied:

- Steady state maneuvers CS23.361
- Gust load CS23.361
- Side load maneuver CS23363
- Horizontal spin maneuver CS23.361
- Side load on ground CS23.485
- Ground load condition as reference for fatigue analysis (weight on wheels condition)

For engine conditions, also CS23.423 and AMC23.371 was used. To get all the loads, the flight manual was necessary with the data from the Lycoming engine model GO-435-C2 and the propeller information from Hartzell; their help is gratefully acknowledged.

The engine mount is a tube structure with welded connection with steel material AISI / SAE 4130 [1], see Fig. 5 below.

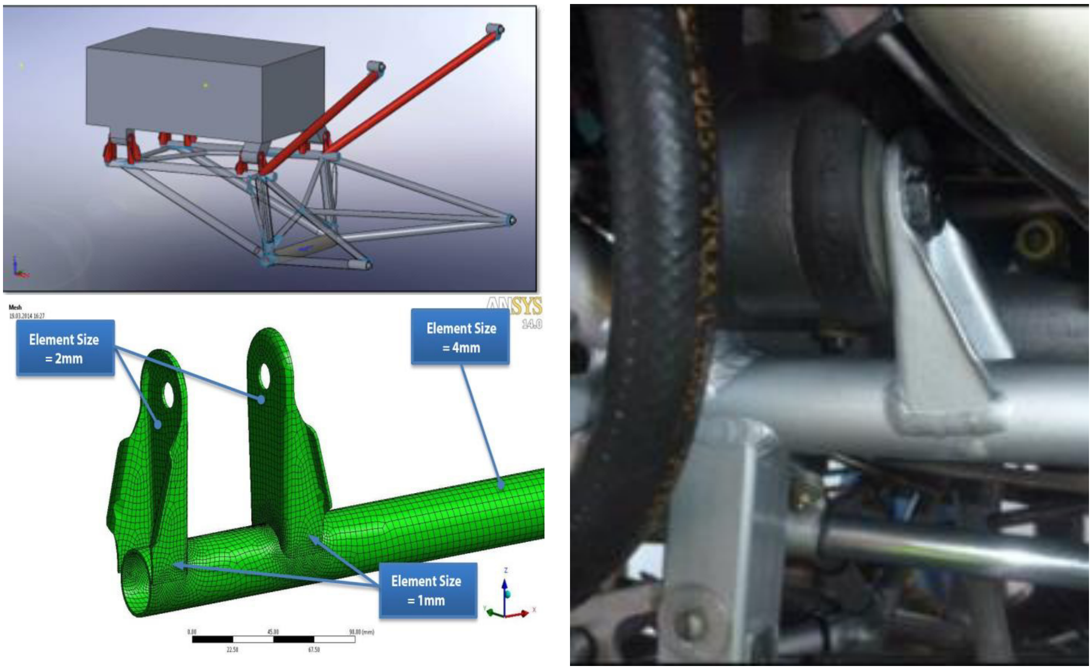


Fig. 5. Engine mount structure with FE model, and detailed picture of aft engine mount tab

All the required loads could be calculated without any problems. The FE code from ANSYS was used to develop a finite element model. First, a simple model was done and afterwards a more complex model was designed. The engine itself was simplified as quadratic bloc. For details see the FE model in Fig. 5 with element sizes of 1, 2, 4mm depending on structural required details. To determine the correct size for surface FE model, a grid converge study was done which results in a mesh size of 2mm and 4mm for a tube diameter of 15mm.

In this FE model the welds were not modeled. For the connection of the tubes ANSYS Workbench ¨bonded¨ approach was used. In the connection area the mesh size was further reduced to 1mm. To improve the model - especially at the connections and interfaces - the FE model was locally refined using a submodel with volume mesh elements, see Fig. 6. The welds were simulated with a typical radius.

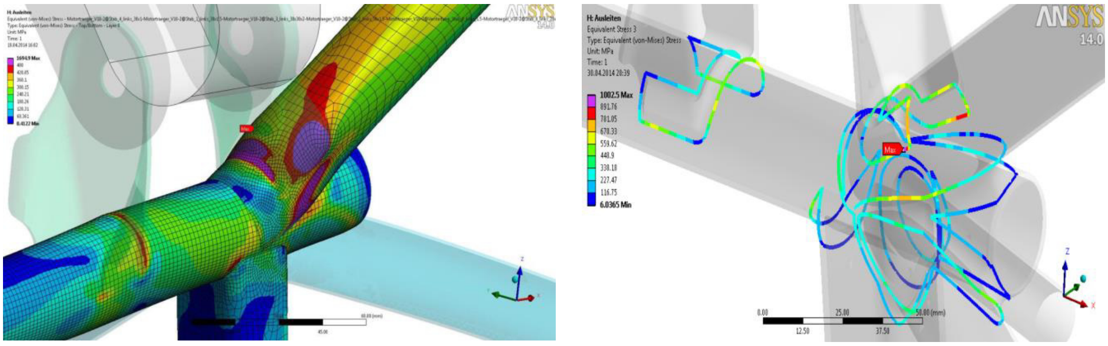


Fig. 6. Critical stresses FE analysis (left), CAB detailed analysis for critical structure (right)

The results of the FE model showed large deformations of 4.0 to 4.8mm at the left hand forward engine mount tab. The static analysis was based on the FKM requirements, see [2]. Based on the static strength analysis the ultimate load cases of steady state 6G maneuver and horizontal spin maneuver exceeded the tensile strength of steel AISI / SAE 4130. Local plasticity was not modeled in detail which would give more accurate results.

