In Flight Load Determination in Critical Structure Elements Based on Operational Load Monitoring System

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Abstract

During flight, an aircraft is subjected to a wide spectrum of time-varying loads. In some cases, the influence of those forces could be significant from the structural integrity point of view. Unfortunately, the basic usage profile of the aircraft provided by the manufacturer does not take into account casual exceedances of operational limits, e.g. high g-level manoeuvres or harsh landing. As a consequence, the equivalent usage and flight profiles can be diversified around the aircraft fleet.

The natural way to increase operational safety of both civil and military aircraft is the Individual Aircraft Tracking (IAT) program by means of Operational Load Monitoring System (OLM) implemented on-board. Such a system combines flight parameters from Flight Data Recorders with acceleration and strain/stress data from the structure “hot spots” measured in real time to determine loads and usage factors of an individual aircraft.

The paper presents the implementation of operational load monitoring system for Su-22UM3K combat-trainer aircraft. Twin seated version of Su-22 is more threatened with higher loading spectrum both during flight and landing. The OLM System purpose is to assist their operation and enable controlled and safe utilization within a period of prolonged service life above 3200 flight hours and 6000 landing number. The system collects strain and acceleration data from pre-defined localization on the airframe in real time - bottom and top flanges of wing main spar near the wing main attachment point, main landing gear strut and main landing gear-wing connection point. Sensors are installed symmetrically on both sides of the aircraft to be sensitive for asymmetrical loading as well as redundancy. Data are post-processed and analyzed periodically on the ground station, to reveal operational loads and detect exceedances both in the air and during landings.

In the paper, in-flight data from the OLM system with load determination from typical maneuvers are presented as well as calculation of individual usage and fatigue profiles for each aircraft being monitored is demonstrated.

1. Introduction

The in-service usage monitoring is an important airworthiness requirement to handle safety of the aircraft. Fatigue load spectra is about to change during operational use, especially for the military aircraft, due to different tactical requirements, new missions, advanced aircraft configurations (e.g. higher masses) and different environments [1]. During the last decades the load and usage monitoring has grown from a simple...
The modern approach for aircraft utilization is inseparably connected with the concept of material fatigue. More than 100 years ago, at the beginning of the aviation, hazards associated with material fatigue were poorly recognized. The aviation industry in 1930-1940, when the first fully metal aircraft structures were developed, simply didn’t deal with the material fatigue phenomenon. At that time, planes were designed focusing mainly on the problem of static strength of the structure. In the next years, development of the aircraft structures due to II World War as well as the rapid evolution of public air transportation caused the increased awareness of the phenomenon of material fatigue. From that point, combination of static strength and fatigue life was taken into account during aircraft designing [2].

The development of aircraft design and operation techniques continues to this day, contributing to the increase of safety and extending the life of aircraft. Unfortunately, the main „milestones” in consciousness regarding the phenomenon of structural fatigue, occurred after fatal aircraft crashes, e.g. De Havilland Comet in1954, F-111 in 1969, Boeing 707 in 1977 and Boeing 737 in 1988 [3].

The rational use of an aircraft, i.e. use in accordance with its tactical and technical characteristics, is possible only in the case of functioning operating system which ensure the optimization of aircraft usage. The quality of the operating system is mainly determined by the maintenance and repair methods as they contain a set of regulations specifying the scope and frequency of service, control the level of reliability and technical condition of the aircraft [4], [5]. Regarding the above, Individual Aircraft Tracking (IAT) with use of Operational Load Monitoring (OLM) system is essential to ensure the implementation of the maintenance and utilization strategy. Moreover, the OLM also allow to use of usually significant functional potential for the ageing aircraft, which, after performing the necessary renovation, will allow their further operation according to the technical condition [6], [7].

The Su-22 „Fitter” aircraft has been in service in Poland since the 1970s. More than 100 Su-22 aircraft were in use in the Polish Air Force in two variants: Su-22M4 combat version and the Su-22UM3K twin-seat trainer. In 2014 Polish Air Force have decided to continue the operation of the ageing Su-22 “Fitter” fighter-bomber. Modernization program connected with verification overhaul aimed for service life extension for the Su-22 was performed.

2. OLM System Implementation

2.1 The initial phase

Operational resurs set by the manufacturer is most often based on fatigue tests and refers to the anticipated load spectrum, i.e. the "average" aircraft operation process. The operational (real) load spectrum differs significantly from the spectrum adopted by the constructor during the determination of a service life due to training program differences or performing various missions by a single aircraft version. The life extension program for the Su-22 „Fitter” aircraft includes flight tests, a Full Scale Durability Test (FSDT), and operational loads monitoring (OLM) and is focused on the double-seater version of the „Fitter”. The trainers are of special interest because
they accumulate significantly more landing - take-off cycles in their lifetime than the combat variant [8].

