EFFECTS OF SUSPENSION WEIGHT ON FIGHTER FATIGUE DAMAGE

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Abstract

The suspension weight of fighter aircraft is part of the service load and usually assumed fixed. Variation of suspension weights is investigated through surveying actual "Flight Parameter Recorder" (FPR) data. Investigation showed that actual suspension weights changed considerably and irregularly. For the fighter considered, results of FPR recorded histories for 3 aircraft showed that the actual fatigue damages were about 20% lighter than the design assumption. It is significant, necessary and possible to calculate fatigue damage based on actual suspension weight for each flight in order to accumulate fatigue damage correctly and control service life individually.

1 Monitoring aircraft service load history

The cost of purchasing modern aircraft is so high that the operators are always trying their best to make full use of the potential of every aircraft available in service by prolonging their service life. However, the cost of dealing with faults in aircraft structure is also very high especially if the faults may possibly involve flight safety. This consideration would force people shorten aircraft service life conservatively in order to keep a large safety margin. The contradiction between making full use of potential and controlling safety risk reasonably has been puzzling all the aircraft industry personals ever since and promoting the innovation in aircraft life research and management techniques. As the research in fatigue of materials and structures advances [1], people understand more fatigue mechanisms and can predict fatigue life under the fixed usage with certain confidence.

Nevertheless, aircraft service life depends not only on the inherent characteristics of material and manufacture quality, but also certainly on the subsequent actual usages of the products. Without knowing the actual loads subjected during usage it is not possible to determine the life of a product by either calculation or experiment. The load spectra used in calculation or experiment are "design load spectrum" under some presumed usage conditions [2]. The service life given in this case can be considered as the average life under the expected usage for a fleet. It is not possible to get rid of the above mentioned contradiction based on fleet average to manage life [3].

With the advances in modern electronics, flight parameter recorder (FPR) has been already widely installed in modern aircraft so it is possible now to monitor full usage and load history for every aircraft in long time without too much burden [4]. Such the idea "Fatigue life monitoring of individual aircraft" [5] provides a possible way to control the flight hours of each aircraft up to its utilizable potential under the acceptable safety risk based on its actual recorded load history.

Obviously the key step of "Fatigue life monitoring of individual aircraft" is to record load history related parameters by air-borne avionics (mostly FPR) in real time during all flights. Usually parameters are measured in equal time intervals, digitalized and stored during flight, then dumped to the ground computer after some time. The dumped data are used to form a "real load spectrum (history)" after the necessary data processing [4]. The individual aircraft life (flight hours) then can be adjusted by comparing the fatigue damages calculated based on this real load spectrum and design load spectrum. Recorded data (by FPR) related to structural load mainly include: load factors in different directions at the center of gravity (c.g.) of aircraft (by accelerometer), residual fuel weight (by fuel flow meter) and so on, occasionally may also include strains (stresses) at special critical locations. The variable suspension weight during take-off is also a part of the real load, but it is usually not directly measurable and to be derived indirectly. The goal of the present study is to examine the effect of this take-off weight variation on aircraft fatigue damage.

2 Measure of fatigue damage

The relative fatigue damage subjected to one stress cycle is defined as the following eq.(1) usually based on the S-N life curve [1] under constant amplitude fatigue tests of the material.

$$d'_i = 1/N_{f\,i} \tag{1}$$

Where subscript i identifies the load cycle within a spectrum, N_f the failure life (in cycles) on the S-N curve corresponding to the stress.

Typical S-N curve is usually expressed [1]as,

$$N_{f\,i}\, S_i^m = C \tag{2}$$

Where m and C are material constants determined by experiment.

Substitute eq.(2) into eq.(1),

$$d'_i = S_i^m / C. \tag{3}$$

Where the denominator C in eq.(3) acts as a reference to transform the "damage" into a dimensionless parameter (relative damage), hence the item S_i^m can be defined as the "generalized fatigue damage" with its special dimension, i.e.

$$d_i = S_i^m . \tag{4}$$

In the above equations, parameter S characterizes the load cycle which can be treated as an equivalent cyclic stress by combining both the peak and the amplitude of the specified load cycle and it is generally expressed as

$$S_i = S_{eqv,i} = (S_{\max\, i} - S_{\min\, i})^{r-k} \times (S_{\max\, i})^k \tag{5}$$

