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SIMULATION MODEL OF INVESTIGATION OF CRACK GROWTH PROCESS IN FIGHTER STRUCTURAL COMPONENTS

Snejana YORDANOVA[*], Lubomir DIMITROV[*], Dimosthenis MICHALOPOULOS[**]
[*]Technical University of Sofia, Bulgaria
[**] University of Patras, Greece

Abstract: In the present paper the use of modern approaches towards the evaluation of the reliability and strength of randomly loaded components are examined. A fighter airplane during flight operation is examined and its structural components (body, wings and tail) are loaded with randomly varying forces. A MATLAB environment model based on Fracture Mechanics Approach, and employing "Monte Carlo" stochastic methodology for determining the strength of these components was devised. The simulation model determines the time between two consecutive maintenances and to guarantee the pilot's safety during the exploitation of the fighters. By the use of this model, simulation on the reliability of different aircrafts could be made. The only requirement is to have enough and reliable input data.

Keywords: simulation modeling, crack propagation, fracture mechanics, "Monte Carlo" method, MATLAB

1. Introduction

Simulation modeling is a universal and powerful approach for investigation and evaluation of the effectiveness of systems whose behaviour depends on the impact of random factors [1, 2]. Airplanes and military fighters belong to such systems because they are subjected to varying loads during flights [3]. For instance, fighters during their flights experience overloads ($n_y = Y/G$) up to 8 - 10 times higher than the gravity force. In this case static strength cannot be used for the evaluation of the structural components toughness and the structural components fatigue must be taken into account. One of the best approaches for solving fatigue design problems is Fracture Mechanics Approach [3, 4, 5].

In addition, MATLAB [6] is a software environment for computer simulation that enables building of models and carrying out simulated experiments and investigations for solving of a wide variety of problems. It can be successfully applied for modeling of processes of cracks growth in the fighter structural components subjected to varying loading during flight.

2. Input Data

Figures 1a and 1b, show the varying forces acting on a fighter during its flight. These are weight G, and lifting force Y. During the experiment the thrust and drag forces are assumed constant.

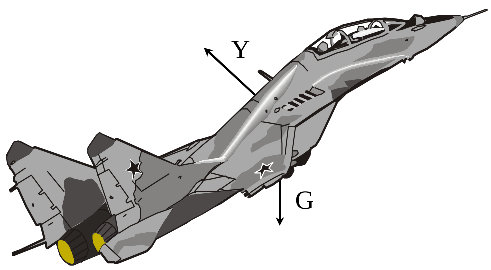

Figure 1a. Weight (G) and lifting force (Y) acting on a fighter during its flight

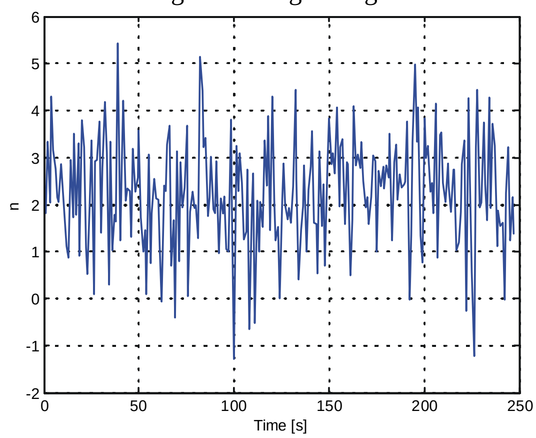

Figure 1b. Experimentally obtained correlation between lifting (Y) and weight (G) force during fighter's flight
Figure 1. Loading of a fighter during its flight

The structural integrity of fighter airplane components is limited by their ability to resist varying loads during their service life. An experimentally obtained loading of the components is shown in figure 1b. In our further analysis, we approximate the type of loading shown the figure 1b with a cyclic loading without a mean stress. Due to this loading the strength of the components decreases in time and finally they fail. This failure is the result of the appearance and growth of fatigue cracks. Therefore it is very important to develop reliable methods for prediction of the aircraft structural components fatigue resistance in correspondence with [7]. One of the best approaches for modeling of this process is Fracture Mechanics Approach [4, 8], which allows following the process of initiation and growth of fatigue cracks.

The goal of this work is to develop a simulation model based on the advantages of Fracture Mechanics using the MATLAB environment. The model is designed to be used for the analysis of fatigue crack initiation and growth for structural components of aircraft in order to determine their service life and to predict potential failures.

