FLIGHT LOADS AND CUMULATIVE FATIQUE DAMAGES MONITORING FOR EACH AIRCRAFT DURING SERVICE LIFE

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Keywords: variable loads, cumulative fatigue damage, flight parameters, flight data recorder (FDR).

Abstract: The main purpose of this paper is the development of analytical-experimental algorithms based on FDR data to recover variable flight loads with optimal accuracy. This makes it possible to create automatic system for operational flight loads control and consumption of structure service life. In this case, the dependence of variable loads on the load factor in center of gravity (CG) is of statistical nature. Steady-state loads are recovered on the basis of flight parameters. The accuracy of this method is shown. The quality of monitoring is acceptable if numerous flights are processed and is comparable with accuracy of direct stress measurements. It is demonstrated that accuracy improvement can be done by increase of the sampling rate of FDR parameters.

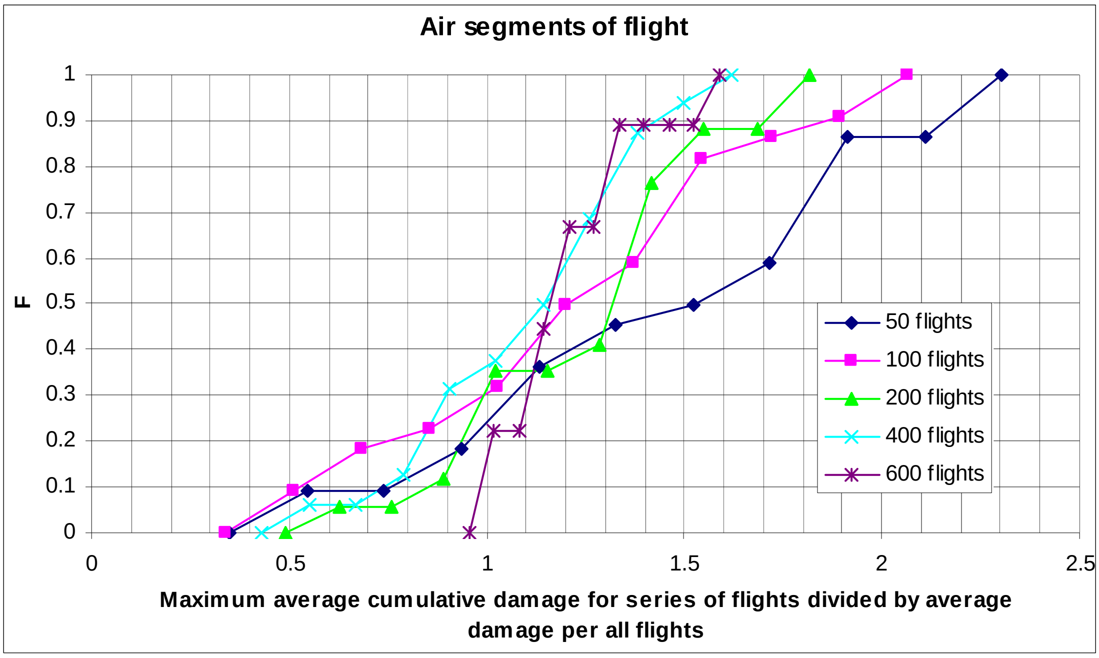
1 INTRODUCTION

The paper is devoted to the problem of creating system for acquisition and analysis of flight data using modern possibilities of recording, processing and transferring in-flight data. Development of methods and means for monitoring of variable loads in service, acquisition and analysis of relevant statistics is the necessary condition to increase aircraft operation safety concerning structural strength. The processing of vertical load factors registered by emergency flight recorders has been performed for 27 Yakovlev-42 type aircraft of four airlines based in the airports of Samara, Donetsk, Krasnodar and Kazan. The total number of flights is 15,000. The statistical researches were carried out for cumulative fatigue damages caused by vertical overload and for extreme values of overload. Air and ground stages were considered in each flight. The variation of the cumulative fatigue damages for different flights series is shown in Figure 1 (the *S-N* curve of metal structure with power m=4 was used).

Analysis of such information demonstrates:

- Scattering between individual aircraft generally depends on airlines (geographical location, routes, roughness of runways);
- Scattering is getting stabilized when number of flights is over 600 provided by a regular operation throughout a year;

- cumulative fatigue damage of an airframe and landing gears per ground stages of flight can vary significantly if airlines are based in different airports, causes the need for which monitoring.



