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FIELD REPAIRS OF AIRCRAFT ENGINES

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Abstract

The challenge to the manufacturer or service provider is how to assess and define true customer expectations and then how to design, manufacture and sell the product to best meet those expectations. Each product must provide operational capabilities, which allow military forces to maintain technical and logistic superiority over a potential adversary even if it is just natural or induced environment, which can be expected over the operating and maintenance portion of life cycle. Battle damage repair is a critical factor in managing operation. We acknowledge that traditional cost minimizing measures are not always central and other performance measures such as time of repair, reliability and availability become more relevant. Assessing aircraft damages in the field and making appropriate decisions on the reparability, making repairs at the lowest repair level possible and evaluating airworthiness of subsequent repairs is critical to the air forces maintaining its force projection capability.

Among other, combat damage of helicopters, damaged areas and erosion on leading edges of the compressor first stage rotor blades, achievable and optimum solution, goal function – duration minimisation, goal function – cost minimisation are presented in the paper.

Keywords: *transport, aviation, aircraft, field repairs, optimization*

1. Introduction

Physical and chemical phenomena, developing under effect of ambient conditions on the ground (both during stops and storage of aircraft) and in flight, amplified by effects of various operational and combat forcing factors, result in damage[1]. Damage is removed by restoration[2]. Restoration means organizational and technical activities of various scopes such as repair and overhaul. Definitions of the terms: renewal, repair, overhaul are not very precise. The following definitions of these terms are most often used in aircraft operation:

- Restoration of aircraft (assembly) – is restoring the original properties or properties sufficiently close to the original ones. Restoration process is a forced one (repair) but it can also take place automatically or is scheduled (overhaul).
- Repair of aircraft (assembly) – a set of organizational and technical activities that restore an object to a desirable reliability condition. Operations aimed at restoring serviceability to an object.
- Overhaul of aircraft (assembly) – is a set of organizational and technical activities, performed in order to restore operability to an object; these activities are envisaged in advance by the object's manufacturer and scheduled or unscheduled, e.g. in case of an extensive damage, requiring special tooling; this is a comprehensive repair of all assemblies.
- Field overhaul – a particular type of overhaul or, more often, a repair, provided in conditions of limited technical capabilities, e.g. during natural disasters, forced landing or combat operations that generate so called battle damage.

[1] The term „damage" will mean also other forms of changes in elements, assemblies and the whole aircraft such as a failure, malfunction, going out of adjustment, etc.
[2] In the literature a synonym of restoration is often bringing back to operational status. [6].

Assemblies and installations as well as components of aircraft structure and engines are exposed to various extents to operation-related damage including battle one (Fig. 1, 2, 3). Most often this damage is of a complex type, i.e. in addition to damage of the aircraft skin also damage of assemblies, electric and hydraulic installations, etc., actuators (e.g. of the control system) occurs.

A degree of aircraft damage is defined by:

- the number of damaged assemblies, subassemblies, parts, etc,
- the nature of the damage,
- geometrical dimensions and the number of damaged areas.

Operation-related and battle damage can be split into that already recognised in the past and damage occurring in current operation, the nature of which has not been described in the relevant documentation. The damage nature determines who and using what kind of technology removes it, restoring aircraft's serviceability.

Catalogued minor damage. Can be repaired by the user on its own or by a repair organisation if it holds an adequate certificate (granted by a state supervisory organisation) and authorisation (granted by the aircraft's manufacturer).

Catalogued medium or large damage. Technical documentation for repair of the damage is developed by either the user or a repair organisation provided it holds an adequate certificate and authorisation. This documentation is approved by the manufacturer. The damage is repaired by the organisation that developed the repair documentation.

Non-catalogued rapid damage. This is damage concerning in particular highly-loaded design elements. Both the repair procedure and repair itself is provided by the manufacturer through its repair organisations.

In operation of aircraft (A/C) the primary requirements are operational readiness and reliability. This means A/C readiness for operation on request, maintainability and correct operation in extreme (combat) environment. Aircraft must provide operational capabilities allowing military units for maintaining technical and logistic advantage over a potential enemy even if this is only the natural or imposed environment that can be expected during operation in the A/C lifetime. Usually a reduction or loss of these operational capabilities occurs, leading o immediate loss of human lives and the equipment.

