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STRUCTURAL LIFE RESPONSE IN A FIGHTER AIRCRAFT DUE TO SYSTEMS COMMAND AND CONTROL

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Abstract. *The fatigue resistance and damage tolerance capability of any new fighter aircraft type are to a great extent settled and built into the airframe and mechanical systems during the design and qualification phase. This makes the mission analysis crucial since load spectrum development, structural sizing and test verification program will be founded on this prediction of expected future usage. However, there are certain characteristics of modern generation fighters that need to be considered apart from traditional experiences from older generation fighters. In the present paper examples are given which reflect such matters. Certain flight manoeuvres are highlighted which in combination with an advanced flight control system may cause unexpected impact on the fatigue loading of airframe and systems structure. Examples include the many small load variations on the canard due to the digital control system which may cause structural failure unless the resulting totally different load profile on this structural element is understood and handled. Other examples include less flight critical structures where, however, the consequences in terms of increased cost for inspection, repair or replacement motivate some type of rectifying action.*

1 INTRODUCTION

Over the past few decades design of civil aircraft structures has come to rely on fracture mechanics based concepts both in terms of structural safety, by means of damage tolerance, and in terms of economical fatigue life, or so called durability. For military aircraft the US Air Force has been the single most important organization pushing for damage tolerant design of firstly the airframe, but more recently also parts of the engine and various mechanical systems in the aircraft, see Refs [1, 2, 3]. The Swedish JAS Gripen fighter is also designed based on damage tolerance principles closely following the procedures devised and recommended by the US Air Force. Whereas the overall design concept, both in terms of analytical procedure and the experimental test programme, has been described elsewhere, e.g. Ref. [4], there are certain characteristics of modern generation fighters that need to be considered apart from traditional experiences from older generation fighters. This includes certain flight manoeuvres which in combination with an advanced digital flight control system may cause unexpected impact on the fatigue loading of airframe and systems structure. The importance of such events is emphasized together with a discussion of future changes in operational loading due to the ability of digital flight control systems to improve aircraft performance after the aerodynamic and structural designs are complete.

2 DIGITAL FLIGHT CONTROL SYSTEMS AND LOADS

Modern generation combat aircraft have several features and duties that make individual aircraft tracking even more crucial than before. Multi-role and swing-role capacity will lead to aircraft that will encounter a larger variability in fatigue loading. It is not unlikely that revisions of digital flight control systems will be made during the service lifetime of the aircraft if tactical advantages can be gained. Such revisions can bring both advantages and disadvantages for the airframe structure.

A specific question of concern is the impact a revision of the digital flight control system can have on the operational loading. One of the advantages of a digital flight control system is the ability to improve aircraft performance after the aerodynamic and structural designs are complete. This flexibility of the system will be utilised when tactical advantages can be gained. Such revisions can bring both advantages and disadvantages for the airframe structure in terms of damage tolerance and durability.

Figure 1: Control surfaces on a modern fighter aircraft.

2.1 Load alleviation

The flight control system can for example be used to reduce undesired cyclic loads for structural items that may have encountered more fatigue damage than expected. However, by reducing undesirable loads for one structural part, an increase in the severity of fatigue loading may result at other locations. An example of this is an aircraft with movable canards where changes in pitch control laws may alter the load balance between the canards and the elevons. A reduction of canard loading must be met by an increase of the elevon loading in order to maintain performance and vice versa. In calculations of balancing the aircraft for a sub-sonic flight condition consisting of a pull-up manoeuvre at medium altitude to max load factor with either maximum load on the canard or with a 20% reduced canard load, the torsion moment on the outer and inner elevons increase with about 45%. If such a change in the flight control law is made, it will affect the cyclic loading as well and therefore will have significant impact on the life of several structural parts.

A frequently studied type of structure that suffers from fatigue loading is the attachments of the wing to the fuselage. Such structural parts can either be provided with larger strength margins or be designed for a lower weight if the wing root bending moment can be alleviated. JAS Gripen has such ability through an elevon split mode for load factors higher than 2g below the limit load factor. The elevon split reduces the bending moment at the root by moving the aerodynamic centre of the wing inwards. This is mainly done for static strength reasons but has also a certain effect on the fatigue strength of metallic parts. For composite structures, the load alleviation has a much more pronounced beneficial effect on fatigue strength and damage growth rate since it is the high compressive peak loads that appear to govern the fatigue life performance, [5].