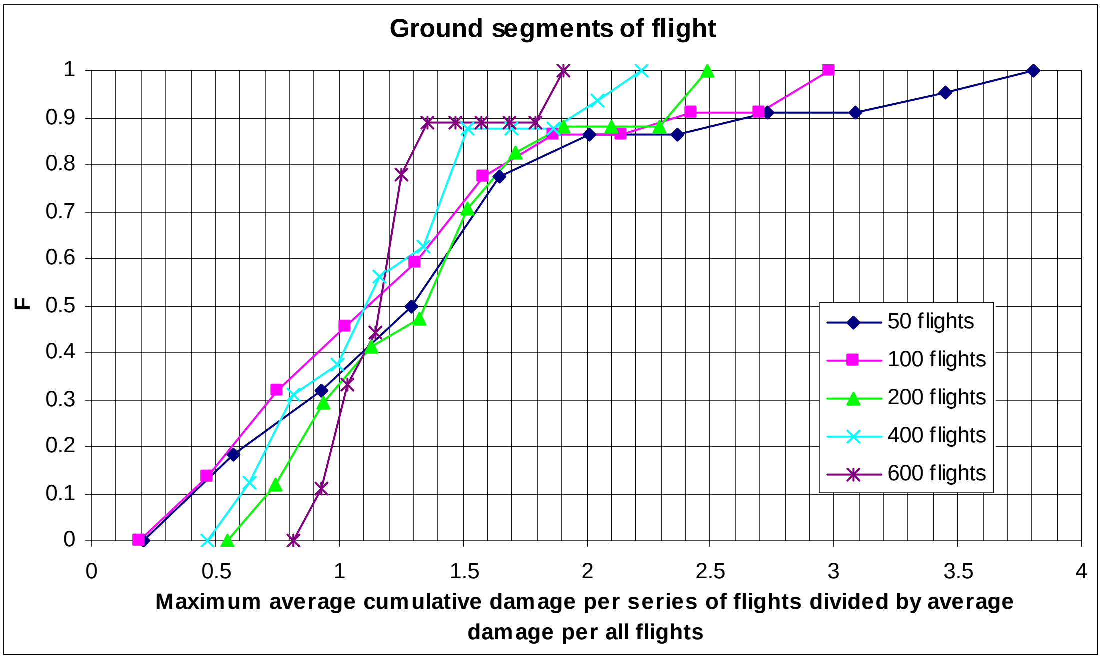


Figure 1 Cumulative distribution curve of relative maximum damage for different flight series

Scattering between different individual aircraft and scattering by different flight time should be taken into account to validate the maintenance schedule at different crack growth rate (for example, if crack propagation is high and critical size is small, inspections of the structure should be more frequent, so we have to estimate the aircraft that is under the hardest conditions between inspections).

The estimation of scattering of cumulative fatigue damage for composite structure was done in accordance with the present knowledge of fatigue accumulation in composite materials.

Statistics of vertical load factors exceedance rate per air and ground stages of Yakovlev-42 aircraft service were used for these purposes. Load factors have been converted into plane stresses of upper and lower wing panels using steady-state loads of a Russian aircraft is being designed in present time.

Table 1 consists of recommended factors of reliability η_3 which describe individual loading scattering (Method of compliance 25.571).

	Air					Ground				
Number of flights	50	100	200	400	≥ 600	50	100	200	400	≥ 600
η_3 metal	2.7	2.5	2.2	2.1	2	4.2	3.4	2.9	2.6	2.3
η_3 composite	14	9	7	5	4	14	9	7	5	4

Table 1: Factors of reliability for individual loading dispersion

So it follows that realization of monitoring can increase the service life of the fleet at least twice as much.

The main purpose of this paper is development of optimal analytical-experimental algorithm to recover variable loads, based on FDR data. This makes it possible to create an automatic system to check operational flight loads and consumption of structure service life. Cumulative fatigue damage is estimated by analyses according to standard techniques. The control staff of airlines performs processing when aircraft returns to the baseline airport using software included in standard flight control or by onboard PC after the flight.

The structure of the monitoring system:

- Standard emergency, and Quick Access FDR:
    - recording main flight parameters as time functions: aircraft weight, fuel weight, load factors, angular velocity, altitude, speed, Mach number, rudder angles, thrust and other.
- Automatic processing after flight:
    - Recovering variable loads using analytical-experimental algorithms;
    - processing of load time sequences and calculation of relative cumulative damages of aircraft structure and landing gears (as part of cumulative damages per typical flight used in ground fatigue tests) for this specific flight;
    - Survey of total fatigue consumption of aircraft structure and landing gears.

A sample list of main procedures to develop a monitoring system for mid-range airplane is shown below:

1. identifying and screening of drop-outs and recovery of information (for all parameters and the types of drop-outs);

2. control of "zeros" of all parameters in the air and on the ground;
3. distinguishing of flight stages
4. development of algorithm; recovering variable loads (mean and peak values, accumulated fatigue damages) for:
    a. wing: bending moment for upper and lower panels in 6 cross sections;
    b. engines: vertical, lateral and longitudinal forces, yaw and pitch moments;
    c. landing gear: vertical, lateral and longitudinal forces for main and nose landing gears;
5. documentation development for special maintenance cases;
6. estimation of frequencies of load factors and rudder angles per flight stages.

2 APPLICABLE APPROACHES FOR MONITORING IMPLEMENTATION

Spectral, correlation and regression analyses of strain gauge measurements during flight tests are demonstrated, these statistical dependences between loads and load factors for main flight stages are sufficient for variable loads monitoring (fatigue damages accumulation). In general, correlation between loads increments and overloads for main flight stages is significant only in certain frequency range. Variable loads which are critical for aircraft fatigue are located in frequency range from 0 Hz to 10 Hz. Emergency FDR of Yakovlev-42 type aircraft record load factors 8 times per second, this sampling rate is insufficient for monitoring purposes.