Flight tests had the purpose of quantifying the flight loads in high g-force manoeuvres with a symmetrical character such a loop or dive exit and to obtain general information about the structural response of the airframe during flight manoeuvres. The quantified loads serve as an input for usage profile calculations. During the tests 10 flights with a total duration of 8 hours were performed. In total 25 landings (including 15 touch-and-go landings) were performed, with varying recorded g-forces.

The results from flight tests and detailed calculation of the load distribution have served as a basis for the FSDT load sequence. The test was carried out on an taken out of service aircraft, equipped with the same set of sensors as during flight test for comparison purposes. Loads were exerted on the structure by means of hydraulic actuators which number varied between stages of the test. Flight and landing loads were exerted by means of actuators mounted to the wings and landing gear, while seven actuators underneath the fuselage (from front landing gear to horizontal stabilizer) allowed to distribute reaction forces. Loads on the fixed bulkheads No 4 and 34 were also monitored throughout the test by means of load cells.

The results of the test have proven, that the Su-22 aircraft structure is capable to be operated with the desired flight profile 800 Flight Hours after the verification overhaul. The results of the test were moreover used to define Individual Aircraft Tracking (IAT) program, based on vertical overload recorded by Flight Data Recorders for combat version, and permanently installed OLM for twin-seated trainer Su-22UM3K aircraft operated in Polish Air Force.

2.2 Design of the OLM System for Su-22UM3K Aircraft

After the initial phase end, the Operational Load Monitoring System (figure 1) was implemented on-board of six Su-22UM3K combat-trainer aircrafts during their overhauling with stain gauges and 3-axis accelerometer sensor network installed and connected. The OLM System purpose has been to assist twin-seated Su-22UM3K operation and enable their controlled and safe operation within a period of prolonged service life above 3200 flight hours and 6000 landing number.

![Figure 1. Block diagram of the OLM](image-url)
The heart of the system element is airborne multi-role recorder with integrated data acquisition. It controls signal acquisition and archiving from permanently bonded strain gauges sensor network and MEMS accelerometer [9]. Data recorder is equipped with adequate analogue and digital user modules to acquire data from 8 strain gauges, 11 parameters from Built-in Test for supervising the operation of the device, 13 GPS parameters and 3-axis accelerometer. One user slot is filled with dummy module presently, and is ready to use in the future upgrade for chosen type of sensor and measurement task, as the recorder has a modular architecture and can be reconfigured as needed. MT-1 is a custom-made and certified additional unit for strain gauges bridge complementation as well as for shunt calibration of strain gauge measuring channels. DC-DC converter is implemented to stabilize voltage from on-board dc power supply to prevent under- or overvoltage during powering on other installed equipment.

The main data source for OLM is integrated network of 8 strain gauges, mounted on predefined structural “hot spots” for monitoring the operational loading both during flight and landing to determine load exceeds e.g. harsh landing. Wide bandwidth accelerometer is used for load determination in three mutually perpendicular axis nx, ny and nz. Additionally, parameters like power-up and time-on counter, internal voltage values on buses for e.g. sensor excitation and digital components, error counter, chassis and internal temperature and chassis status as well as GPS navigation data are acquired.

2.3 Location of the OLM System Elements

The main data source for OLM is integrated network of 8 strain gauges, mounted on predefined structural “hot spots” for monitoring the operational loading both during flight and landing and 3-axis accelerometer for load determination (figure 3).
A pair of strain gauges (T1 and T2 on the LH side, T5 and T6 on the RH side) are bonded on bottom and top flanges of wing main spar, near the wing main attachment point. Measurement from those channels are used during flight to determine loading in certain manoeuvres and aircraft configuration. For exceedance during landings, one sensor is installed on main landing gear strut (LH side – T3, RH side T7) to measure longitudinal loads, and second sensor (LH side – T4, RH side T8) is bonded on the gear-wing connection to measure lateral loads. Sensors are installed symmetrically on both sides of the aircraft to be sensitive for asymmetrical loading as well as for redundancy. Accelerometer is used for load determination in three mutually perpendicular axis nx, ny and nz. It’s located near the centre of gravity point on the top of the fuselage.

Main components like DAQ SSR-500, MT-1 and DC-DC converter are located on the top of first technical hatch of the aircraft.

3. In-flight load determination

In a basic approach, each flight consists of start, flight with manoeuvres and landing. Due to the design assumptions, the OLM sensors are mainly subjected to compressive loads during operation. In this case, there is no risk of fatigue or static damage by direct tearing of the monitored elements. However, these records provide indirect information about the overall load level in the structure. The characteristic load features during the flight are shown in the diagrams on figure 3.