3. Theoretical background for simulation model development

The simulation model is based on statistical experiment, employing the Monte Carlo method [9], whose practical implementation is expedited by means of computers and appropriate software. The development of the simulation model should comply with the following basic requirements:

1. The model has to follow the logic of operation of the investigated system;
2. The model must be able to conduct statistical experiments.

For the model, we consider that a crack is initiated when it has a minimum length of 15 μm. Further the initial crack grows according to Paris formula [4]:

$$\Delta a = C(\Delta K_1)^n \tag{1}$$

where:

Δa - Gradient of crack length;

C and n - Coefficients depending on the material selected;

ΔK_1 - Effective stress intensity factor, determined according to Eq. (2):

$$\Delta K_1 = K_{max} - K_{min} = (\sigma_{max} - \sigma_{min})\sqrt{\pi l_i} \tag{2}$$

Variables in equation (2) are:

σ_{min} and σ_{max} - Minimum and maximum stress for a loading cycle;

l_i - Crack length after **i** loading cycles.

These parameters can be determined as follows:

$$\left.\begin{aligned} \sigma_{max} &= \frac{\sigma_s}{n_{exploat}} n_{max} \\ \sigma_{min} &= \frac{\sigma_s}{n_{exploat}} n_{min} \end{aligned}\right\} \tag{3}$$

where σ_s is Yield strength and $n_{exploat}$ is Coefficient of maximum overloading (it is assumed to be 9)

$$l_i = l_0 + \Delta a \tag{4}$$

where l_0 is initial crack lenth.

The input data for the material are taken from [11]:

σ_s - Yield strength (2024-T3) = 5.10^8 Pa;

C - Coefficient = 5.10^{-7};

n - Coefficient = 2;

M - Mean value – taken from table 1;

σ - Mean square deviation–taken from table 1;

N - Training flight duration–taken from table 1;

l_0- Initial crack lenth (input from the screen);

N_real Experiment number (input from the screen);

K_{1C} Critical value for the effective stress intensity factor.

For the investigation of the crack growth process, 8 loading blocks were used corresponding to 8 types of training flights with different loading regimes. The loading regimes probability characteristics are shown in table 1.

Table 1

n_y	1	2	3	4	5	6	7	8
M (m)	2.2321517	2.0134684	1.5956750	1.4785727	1.2684514	0.9690766	1.6627081	1.6495158
σ (s)	1.2112589	1.2773966	1.0241889	0.8260998	0.8206914	0.2705131	0.9129932	0.9492946
N (T)	7590	7848	7600	5402	19890	11252	8707	4957

The selection of a loading block is a random variable that obeys even probability distribution law and depends on the reiteration frequency of each of the eight types training flights in a sample of 120. According to the frequency of appearance (figure 2), the cumulative frequency f f_i is determined as $P_i = f_i/120$ (i = 1, 2, … 8) (figure 3). As a result, the interval of generation of random numbers (0 - 1) is subdivided into 8 other intervals with different widths, as shown in figure 4, according to the probability of the corresponding flight task. Thus the probability that a given number will fall in a specific interval is proportional to the interval width. In this way the distribution of training flights or of the respective loading is obtained.

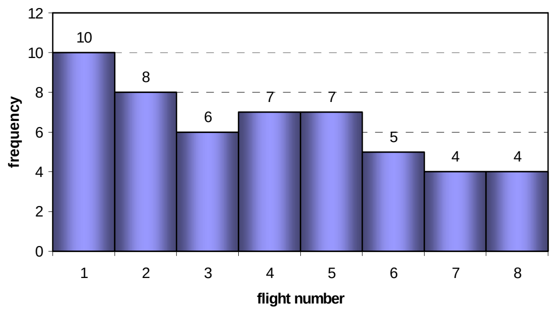

Figure 2. Frequency versus flight number

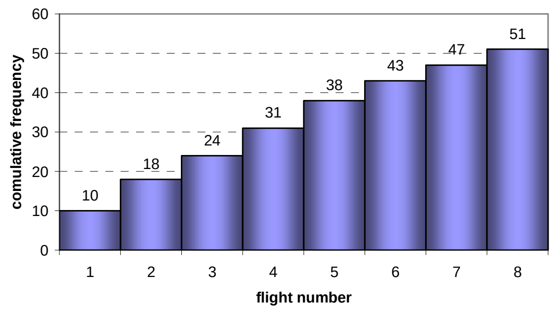

Figure 3. Cumulative frequency versus flight number

After selection of a loading block, random numbers are generated, i.e. the loads n_i are normally distributed with mean value m and variance s. The generation process continues until the first minimum and the first maximum load are determined and thus a complete loading cycle defined (figure 5).