The algorithms of cumulative fatigue damages evaluation caused by forces and moments in different sections of an aircraft use statistical dependences of loads on vibrations intensity (mean square value off load factors) and on vibrations duration (cumulative fatigue damages caused by load factors). Steady-state loads are recovered using recorded flight parameters. Sampling rate of FDR is sufficient for steady-state loads but it isn't sufficient for dynamic increments of loads. Frequency of variable loads (cumulative damage) per flight stages is calculated with some error due to statistical evaluation. This error decreases if number of flights grows. The load extremes are used to form load cycles. Cumulative damage is calculated using full cycles method, linear summation, power relation for S-N curve (dependencies are given below for metal structure with power 4).

3 EXAMPLES OF DEPENDENCE USED IN THE MONITORING OF CUMULATIVE FATIGUE DAMAGE AND EXTREME LOADS

Dependencies are given as a result of flight tests of two modern aircrafts: a passenger and an amphibious (used in fire fighting mission). The loading of lower and upper wing panels in 6 cross sections, forces and moments in engines CG (on pylons under wing), forces on main and nose landing gears are taken into account for the passenger aircraft. Bending moments of a wing and a fuselage, forces in engines CG are considered for an amphibious aircraft.

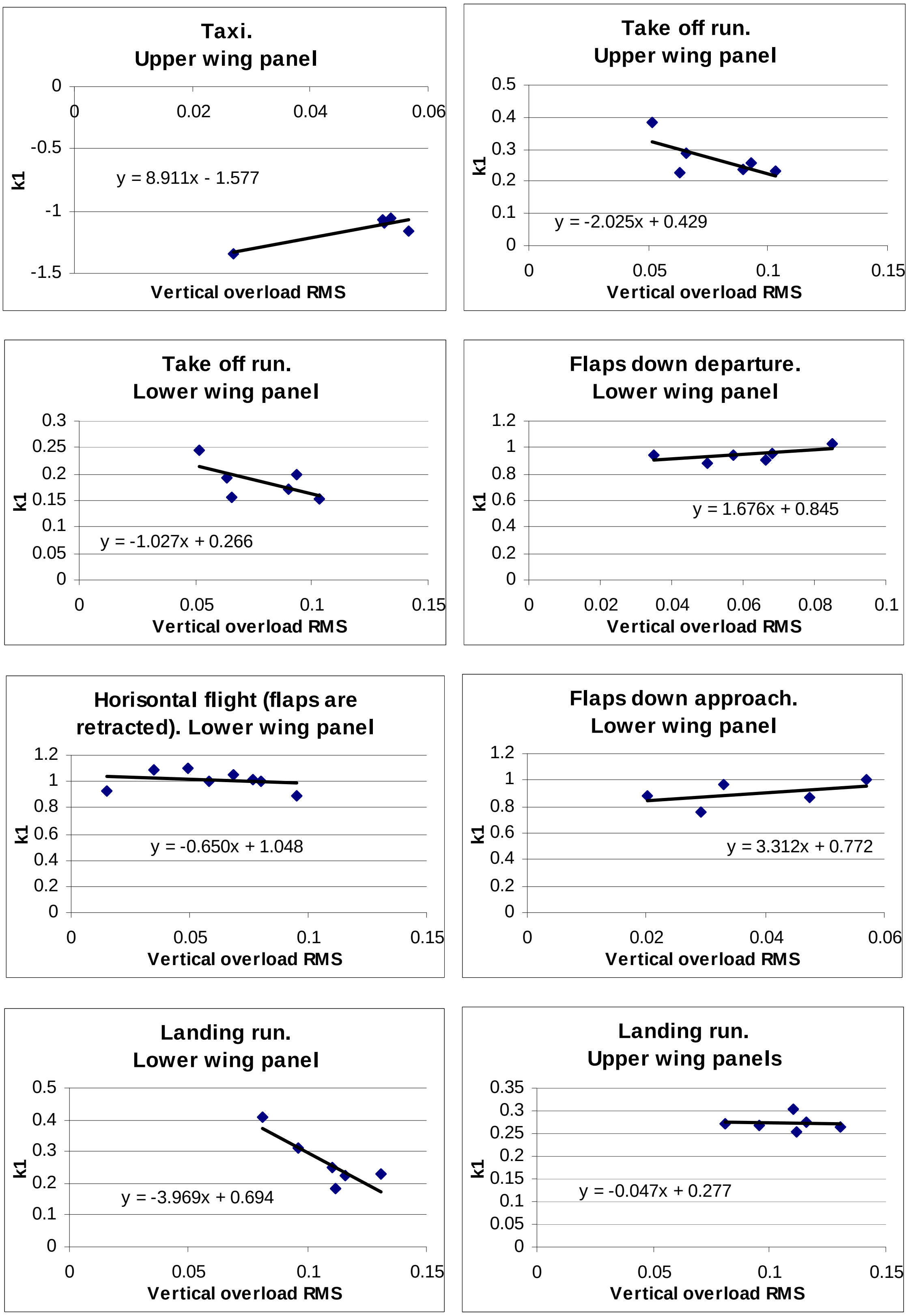


Figure 2: Example of statistical dependence for equivalent load

Figure 2 shows example of recovered cumulative fatigue damages caused by bending moment in one cross section of a wing of passenger aircraft (RMS – root mean square value). Factor k1 was calculated for each flight stage as:

$$k1 = \frac{M_{bend}^{eq}}{M_{bend}^{aver} \cdot n_y^{eq}},$$

where M_{bend}^{eq} – equivalent bending moment per flight stage;

M_{bend}^{aver} – average bending moment per flight stage;

n_z^{eq} – equivalent vertical overload per flight stage.