Fig. 1. Characteristic damage of GTD-350 engines

2. Diagnosability in field conditions

In case of combat operations and field overhaul, an important element that is subject to assessment is the duration criterion. Users expect that determined A/C features, specified in the

Fig. 2. Characteristic damage of RD-33 engines

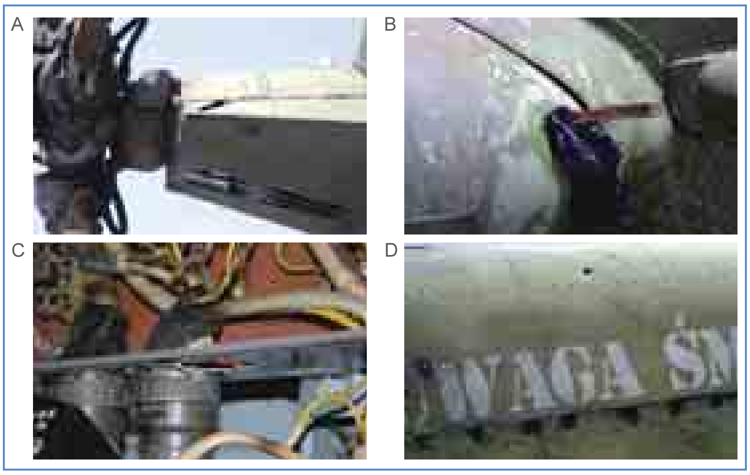

Fig. 3. Combat damage of helicopters; A – damaged final gearbox; B – damaged fuel tank; C – damaged AC distribution box; D – damaged vertical stabiliser (bullet hole)

design phase, will allow after the restoration (overhaul) for its further operation. A degree of suitability of aircraft and its propulsion system for operation in conditions determined by the operating system is determined by operability, and diagnosability is a part of operability. High diagnosability is provided by:

- easy access to elements that are subject to adjustment and replacement,
- easy implementation of maintenance, repair and overhaul operations,
- low frequency and labour intensity of maintenance operations,
- high commonality of parts,
- universal nature of maintenance tools and equipment.

Diagnosability [4, 5, 6, 8] is assessed by means of a level of value of features referring to capability of performing diagnostic tests as well as credibility of current, past and future conditions of the A/C obtained from these tests, taking into account environmental effects. Diagnosability is assessed by means of average diagnosing duration, T_{ds}, calculated according to the following formula:

$$T_{ds} = \frac{1}{N}\sum_{i=1}^{N} q_i t_{dsi}. \tag{1}$$

Examples of typical battle damage of aircraft engines are shown in Fig. 4 and 5. Total or partial destruction of engine elements in the form of deformation, material rip-off, etc. is visible.

Fig. 4. Damaged areas and erosion on leading edges of the compressor first stage rotor blades

Fig. 5. Damaged areas (overheat, damage of the calorisation layer, material losses, deposit of burnt sand) on the compressor first stage guide vanes

Because of their design, aircraft assemblies and installations as well as engines, the way they are exposed to combat damage varies. Most often this damage is of a complex nature and includes many installations and assemblies. An extent of damage can be determined basing on the number of damaged subassemblies, the nature of damage, geometrical dimensions, and the number of damage points in the given area. Duration of aircraft repair (overhaul) determines whether the aircraft can be used for a given operation or even in further combat operations. Post-accident or post-failure repair is a set of more complex operations and it needs a much more extensive analysis of feasibility under given conditions. It is conducted if a damage of aircraft results from a rapid and unforeseeable event that represents a disruption of correct operation. Labour intensity and a scope of repair are random features and they are determined by:

– time of waiting for repair,

- diagnosing of the damage,
- accessing the damaged element (assembly),
- waiting for spare parts,
- repairing the damage,
- installation of assemblies and installations,
- check of the operations performed and diagnosing,
- handing over the A/C (propulsion assembly) to the user.

A characteristic feature of particular repair types is their labour consumption needed to restore the operational potential, measured with the number of man-hours and representing the total sum of work of the whole personnel conducting the repair.