For the specified loading cycle the growth of the existing crack is computed according to equations 1 ÷ 4. Next the effective stress intensity factor ΔK_1 is compared with the allowable (critical) one K_{1C}. Failure appears when $\Delta K_1 > K_{1C}$. If the length of the examined crack is still not critical, the next loading cycle is generated. If the flying task (type of load) duration is over, a new flight load is generated and the process is repeated. This procedure could be repeated until the failure of aircraft components appears. After that a new start of the process is simulated. The total number of flights *N_real* is specified by the user in the beginning of the computer simulation.

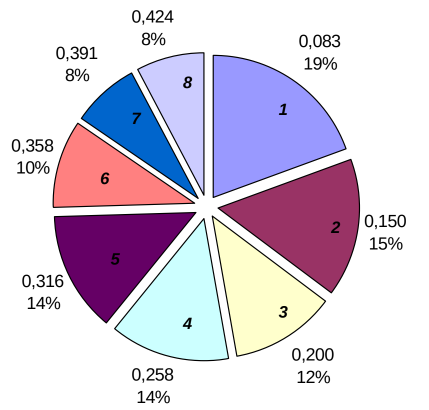

Figure 4. Intervals according to the probability of the different flight task (loads)

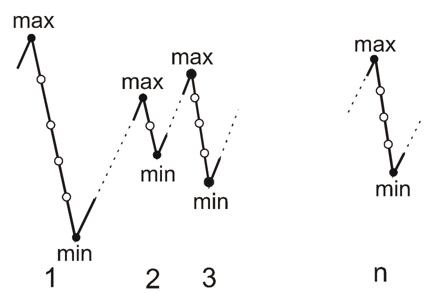

Figure 5. Determination of loading cycle

The result of the computer simulation is the calculation of:

a) The mean mathematical expectation and variance for the critical crack length l;
b) The failure time T_{raz};
c) The number of cycles needed for this failure *N_cycle*. This data is recorded for used in further statistical processing and analyses.

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The algorithm for the simulation program is shown in figure 6.

4. Results from computer simulations

The algorithm shown in figure 6 is realized in a developed MATLAB simulation model which is used to investigate the structural integrity of the aircraft components. Figure 7 illustrates the fatigue crack growth as function of the loading cycles for each of the flight loads n_y, generated in time according to figure 8 for each one of the flights. The crack length, the time needed, and the number of cycles to fracture are shown on the top of the graph.