Equivalent load is a maximum of «zero-tension-zero» cycle, which gives cumulative fatigue damage equal to fatigue damage per flight stage caused by initial load.

Figure 3 represents the dependences of maximum and minimum values of wing bending moment in one cross section of the wing on maximum and minimum values of vertical load factor in aircraft CG. Factors $k2$ and $k3$ are the maximum and minimum values of bending moment for some flight stage divided by the average moment.

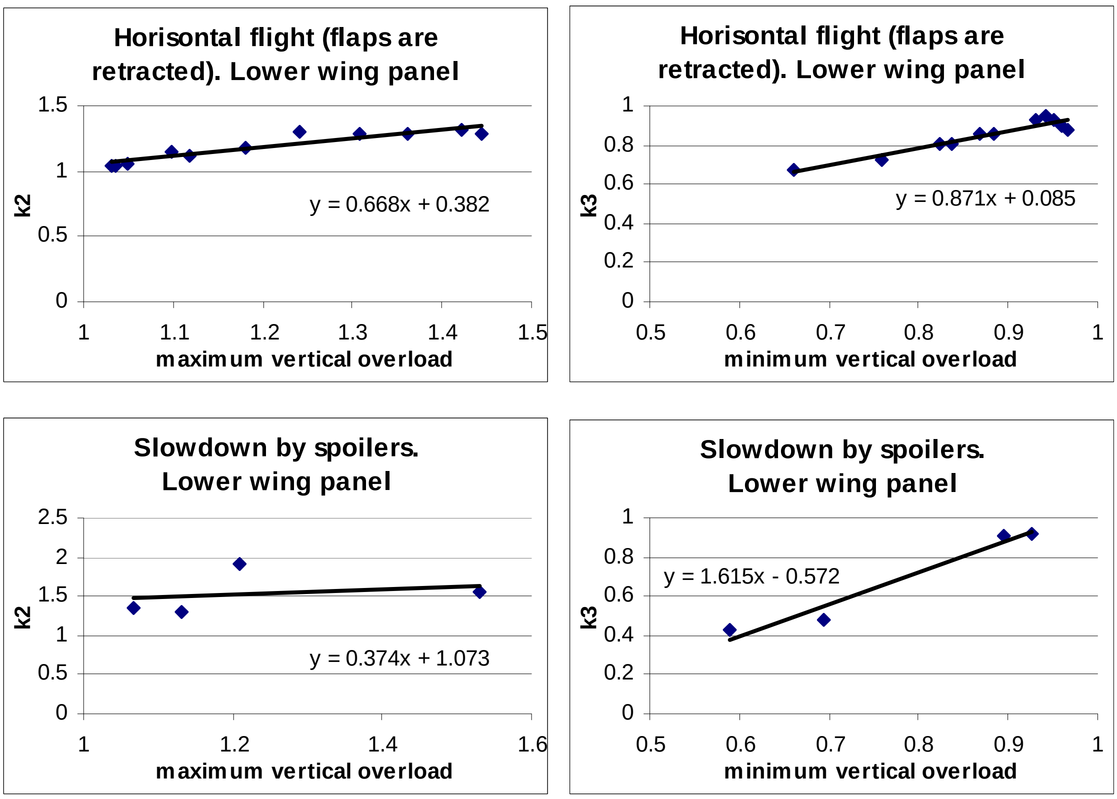


Figure 3: Definition of maximum and minimum loads in flight stage

Figures 4–5 demonstrate examples of dependences to estimate the cumulative fatigue damages of the amphibious aircraft for such flight stages as «water scooping» and «water discharge». Factor $k4$ is the equivalent load divided by equivalent vertical overload. The following loads are given: bending moments in one cross section of the wing and the fuselage, vertical and lateral acceleration forces in the engines CG.