Where the indices r and k usually take the values of r=1, k=0.5; Hence the equivalent cyclic stress of the ith cycle becomes

$$S_{eqv,i} = \sqrt{(S_{\max\, i} - S_{\min\, i}) \times (S_{\max\, i})} \tag{5a}$$

Assuming that the relative fatigue damages of all cycles within the spectrum acuminate according to Miner's linear rule[6], i.e.,

$$D' = \Sigma\, d'_i , \tag{6}$$

Then the total generalized fatigue damage (simply referred as damage hereafter) becomes,

$$D = \sum S_{eqv,i}^m = \sum [(S_{\max\, i} - S_{\min\, i}) \times (S_{\max\, i})]^{m/2}. \tag{7}$$

3 Influence of take-off weight on fatigue damage

Load factors (n_g at c.g.) recorded by FPR are not actual flight loads. The instant load acting on the whole aircraft at any time t relates the aircraft weight, fuel weight, weapon and other weights during flight through the eq.(8),

$$P(t) = n_g G = n_g (G_1 + G_2 + G_3) \tag{8}$$

Where G_1 represents fixed aircraft weight including empty aircraft, fixed basic equipment and the crew; G_2 instant fuel weight measured by flow meter and recorded by FPR; G_3 variable weight during each take-off, possibly weights of passengers, cargoes, weapons and suspensions.

For most aircraft structures, their internal stresses are linearly related to the total aircraft load,

$$S = A \cdot P(t) \tag{9}$$

Substituting the load eq.(8) into eq.(9), the structure damage [7] calculated by eq.(7) is,

$$D = \sum S_{eqv,i}^m = A^m \sum [(P_{\max\, i} - P_{\min\, i})^{m/2} \times (P_{\max\, i})^{m/2}]. = A^m \sum G_i^m [(n_{g\max i} - n_{g\min i}) \times (n_{g\max i})]^{m/2}. \tag{10}$$

In the last 2 equations, A represents the linear coefficient transforming total load to a special structure detail (detail characteristic coefficient). When the total load on aircraft instead of any special details is concerned, the sum item (without involving A, or assuming A=1) at the right hand of eq.(10) is usually unmistakably termed as fatigue damage for the whole aircraft (hereafter in the paper).

The influence of fighter suspension weight on aircraft structural fatigue damage is usually considered not so significant that generally the typical design configuration can be of good representative without the need to examine weapon suspension variation in details. Here quantitative examination of take-off weight on fatigue damage is carried out for a fighter with the emphasis on the actual variation of weapon suspension.

3.1 Damage differences in one cycle

Firstly, the differences in fatigue damage during one load cycle (load factor 1g to 3g) are examined by considering a fighter (G_1 = 17020kg) with following 5 different take-off configurations:

- Case 1, the typical design configuration to be the comparison reference: fuel G_2 =3000kg, G_3 = 1380kg;
- Case 2, the main fuel tanks full filled but no suspension weight: fuel G_2 =6000kg, G_3 = 0;
- Case 3, a sort of weapon configuration: fuel G_2 =3000kg, G_3 = 1670kg;
- Case 4, the suspension configuration to be of certain average: fuel G_2 =3000kg, G_3 = 160kg;
- Case 5, an actual flight randomly picked up: fuel G_2 =4000kg, G_3 = 330kg;

In damage calculation, it is assumed that m =4 in eq.(10) and the influence of the linear coefficient *A* is cancelled out by examining the damage ratio (%) as shown in Table 1 below.

Table 1 Damage ratios for different weight cases

Case	1	2	3	4	5
Suspension weight	1380	0	1670	160	330
Take-off weight (kg)	21400	23020	21690	20180	21350
Damage ratio (%)	100	133.90	105.53	79.07	99.07

For the 5 cases in consideration only, damage ratio for the harshest case is about 34% higher than for the reference case, while the damage for the lightest case is about 20% lower than the reference. The result means that the scatter in fatigue damager could be over 50% of the design basis. It is clearly seen even for fighter aircraft the influence of variation in take-off weight on aircraft fatigue damage is in fact remarkable hence cannot be overlooked.