There exist several other possible reasons for flight control law changes than load alleviation. The gust response of the aircraft may for one or another reason need to be alleviated e.g. for aiming purposes. This can be achieved by making the canards more active and responding to the gust executions. This will, on the other hand, generate a more inflated and severe fatigue spectrum.

2.2 Flight control system induced loading

A flight phase which also may increase the severity of the cyclic loading of canards is flying in close formation. The aircraft flying behind another aircraft may encounter turbulent air generated by the lead aircraft. The flight control system will react on this disturbance through small and frequent canard movements. In the left part of figure 2 the measured canard rotation angles are shown for both the lead aircraft (blue curve) and for the aircraft flying immediately behind (red curve).

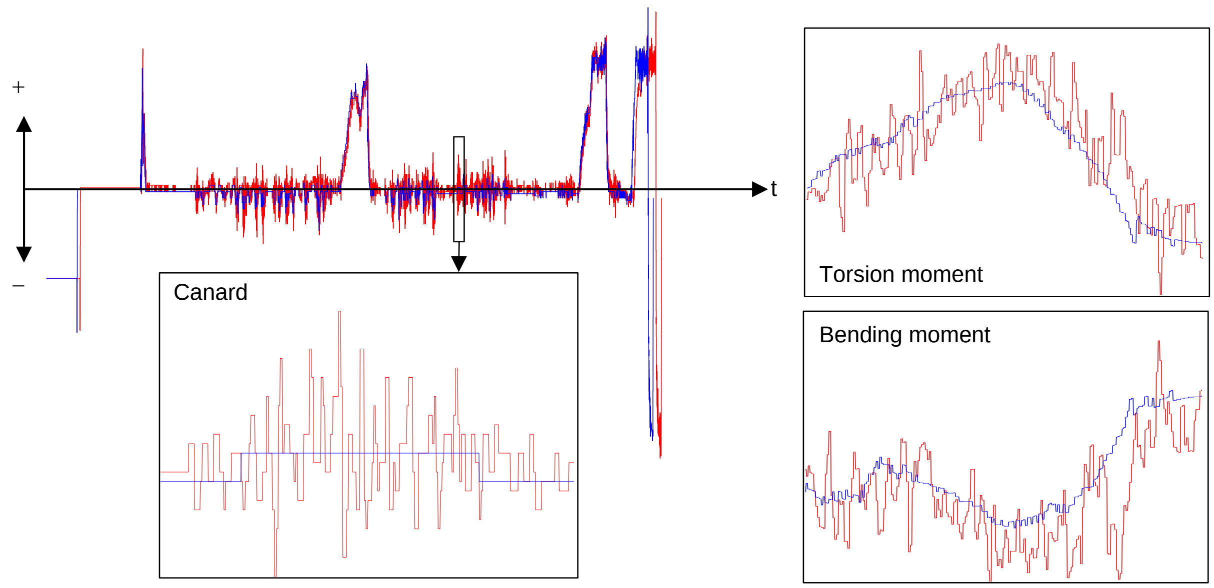

Figure 2: Left part - Canard rotation angles during close formation flying. Right part - Calculated torsion and bending moments in the canard. Blue curves are for lead aircraft and red curves are for the second aircraft

These frequent movements will result in bending and torsion moments in the surrounding structure. The magnitude of the moments depends on several other flight conditions such as speed, altitude, angle of attack, load factor etc. and can be calculated using aerodynamic and flight mechanics models of the aircraft, see the right part of figure 2. The consequence in terms of fatigue life that these load fluctuations have on the airframe depends on the specific design of the canard installation. The canards in JAS Gripen are attached to the fuselage through a pivot axle to an outer and inner beam. The movements of the pivot axle are generated by a duplex servo actuator, see the left part of figure 3.

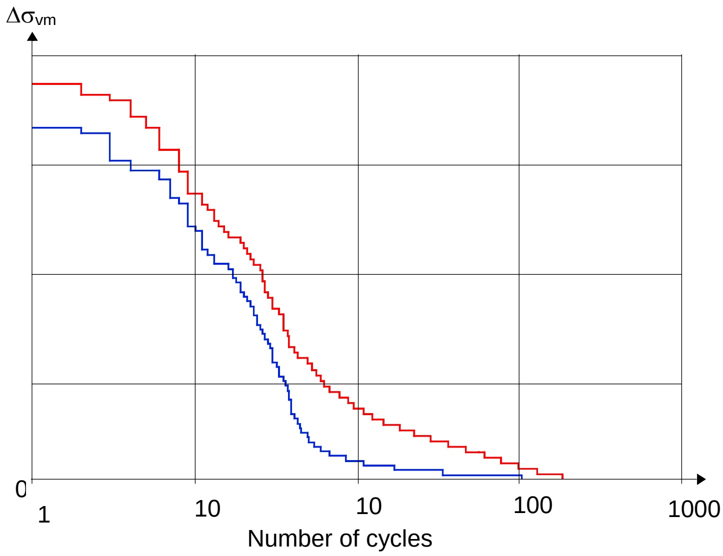

Figure 3: Left part - the pivot for the attachment of the canard. Right part - von Mises stress range spectra. Blue curve is for lead aircraft and red curve is for the second aircraft