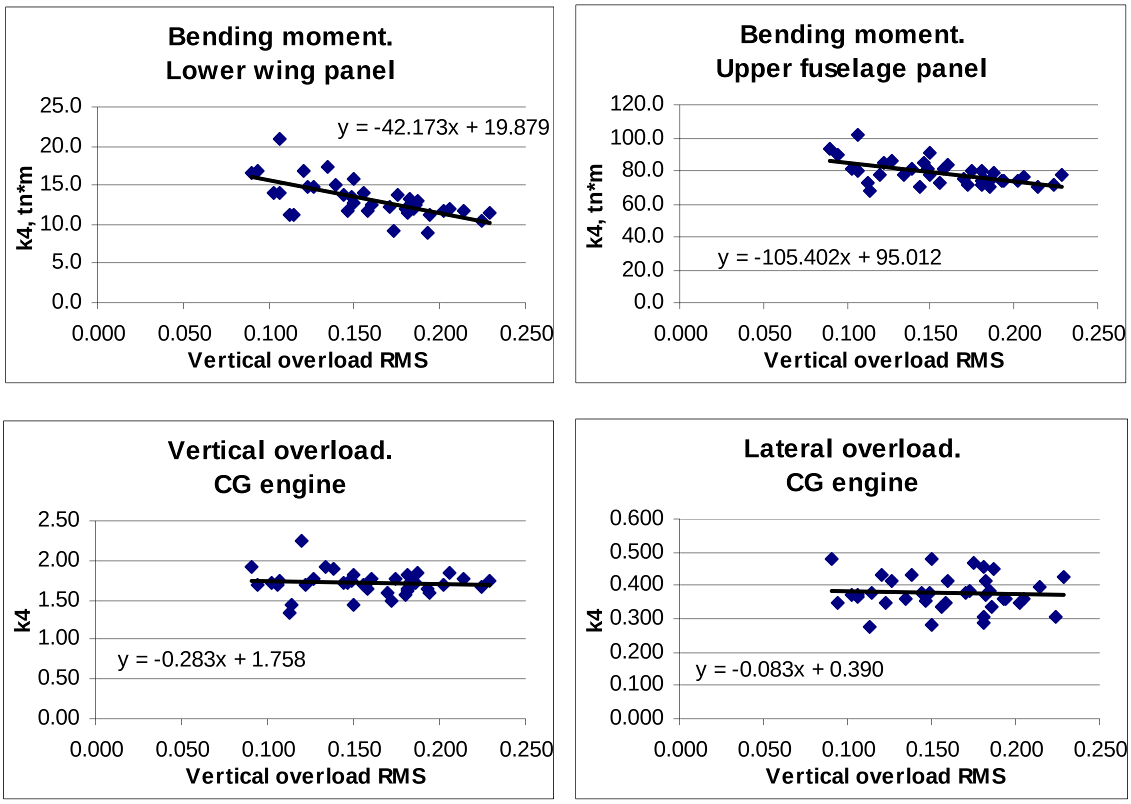


Figure 4: Recovering of equivalent loading during water scooping

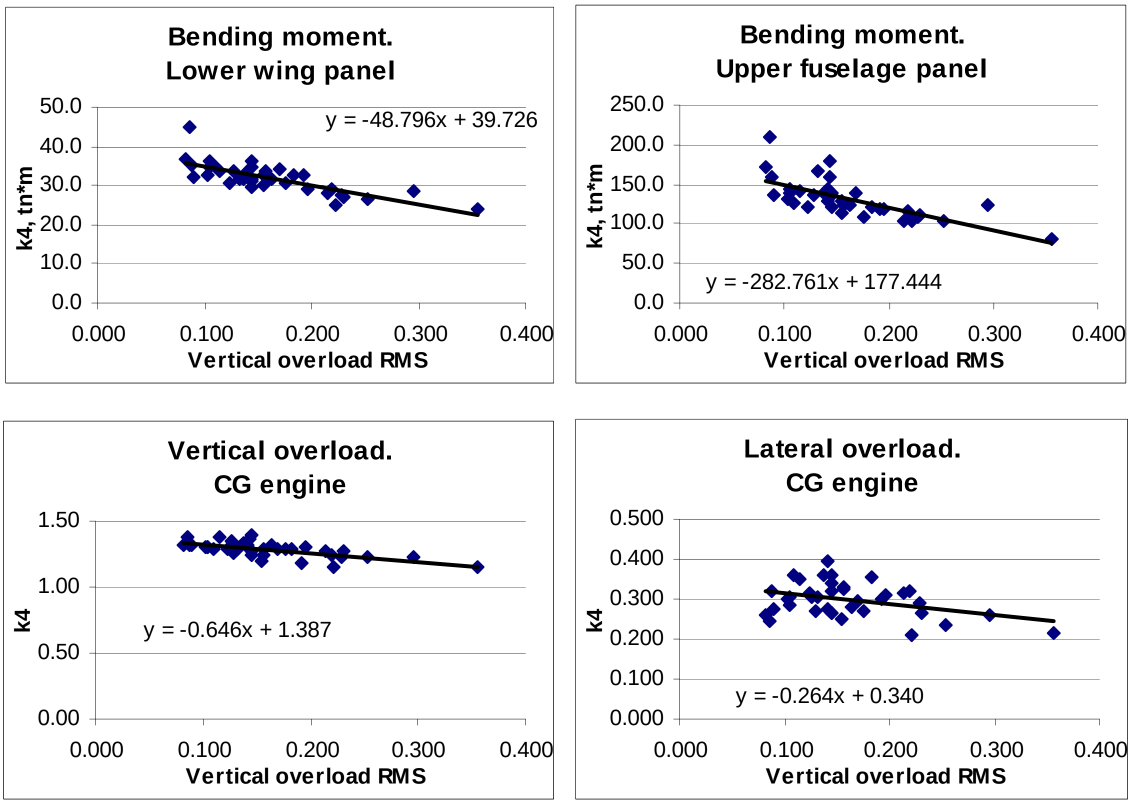


Figure 5: Recovering of equivalent loading during water discharge

4 THE EFFECT OF SAMPLING RATE ON RECOVERING OF ACCUMULATED FATIGUE DAMAGE

One of the disadvantages of modern FDR is the low sampling frequency of the flight parameters. It is insufficient for investigation of flight accidents too. Flight test data show that atmospheric turbulence can cause 6g per second of overload gradient. 8 times per second sampling rate is, of course, too low. During hard landing these gradients can be even higher. Researches demonstrate that 8 times per second sampling rate is enough for recovery of average loads and its RMS values, but it isn't enough for recovery of accumulated fatigue damages caused by variable loads. As an example, figure 6 shows dependences of CG vertical load factors RMS on sampling rate. The data were acquired during horizontal flight (flaps were retracted). Appreciable turbulence was registered in 3 different flights. It follows from this Figure that RMS value doesn't depend on sampling rate.

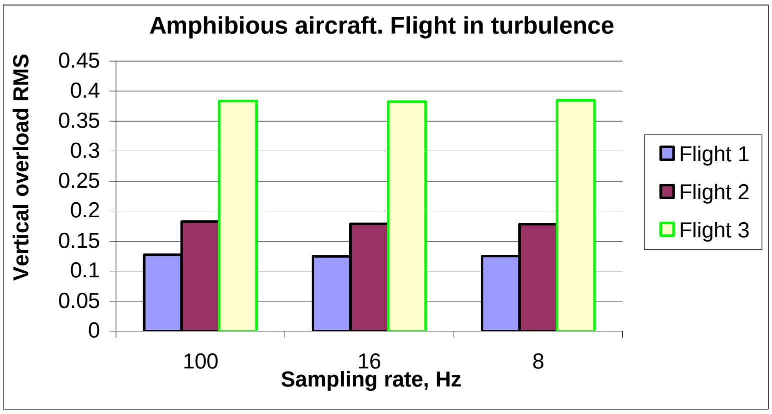


Figure 6: Influence of sampling rate on vertical overload RMS