Therefore at the critical connections the special hot spot procedure (CAB process) [3] was used to perform the static analysis on the weld, see Fig. 6. The equivalent van-Mieses stresses at some locations were in the range of 87ksi. Also the upper bolt connection to the fuselage had very high stress levels as well.

A lot of effort was spent to determine the impact on local yielding at the high stress areas in the detailed analysis. The so called CAB method was very helpful. The safety factors at critical locations showed values above 1 for all load cases up to Nz=6G (limit load) with exception of the horizontal spin load condition. This load case will no more be practiced in the civil operation based on pilot interview. This restriction has to be included in the flight manual for civil operators.

5. Fatigue Investigations

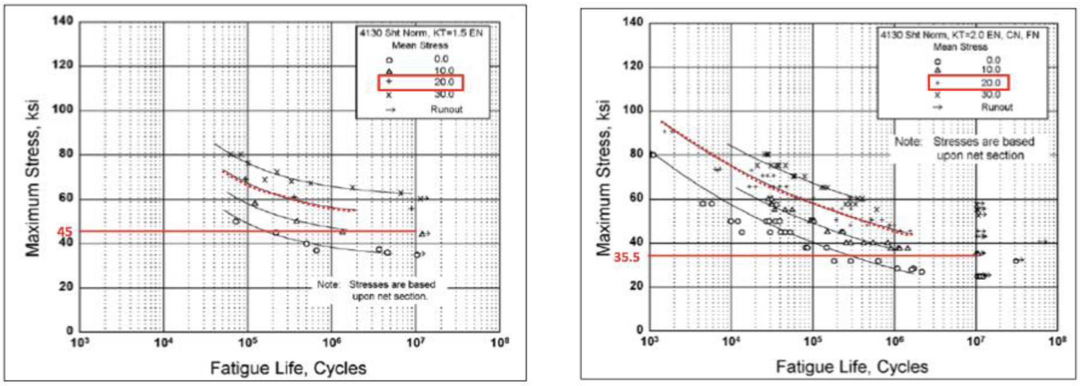
Based on the spectrum information from the test and the Nz exceedance data for the Swiss Air Force usage a Rainflow Counting Matrix was developed. A lot of knowledge of the period of Swiss Mirage III test development has to be applied to determine the 32 by 32 Rainflow Counting Matrix for the test spectrum. The military P-3 usage spectrum contains information of recorded Nz data from 1961 until 1990.

With the corresponding FE results for the Nz values, the spectrum could be converted to stresses at the critical locations based on the principal stresses of the FE sub model data. The most critical locations are the aft engine mount tab, and upper connection bolt to the forward fuselage, see Fig. 5. For fatigue investigations the flying steady maneuver loads are contributing to the fatigue damage.

In the first approach MIL-HDK-5J data [4] for steel AISI / SAE 4130 at kt =1.5 and kt=2.0 was used for max/min stress level (severe cycle) to see if the fatigue life is in the area of the durability life. This kt values are considered because the engine mount tab has a stress concentration factor of kt of 1.25 and the connection bolt a kt of 2.0. The max stress for the engine mount tab was 35.5 ksi respectively 45 ksi for the connection bolt at mean stress of 20ksi. Both values are below the red dotted curve at 107 cycles, see Fig. 7a and b. This confirms that the two locations have a durability life.

To get more confidence in our analysis, we also used the local strain life approach with strain life curves. Therefore, the strains from the detailed FE models at the two critical locations (engine mount tab and connection bolt) were taken into account. Using strain life data with stress ratio of R=-1 from [5], we observed maximum strain amplitudes for most damaging cycle of 0.14% (engine mount tab) respectively 0.23% (connection bolt). The strain amplitude of 0.23% showed 100’000 cycles up to failure whereas 0.14% showed infinitive life.

At the end, we have done a train life calculation with Miner damage accumulation using the design test rainflow matrix and the military usage rainflow matrix. For most critical location at the engine mount tab we got a Miner damage sum of 1.2 for the P-3 test spectrum and 0.4 for the military usage spectrum. This was based on the 5’000 FH test life. Based on the Miner damage sum of 1.2 the engine mount could have some cracks at the end of the P-3 fatigue test. The Miner damage sum of 0.4 for military usage would not show cracks at 5’000 FH.



(a) (b)

Fig. 7. (a) Stress life curves for kt=1.5; (b) stress life curve for kt=2.

Nevertheless due to aging of the P-3 airplanes in civil operation careful inspection at the critical areas in the engine mount are necessary.

We recommend the inspection of the 5 most critical locations in the area of the engine mount tab (engine connections) and connection bolt (upper and lower bolt connection to fuselage frame) every 100 FH or once a year. This can be included in the maintenance plan for the regular 100 FH maintenance inspection program.

6. Conclusion

The Pilatus P-3 military trainer was designed in the fifties and operated from 1959 till 1995 for pilot training and transfer flights in the Swiss Air Force. During this period no structural problems were reported which lead to repairs and redesigns. The usage was much less severe than the design/test spectrum which was tested at F+W Emmen Switzerland for 5’000 FH. Since 1995 17 P-3 are in civil operation in Switzerland. The fleet leaders reached close to 5’000 FH. An assessment showed that some locations needed to be investigated in more detail to ensure the structural integrity.

The engine mount was never tested and so no information regarding fatigue life and critical locations was available. In this paper a detailed FE study with fatigue investigations is presented. The fatigue life calculations showed that the life is close to the area of durability life. It is recommended to use at least two methods for fatigue analysis to better understand the sensitivity of the fatigue life. Keep in mind that the fatigue life curves belong to 50% probability rate of failure. Five locations should be inspected at the engine mount every 100 FH to ensure a safe operation.

Acknowledgements

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