The torsion and bending of the pivot axle will generate a biaxial stress state at the surface of the pivot. Bending and torsion moment sequences have been calculated for the complete flight for both lead aircraft and the aircraft flying behind. The von Mises stress on the surface of a round bar is proportional to the torsion moment T and the bending moment M through $\sqrt{4M^2 + 3T^2}$. This relation has been used to calculate stress spectra in terms of von Mises stress for both lead and the second aircraft as compared in the right part of figure 3. The relative life factor, of the canard pivot, between the two aircraft depends on the stress level but is typically 2 at stress levels which should result in a life limitation for a typical fighter design life (the actual stress is far below that level in Gripen).

The operational loading of the canard is also recorded by the loads monitor system through use of strain-gauge bridges. The analysis of the strain signals, both in terms of torsion and bending moment calculations as well as cycle counting according to the rain-flow algorithm, is done on-line during flight. In order to check the effect of close formation flying further, an individual aircraft which has been used in close formation training has been selected. The rain-flow matrix for the torsion moment was extracted from the period of interest as well as the median rain flow matrix for the complete fleet of aircraft for all time. In order to make fatigue tests with these two spectra, reconstructions of the load sequences were necessary. The reconstructions were made using algorithms [6-7] which produce a time sequence which will give exactly the same rain-flow matrix as it was derived from. The testing was done using coupon specimens of aluminium AA7010 and furnished with a central open hole and an electro-spark machined flaw at the edge of the hole. The stress level in the test with the median spectrum was selected to result in a slow crack growth life regime typical for a fighter aircraft, i.e. 10000 flh. The crack growth life of the specimens subjected to the spectrum as obtained from the aircraft flying in close formation training was about 2.3 times shorter, i.e. in the same regime as for the calculated example given above, see results shown in figure 4.