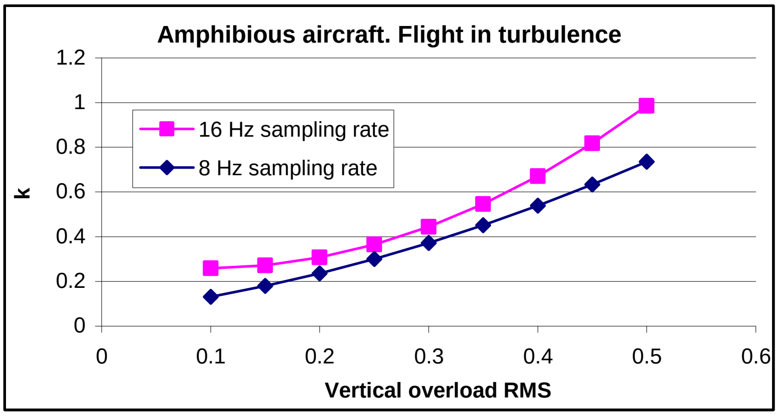


Figure 7: Influence of sampling rate and turbulence intensity on cumulative fatigue damage caused by vertical overload

However, for this flight stage sampling rate significantly influence on the value of cumulative fatigue damage caused by vertical load factor (Fig.7). *k* factor is damage calculated for certain sampling rate divided by damage when sampling rate is 100 Hz. The influence of sampling rate is significant for the ground stage also (Fig.8). In this case sampling rate was 128 Hz. This fact demonstrates that correcting factors should be used due to low sampling rate of FDR parameters. The increase of sampling rate of main FDR parameters will cancel the statistical approach in monitoring and will improve the accuracy of recovering of variable loads repeatability.

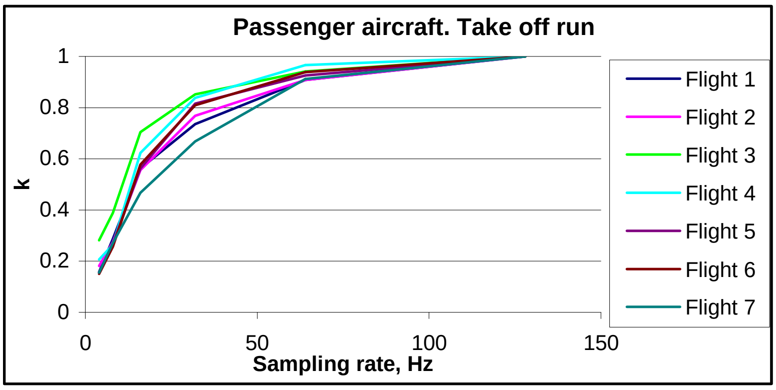


Figure 8: Influence of sampling rate on cumulative damage caused by vertical load factor (take off run)

5 RECOVERING THE ENGINE THRUST

Thrust is calculated analytically thru rotor revolution per minute (N), Mach number (M) and flight altitude (H). Figure 9 shows comparisons between measured thrust and calculated thrust for some flight stages.