3.2 Damage differences in one landing

In the Table 2 below, fatigue damages of the whole aircraft resulted from multiple peak-valley load cycles in one complete flight (one landing) are calculated (assuming *A*=1). Slightly different from Tale 1, the case 5 here is another randomly picked flight with actual data (G_1 =17020kg, G_2 = 5500kg, G_3 =510kg), then for all other 4 cases the values of G_1 (17020kg) and G_2 (5500kg) are the same only G_3 values vary accordingly as in Table 1.

Damage accumulation are calculated through 3 different “sequence counting” methods for random variable sequences: reversal counting which treats every load range (reversal) as half cycle, up-reversal counting which counts all the up-loading reversals as full cycle but omits all down-loading reversals, and the rain flow counting which try to “pick up” full cycles by a so-called “rain flow principle”. There would not be any difference for calculations in Table 1 (constant amplitude full cycle), but the differences in damage by 3 counting methods are clearly seen in Table 2 for random variable load histories [8]: damage calculated by rain flow counting is always the biggest; damages by two reversal counting are much smaller than that by rain flow counting, but they are comparable.

Table 2 Damage and ratios of one landing

Case	Case 1	Case 2	Case 3	Case 4	Case 5
Suspension	1380	0	1670	160	510
Takeoff weight kg	23900	22520	24190	22680	23030
Rain flow	1182.7	921.98	1243.9	949.76	1012.7
	100%	77.95%	105.17%	80.30%	85.62%
Reversal (half cycle)	576.7	449.87	606.37	463.37	493.98
	1007%	78.02%	105.16%	80.36%	85.67%
Up-reversal	551.8	430.11	580.32	443.06	472.43
	100%	77.95%	105.17%	80.30%	85.62%

However, if we only consider the influence of different take-off weights by looking at damage ratios of 4 suspension cases with respect to the corresponding design configuration case 1, the conclusion will be always the same no matter what counting method is used: scatter of damage from different suspension weights accounts for about 27% of the reference level, which is quite significant.

4 Effect on accumulated fatigue damage

Usually it is rather difficult to know for sure which weapons are actually carried for each flight of every fighter aircraft. After carefully examined the data from the FPR in concern, we found that a recorded "digit bit (1/0)" can indicate whether there is any weapon at each suspension location. Combined with predictable practice, knowledge of weapons and suspension brackets, we can work out the suspension weight during take-off, so the fatigue damage can be calculated more accurately flight by flight based on the data from FPR.

We randomly sampled a batch of recorded data from FPR and calculated the take-off suspension weights for each fight. There are 146 flights covering 18 fighters from units equipped with this type of fighter and a time span of 3 years. The suspension weights are classified into 6 cases and their statistics are shown in Table 3. The damages calculated corresponding to actual instant fuel weights are also listed and summed in Table 3. It is seen that the suspension variation is actually more complex than the cases previously presumed even if the variation in fuel weight is not included.

Tab. 3 Cases of suspension weight and their damages

Cases	Flights	Proportion %	Weapon kg	bracket kg	Calculated damage
1	2	1.37	420	240	583
2	5	3.42	360	150	14579
3	11	7.53	255	90	10029
4	1	0.68	210	120	238
5	40	27.4	105	60	57934
6	87	59.59	0	0	34052
Total	146	100	9855	4740	423883

Based on the sample in Table 3, the average weapon weight per flight is 67.5kg, average bracket 32.5kg; conservatively covering 85% possibility (assuming normal distribution) for a safety margin, the "typical" weapon weight per flight will be 180kg, and bracket 86.6kg. Of course, the average and typical suspension weights will vary a little bit with different statistical samples. Total damages are calculated and compared in Table 4 for the 146 flights assuming suspension weights as design, actual, average, and typical conditions respectively. If the total damage of the design configuration is treated as reference (100%), the actual total damage is about 22% lower than that reference; damages for other 2 cases are also lower than the design one. The damage calculated according to average suspension weight is very close to the actual one (error less than 1%).