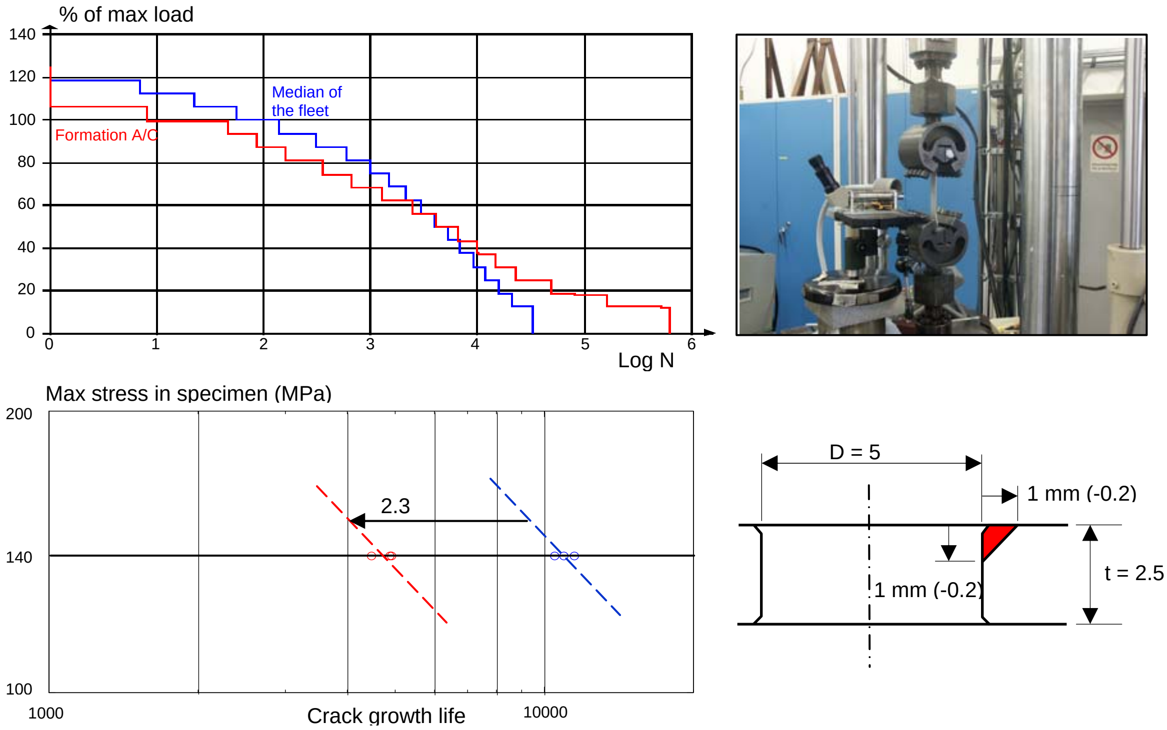

Figure 4: Comparison of crack growth life in fatigue testing using a median spectrum for the fleet (blue curves) and monitored data obtained from an individual aircraft in close formation training (red curves).

Another structural part that is affected in close formation flight is the actuator for the canard control. This actuator induces the canard rotation by acting on the flight control system commands. An actuator for a primary control surface consists of a redundant electro-mechanical control servo, hydraulic tandem actuator and triplex position sensors for the main control valve and the actuator, respectively. This configuration enables the aircraft, after failure detection and reconfiguration, to be flown and landed with one or even two of the primary servos or control surfaces failed.

There are, however, some parts of the actuators that are classified as critical parts, and calls for a damage tolerance assessment, since a failure may cause the control surface to come loose and induce flutter.

A key factor in the damage tolerance analysis is the pressurization spectrum for each of the chambers in the actuators, see figure 5. It has turned out that the pressure pulsations induced by the flight control system are far more damaging than actuator loads for manoeuvring. The most damaging cycles are those which arise from chamber pressure fluctuations due to small control surface movements. An additional complication is present for the duplex servos since "force-fighting" between the two systems can occur.

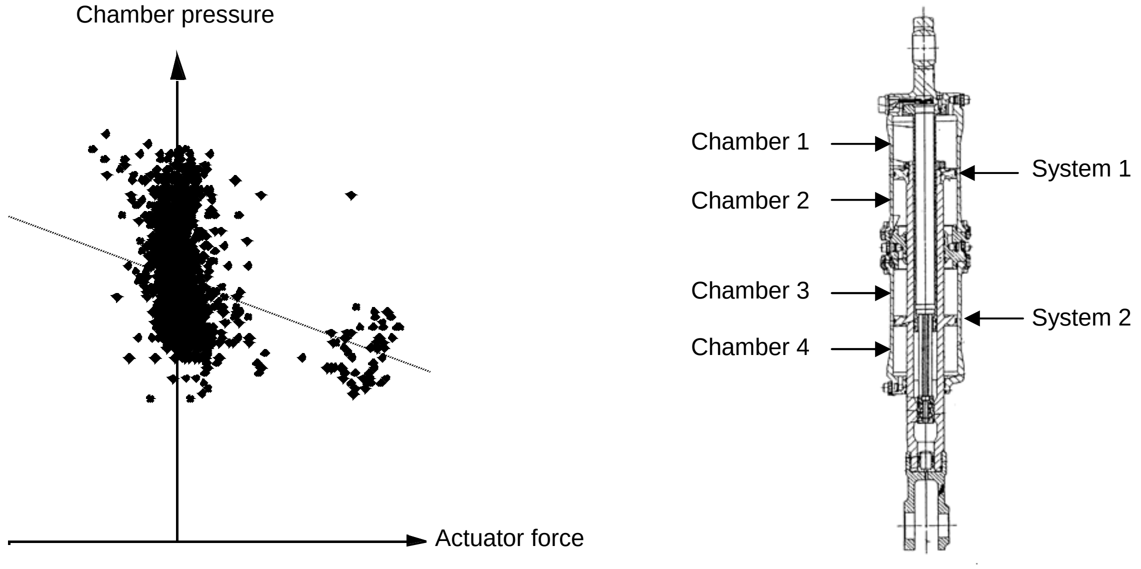

Figure 5: Force-fighting in a duplex servo actuator.

Both the pressure fluctuations and the force-fighting originate from imperfections in the servo valve which control both systems. Valve parameters such as mean pressure, pressure amplification, radial clearance, un-symmetry, combinations of overlap etc. in combination with small sliding movements have a great effect on the pressure fluctuations. Thus, the chambers of the actuators are subjected to large number of low and medium range pressure cycles. These may have a considerable effect on the crack growth rate if they exceed the threshold range.