Figure 3. Loads from strain gauges T1 and T4 during typical parts of the flight
The outlined characteristic parts of the flight are:
- A – aircraft start;
- B – flight with significant changes in vertical overload $nz$;
- C – circles above the runway and Touch&Go landings;
- D – full stop landing.

The figure 3 shows changes on T1 (LH side top flange of main spar) and T4 (LH side main landing gear - wing connection point). It can be seen, that particular flight phases are easily distinguishable even only by strain gauges. Correlation and synchronization of the data from OLM and on-board data recorder give enough information for individual tracking of a particular aircraft.

3.1 Start of the aircraft

During start, main parameters with should be monitored are velocity and strain gauges on the main landing gear (figure 4).

![Figure 4. OLM parameters during start of the aircraft](image)

On the diagram data from landing gear strain gauges are drawn as well as GPS velocity. The first stage of the start is speeding up on the runway, where strain on the main landing gear is dynamically variable and increase its value due to lifting force appearance. In the second stage, the speed is high enough to detach from the ground – strain become stable due to hanging of the main landing gear. In the third outlined area the process of closing the main landing gear is performed. When the gear is fully closed (4) the pilot sets up the control switch to “neutral” position, the hydraulic actuator decrease the pressure, and the gear strut is hanging freely and secured in the bay (step strain value reduction).

The significant parameters for operational use of the aircraft, which can be obtained from that part are: time of acceleration, detachment speed, speed during closing the landing gear, proper control of hydraulic actuators.
3.2 Landing of the aircraft

During landing, main parameters with should be monitored are also velocity and strain gauges on the main landing gear (figure 5).

![Figure 5. OLM parameters during landing with full stop of the aircraft](image)

On the diagram data from landing gear strain gauges are drawn as well as GPS velocity. At the beginning of the landing, the pilot opens the landing gear, which can be easily found on strain readings. First outlined area is the flight with the gear opened, decreasing speed and altitude. In the second stage there is a touchdown followed by landing roll with braking (3).

The significant parameters for operational use of the aircraft, which can be obtained from that part are: speed during opening the landing gear, touchdown speed, touchdown g-level, maximum peak-to-peak strain value during touchdown. Based on OLM data, one should be able to detect e.g. harsh or asymmetric landing and quantify its influence on the aircraft usage.

3.3 Low pass with open landing gear

Low pass with open landing gear is a manoeuvres simulating the touch & go or landing, but is performed without a contact with the runway (figure 6).

![Figure 6. OLM parameters during low pass of the aircraft with landing gear opened](image)
The first stage is a flight with landing gear closed. During the second stage, opening of the landing gear can be noticed as well as the flight with altitude reduction to the minimum. After that there is a sudden increase of the altitude. The landing gear is closed and the aircraft can start to perform other tasks. The set of significant parameters for operational use of the aircraft is synthesis of start and landing monitored values.

3.4 In-flight exceedance

The main „added value” of having OLM system implemented on-board of the aircraft is the ability to detect exceedances of operational use both during flight and landing. Those exceedances can have a meaningful influence on fatigue parameters, like fatigue usage, operational intensity factor and equivalent-to-real flight hours ratio. An example is illustrated on figures 7.

Figure 7. An example of usage exceedance detected by OLM during flight.
On the top diagram there are strain signals from both sides of main spar and the GPS velocity, on the bottom 3 axis accelerations and calculated Mach number. The exceedance during leaving the fall manoeuvre with a very high speed. The acceleration nz exceeded 6 g, and peak-to-peak strain was around 1500 uStr for both top and bottom flange of the spar reaching to the operational limit threshold.

4. Conclusions

Operational load monitoring is a next step toward operational usage optimization of the aircraft. The need for an accurate and reliable fatigue usage monitoring system is in increasing importance to ensure the safe and economical utilisation of aircraft. Especially regarding ageing aircraft, which are now expected to last much longer than first envisaged. Strain based in-flight data recorders are perceived to provide more accuracy over the conventional fatigue g meter, and have thus been implemented worldwide by many military fleet operators [10]. The individual tracking of usage parameters, like fatigue usage, operational intensity and equivalent-to-real flight hours can be performer for separate aircraft as well as detecting the operational exceedances and quantifying their influence on aircraft durability. As far as a fleet of Su-22UM3K is concerned, OLM implementation took effect into decrease in total number of exceed appearance. Also good correlation between strain data from main spar and vertical acceleration nz was observed. Additional parameters during start and landing can be calculated or measured with greater accuracy. All that produce a desired result in better utilization of a whole fleet due to efficient mission planning for each aircraft.

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