Tab.4 Assumed suspension weights and their damages

Cases	actual	average	typical	design
Flights	146	146	146	146
Weapon kg	67.5	67.5	180	930
Bracket kg	32.5	32.5	86.6	450
Damage	423883	427021	435857	541117
Ratio %	78.33	78.91	80.55	100

The real usage of aircraft varies quite a lot with mission and time. Since the above 146 flights only cover a time span of 3 years, we carried out a more throughout investigation tracing complete recorded flight history for 3 fighter aircraft and checked the proportion of flights with any weapon suspension. For some years the flights with weapon suspensions took up more than 50% of all flights, but for some other years the proportion with weapon suspensions might be less than 5%. It is found that actual suspension weights changed considerably and irregularly depending very much on the training requirement and actual arrangement of aircraft usage. As there is not any fixed statistical pattern, it becomes obviously necessary to calculate fatigue damage for each flight based on the actual take-off suspension weight.

For the 3 fighter aircraft in concern, based on their complete recorded flight histories we calculated their total fatigue damages according to actual suspension weights, design configuration case and no weapon respectively. As the total flight hours are different for 3 aircraft, the damages calculated are expressed in the rates (damage/hour) for easy comparison as shown in Table 5.

Tab.5 Damage rates assuming different weights

Aircraft	1	2	3
Flight hours	889	1072.	1098
Flights (landings)	662	837	879
Damage rate/ ratio （design case）	2382 / 100%	1651 / 100%	1980 / 100%
Damage rate/ ratio （no weapon）	1863 / 78.2%	1288 / 78.0%	1568 / 79.2%
Damage rate ratio （actual case）	1873 / 78.6%	1296 / 78.5%	1577 / 79.6%

From the analysis of about 3000 flight hours' FPR data recorded during near 10 years, results in Table 5 show that for all 3 aircraft the damage rates based on the actual suspension are about 20% lower than those based on the design assumption, and only a little bit higher than that of no weapon case. This fact implies that about 20 % life potential could be utilized compared with the service life index given under design load spectrum. This 20% figure is only valid for the 3 aircraft in discussion and will vary for other aircraft, but it clearly demonstrates the necessity to calculate fatigue damage and life consumption based on actual suspension weight for each flight.

5 Conclusion

Based on the recorded FPR data of a certain fighter aircraft, the influence of suspension weight on aircraft structure fatigue damage was studied. The variable take-off weight is an important part of the aircraft load. Even for the fighter aircraft the differences in weapon suspension weight can have significant effect on fatigue damage. The actual total damage of 146 flights is about 22% lower than that of the reference design configuration. Through tracing recorded flight history for 3 fighter aircraft (about 3000 flight hours' FPR data recorded during near 10 years), analysis results also show that the damage rates based on the actual suspension are about 20% lower than for the design case. This study clearly demonstrates the necessity to monitor aircraft load history individually. It is significant to calculate fatigue damage based on actual suspension weight for each flight in order to accumulate fatigue damage correctly, and possible to control service life individually to its full potential.

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References

[1] Miller K.J. A historical perspective of the important parameters of metal fatigue, in: Wu XR and Wang ZG ed. *Fatigue'99-Proceeding of IFC7*:15-40. Beijing, Beijing: Higher Education Press, 1999

[2] Chen Zhiwei. Structural reliable life and spectrum difference factor, *Int. J. of Fatigue* Vol.15(5):389-392, 1993.

[3] Chen Zhiwei, Wang Zhi. The effects of spectrum differences in fatigue life studies, in: *Proc. of 5th Chinese National Fatigue Conference*: 733-737, Weihai, 1991 (In Chinese)

[4] Wu Jiangang, Chen Zhiwei, et al. Study on computer processing of recorded flight data, *Computer Simulation*,.Vol.24 (2) : 18-21, 2007 (In Chinese)

[5] Liu Shuyuan, Jia Guorong, et al. Fatigue life monitoring techniques for individual aircraft, *Proc. of aircraft fatigue life* Vol.4:526-542, Science and Technology Council of Chinese Ministry of Aeronautics and Astronautics, 1993 (In Chinese)

[6] Miner M. A. Cumulative damage in fatigue. *Journal of Applied Mechanics.*1945.12: 159-164

[7] XUE Jun, WANG Zhi, CHEN Zhiwei. Engineering method by analogy for calculating fatigue damage of aircraft structure. *J of Mechanical Strength.* 26(S):138-141, 2004. (In Chinese)

[8] Chen Zhiwei，Wu Jiangang. Study On Generalized Fatigue Damage Under Random Loading， *Key Engineering Materials.* Vol.325, *Proc. of 5th Int. Conf. on Fracture and Damage Mechanics*：1161-1164, 2006.