The aircraft may also need to be manoeuvrable at higher angle of attack than what it initially was designed for. The yaw and pitch control can in such a case be elaborated by differential canard steering which will induce pressure differences on the fuselage. JAS Gripen does not use differential canard control in normal operation but uses the ability in failure situations when the rudder has lost its function. A more frequent use in normal operations will affect the fatigue spectrum of several primary parts, primarily the pivots for the canards and the supporting structure of the pivots.

The same achievement as with differential canards may be obtained with differential controlled air brakes. On JAS Gripen the air brakes work synchronized but can, if needed, increase yaw control effectiveness if controlled differentially.

In the short discussions above, some examples are given of what can be expected to result through pure software revisions of the flight control system. Many more examples can be added if also hardware modifications are considered. In such a situation the possibilities are almost unlimited. One such hardware/software modification can be the introduction of thrust vector control for yaw and pitch. This will of course lead to redesign and reassessment of several structural parts, especially if a new engine is required, but still lots of primary structure will remain the same but realizing quite different fatigue spectra from what they initially were designed for.

3 OTHER LOADING RELATED ASPECTS ON STRUCTURAL FATIGUE LIFE

Every fatigue life assessment effort is founded on an expected future usage of the airframe considered. However, no aircraft will ever operate exactly according to this more or less synthetically derived operational profile. The most straight forward way to overcome this problem and to reduce the uncertainties involved is to monitor the true usage and take appropriate actions during service to maintain safety and improve availability. In spite of the importance of the service monitoring task, the fatigue resistance and damage tolerance capability of the vehicle are however settled and built into the airframe during the design and qualification phases. This makes the operational analysis crucial since load spectrum development, detail structural sizing and the test verification programme will be founded on this prediction. Any actions during service due to monitored deviations from the design conditions must be related to the outcome from the design analyses and test verification programme. If the deviation from the design spectrum is large, the confidence in the rectifying actions might be limited.

The variability in mission and operational profiles that possibly could occur may affect not only the life time for each identified hot-spot but can also alter the ranking of the hot-spots and even initiate new ones. Even though there is only one single operation profile used as the basis for the durability and damage tolerance effort, knowledge of viable variations is of crucial value for the sustainment phase.

The variability in manoeuvring and the development of manoeuvre models can preferably be investigated during the design phase by increased use of flight parameters from flight simulators. Different pilots accomplish manoeuvres differently and statistical significance in manoeuvre models can be obtained from simulations.

In a time of changing political circumstances, new operational needs and altered mission mixes for combat aircraft are likely to emerge. For Sweden this has become very obvious by changing the defence strategy from a force centred on a vast invasion threat over and on the sea during the cold war to something very different today, e.g. joint international peace keeping operations. Such operations may change the tactics and the way of using the aircraft from what it initially was designed for.

A modern generation fighter has also a flight control system which can be used to limit the flight envelope of the aircraft. It is expected that such care-free handling inevitably will lead to more severe flight spectra when pilots more offensively complete manoeuvres at the envelope boundary.

The aircraft may in the future also appear in roles accompanied with one or several unmanned vehicles committed to different duties and guided from the back seat operator in a lead fighter aircraft. How these missions will look like is yet unknown.

Future new armaments may also affect the fatigue life of parts of the aircraft. Weapon pylons, attachments of the pylons to the wing ribs, the ribs themselves and the wing are affected by the weight, stiffness, aerodynamics and release procedure of the stores.

4 CONCLUSIONS

There are certain characteristics of modern generation fighters that need to be considered apart from traditional structural life experiences from older generation fighters. This includes certain flight manoeuvres which in combination with an advanced digital flight control system may cause unexpected impact on the fatigue loading of airframe and systems structure.

There exist several possible reasons for flight control law changes. Load alleviation in order to reduce undesired cyclic loads for structural items that may have encountered more fatigue damage than expected is one such possibility. However, upon such action, it is essential to check for increased stresses in other structural items as result of load alleviation.

It is imperative to realise that the digital flight control system will induce fatigue loads into various structural components during certain flight operations. One example that has been considered in some detail is the resulting stresses in the canard during formation flight. It was shown that a factor of two in relative life of the canard between the lead aircraft and the following aircraft may occur.

Also considered is the pressurization spectrum for each of the chambers in the actuators. It was found that the pressure pulsations induced by the flight control system are much more damaging than actuator loads for manoeuvring.

Finally, it is considered how new tactics and armaments may affect the structural life of the aircraft.

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