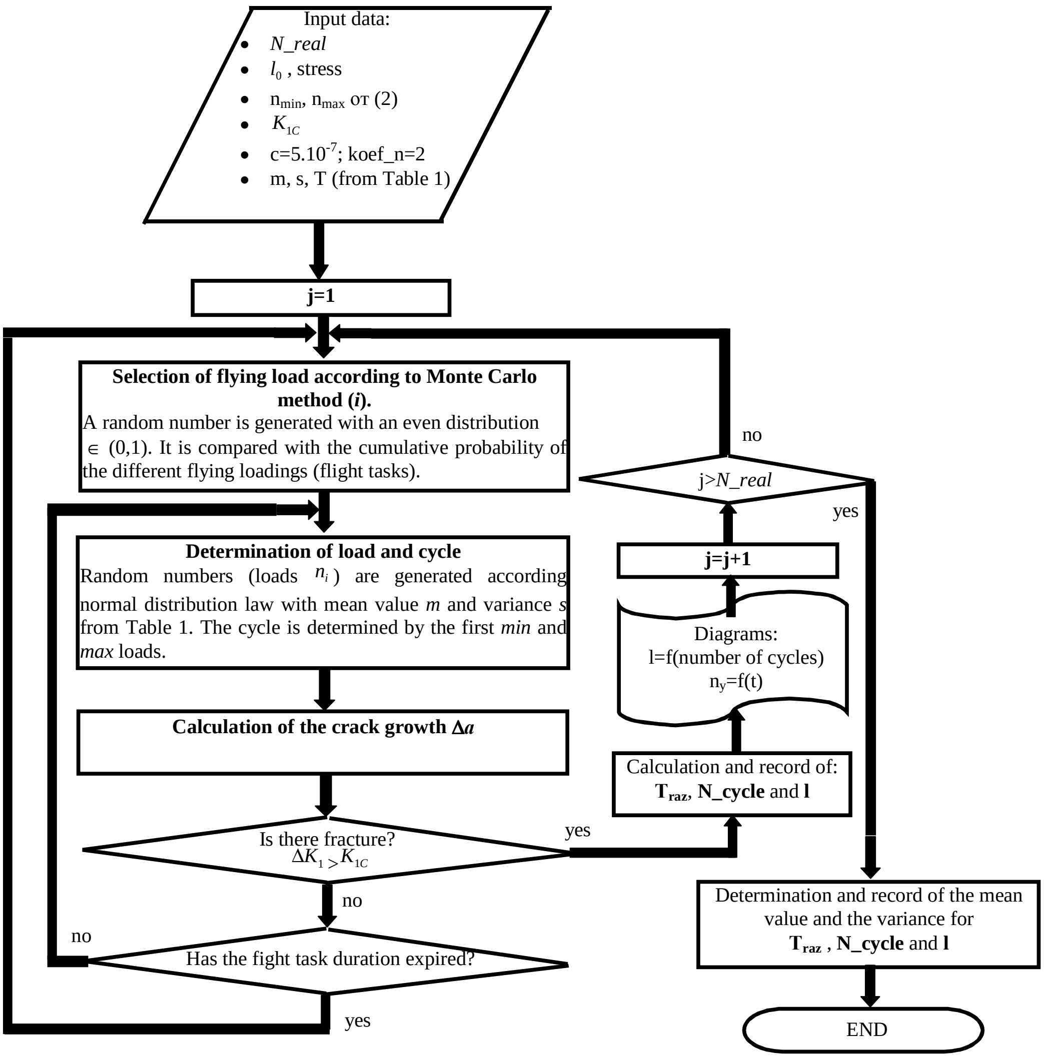

Figure 6. Simulation model algorithm

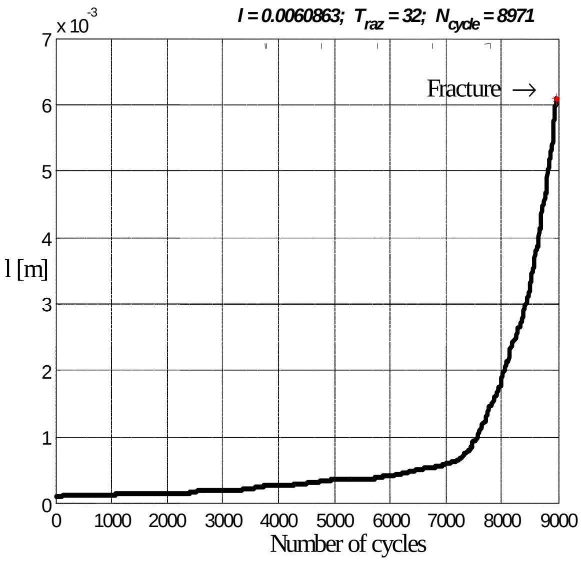

Figure 7. Fatigue crack growth

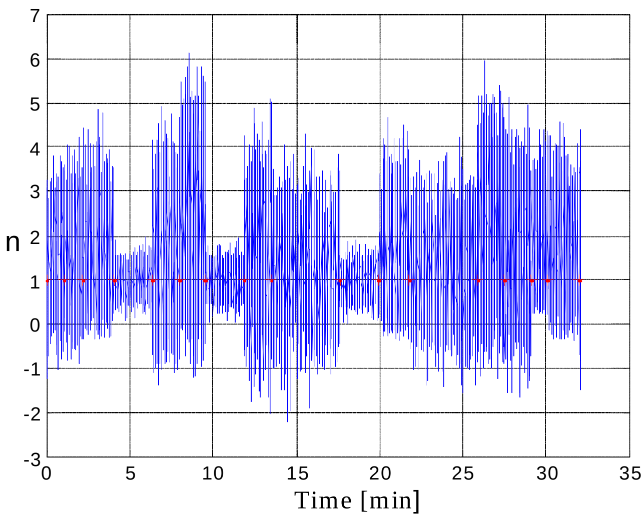

Figure 8. Generated loadings $_{ny}$ for each flight

5. Conclusions

The main results in this work could be summarized as follows.

- A simulation model in MATLAB environment has been developed. The model is based on the Fracture Mechanics approach and the Monte Carlo stochastic simulation and allows investigation of the process of fatigue crack growth in airplane structural components subjected to operational loadings.
- Simulated experiments were conducted which performed statistical analysis of the process of fatigue crack growth in aircraft structural components and prediction of fracture.
- The simulation model is capable of determining the time between two consecutive maintenances and guarantees flight safety, reducing at the same time the cost and duration of experiments.
- By the use of this model, simulation on reliability of different aircrafts could be made. The only requirement is to have sufficient reliable input data.

Future work should be undertaken in order to validate the simulated model and compare the measured and predicted crack length for different loading patterns.

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