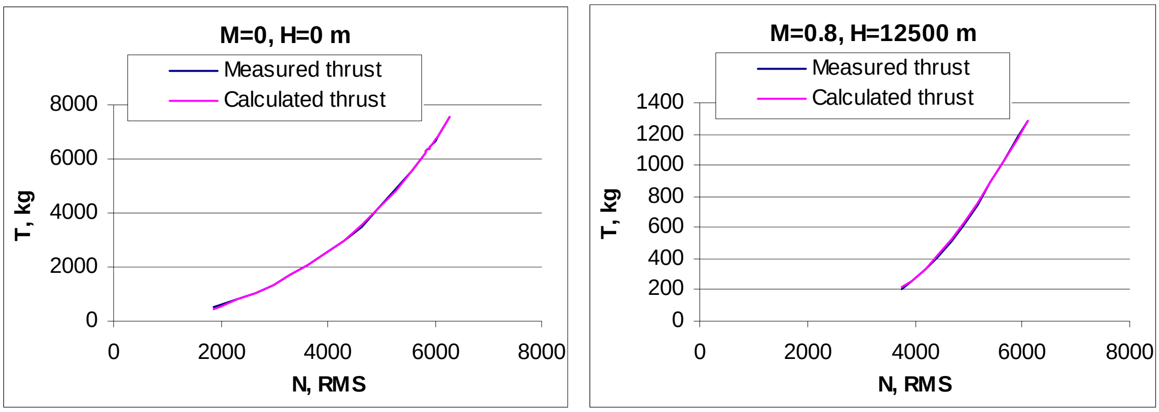


Figure 9: Restoration of the engine thrust

6 MONITORING ACCURACY

It is desirable to research the accuracy of the monitoring of variable loads and accumulated fatigue damages using the strain measurements of a whole flight (beginning from engines start till their stop). Table 2 demonstrates an example of an estimation of the monitoring system accuracy of the amphibious aircraft (M_{equiv} – equivalent bending moment per one flight, FTI – flight test instrumentation, loads acquisition during whole flight; Fatigue – calculations according to algorithms; 6 – fire flight mission; 1 – cargo mission; 7 – training mission). The Table 2 demonstrates that accuracy of total accumulated damages definition will increase if number of processed flights grows. Factor k –is the cumulative damage per all previous flights recovered by monitoring system divided by cumulative damage measured by FTI. Calculated damages of 10 flights differ from measured damages approximately by 12% above for wing cross section and by 3% below for fuselage cross section. The most heavy flight differs from the most light flight approximately by 67 times in terms of fatigue damage.

№	Flight type	Root section of the wing			Middle part of fuselage		
		FTI, M_{equiv}, tn*m	Fatigue, M_{equiv}, tn*m	k	FTI, M_{equiv}, tn*m	Fatigue, M_{equiv}, tn*m	k
1	6	330.6	355.0	1.330			
2	6	222.7	255.7	1.399	270.4	299.5	1.51
3	1	174.6	179.3	1.382			
4	6	271.6	276.9	1.303	307.8	287.1	1.04
5	6	307.8	310.9	1.224	300.4	293.9	0.99
6	6	342.0	340.1	1.146	315.2	316.4	1.00
7	1	151.9	151.7	1.145	211.5	213.7	1.00
8	1	140.9	143.5	1.144	192.2	174.5	0.99
9	1	211.4	190.9	1.123			
10	7	126.4	123.9	1.122	227.5	205.3	0.97

Table 2: Influence of flights number on total cumulative damages

7 LOADING OF HORIZONTAL STABILIZER AND STABILIZER ACTUATOR (POSSIBILITY OF IMPROVEMENT OF MONITORING ACCURACY)

Horizontal stabilizer (HS) is the most difficult part for loads monitoring because it is influenced by flow downstream the wing (extracting of slats, flaps, spoilers and vibrations). Fig.10 shows some time histories of shear force in root section of HS measured in test flights (Q_tens) and analytically calculated using FDR parameters (Q_calc) during some significant stages of flight. Theoretical dependences for aerodynamic forces were used in calculations and correction of aerodynamic derivatives according to flight tests was made. The sampling rate of strain measures and FDR parameters is 64 Hz. The example of recovering of the force (S) on stabilizer actuator is also given in this Figure.

Fig.10 demonstrates good results for steady-state loads (there is a possibility to improve the accuracy for these loads in the case of non-symmetrical flow on left and right parts) and for dynamic loading too. In the case of low sampling rate the cumulative damages are calculated with some statistical error in each flight which is decreased with growth of number of processed flights. So, increasing of sampling rate of main parameters acquisition will help to avoid the statistical dependencies in the monitoring system and will increase the accuracy of restoring of cumulative damages in each flight.

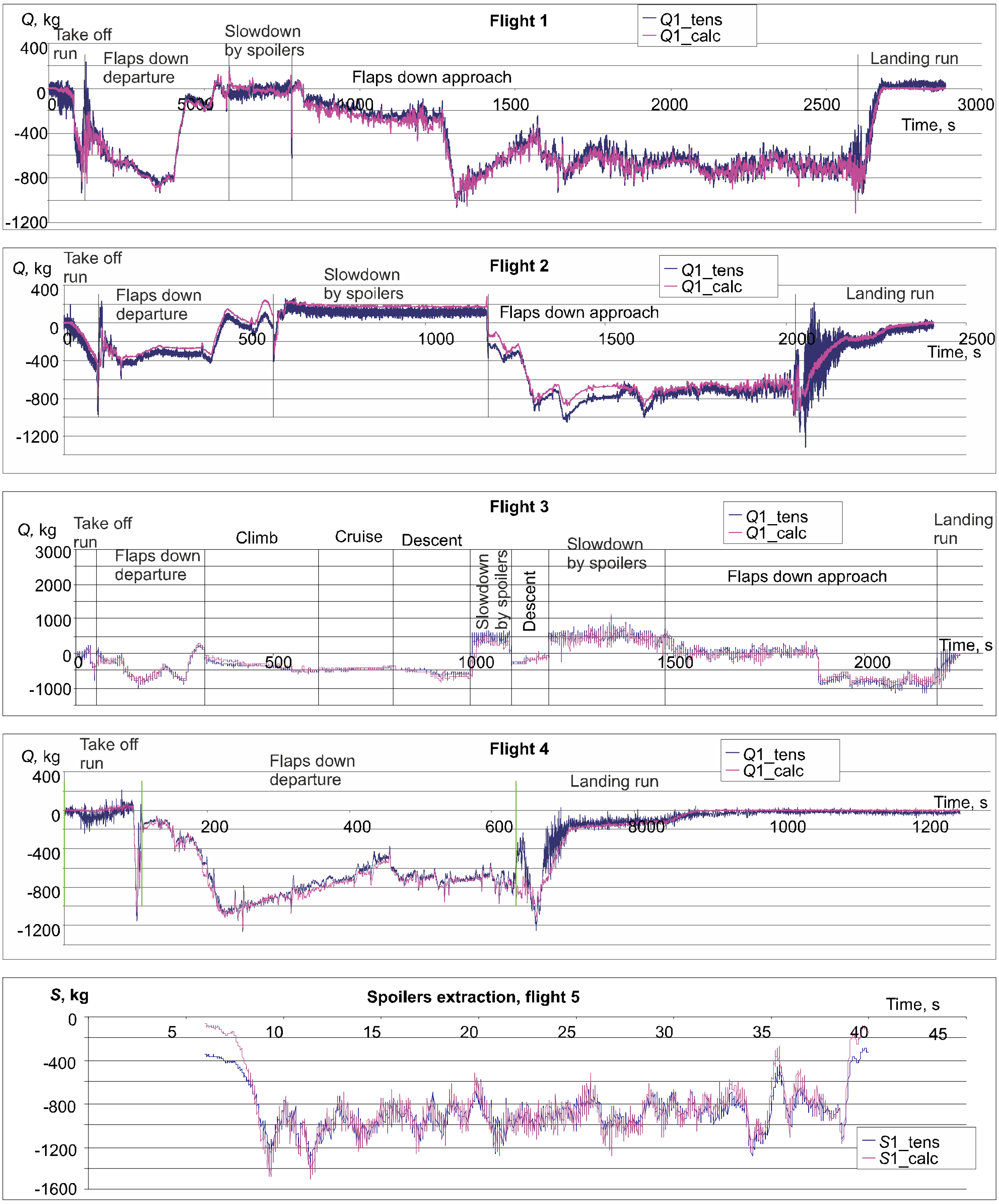


Figure 10: Time histories of shear force (*Q*) in right root section of HS and force (*S*) on stabilizer actuator

8 BENEFITS AND POSSIBILITIES OF MONITORING SYSTEM

- Additional equipment and maintenance cost are absent.
- It is possible to trace fatigue life consumption of each individual aircraft. It will increase the service life of the fleet approximately twice at least and will bring significant economic benefits.

- Monitoring system allows for rational planning of maintenance schedule (inspection, replacing details with limited service life, repairing) bringing economic benefits too.
- Monitoring helps to serve the aircraft more safely because aircraft loading is estimated more accurately with using larger volume of parameters influencing on it, and this has economic benefits too.
- Registration of hard landing loads minimizes check and repair procedures and reduces material losses caused by service cease.
- It helps to develop the pilotage style recommendations (trajectories of climb and descent, take off and landing styles, applying of flaps, slats and spoilers) which will help to reduce loads repeatability and accumulated fatigue damages.
- Aircraft response during take off and landing run and taxiing helps to monitor the quality of runways and taxiways.
- It helps to collect extreme operational loads to update regulation requirements for static strength;
- Monitoring allows obtaining of statistical data about variable loads and accumulated fatigue damages to develop accurately the program of full scale fatigue tests and therefore increase the safety of aircraft service.
- The monitoring accuracy corresponds to strain measurements if flights volume is numerous (tens of flights). To raise the monitoring accuracy in each flight the sampling rate of main FDR parameters (load factors, angular velocities, angles of control surfaces deflection, angles of attack, etc.) should be increased.

9 COPYRIGHT STATEMENT