The extent of rebuilding the object's operational potential (restoration of serviceability) is characterised by the restoration parameter (indicator), WO :

$$WO = \frac{\mathbf{E}[T] - \mathbf{E}[\tau]}{\mathbf{E}[T]} = \frac{\sum_{i=1}^{n} \mathbf{E}_i[T] - \sum_{i=1}^{n} \mathbf{E}_i[\tau]}{\sum_{i=1}^{n} \mathbf{E}_i[T]}, \tag{2}$$

where:

$\mathbf{E}[T]$ – expected value of the object's operation intensity (random variable T);

$\mathbf{E}_i[T]$ – expected value of the object's operation intensity of i-th assembly of the object (random variable T);

$\mathbf{E}[\tau]$ – expected value of the object's operation intensity (random variable τ).

An analysis of random variables and their indicators allows for prediction of objects' restorations (overhauls) and maintaining readiness of, e.g. a fleet of aircraft.

In case of combat operations availability of spare parts is a very important factor. A spare part is any replaceable[3] or substitute[4] part in storage, waiting for being used in a process of aircraft restoration [3, 7].

3. Damage assessment

The process of damage assessment requires flexibility in order to adjust the procedure to any situation that occurred in operation of a given aircraft propulsion assembly. The first phase of damage assessment is a review of the crew's report, if possible immediately after the event, in order to obtain information concerning both the aircraft and its assemblies, conditions under which the damage occurred and behaviour of the A/C after the event. Next a detailed inspection of the A/C external structure and systems is conducted; the scope of this inspection should be as extensive as possible. The inspection should be performed in a structured manner in order to identify any damage and avoid a possibility of overlooking any hidden damage that may cause secondary damage. Secondary damage may be a much bigger threat than primary one. Documenting the inspection represents a significant element for both the given event and for a broader picture of the situation as it provides a possibility of use of the information by other maintenance systems.

The key factor for a possibility of using damaged aircraft and its propulsion assembly again is damage repair duration. The indicators that characterise labour intensity are:

- average labour intensity of damage repair,
- average duration of damage repair,
- average downtime caused by damage repair.

[3] Replaceable part: a part that replaces a damaged element, having the same properties and performance.

[4] Substitute part: a part that has all features of a replaceable part and that can be made of a different material, according to another manufacturing technology, etc.

4. Optimization of field overhaul duration

The most important element of a field overhaul (and not only it) is definition of the problem, i.e. determination of the object of the study, the purpose of the analysis as well as the requirements and constraints [1,2]. For complex problems a task of many inputs and outputs, i.e. a multi-dimensional, multi-criteria task is obtained. It is also necessary to specify the manner of optimization, i.e. whether this is striving for minimisation or maximisation.

Any system is characterised by a set of equations and inequalities that result from logistic means and conditions. Knowing the decision values (ZD) and criteria (*K*), the known mathematical formulas should be transformed in such a way to obtain relations of the $K = f(ZD)$ type.

In order to start operations designed to find the solutions, the decision (control) variables effects of which on system responses (criteria) is, due to some reasons (e.g. engineering, economic, etc.) crucial are selected. In addition a scope of variability should be determined for these variables. Usually three decision variables are used for calculations. Next an identification of the criteria values is performed, i.e. determination of resultant values that are particularly desirable (e.g. execution time or cost of manufacturing) as well as the type of optimisation (minimisation or maximisation) is selected for individual criteria values. Composition of the personnel, stock of spare parts and stock of maintenance equipment have been found to be the most important elements of a field overhaul system. The decision variables must meet constraints imposed on them.

Because of discretisation of decision variables, a Pareto set is not continuous but rather some subsets of values can be identified. They represent correctly an idea of the compromise sought. When the duration criterion decreases, the cost criterion increases. Using the pseudopolyoptimisation approach [1, 2, 7], the optimum solutions have been found for the *alfa* weight coefficients from 0.1 to 0.9 and *beta=1-alfa* and for the goal function in the form of: $fc = alfa \cdot fc_{duration} + beta \cdot fc_{cost}$, these solutions were designated with numbers from 1 to 9. An exemplary goal function for alfa=0.7 and beta=0.3 is shown in Fig. 6.

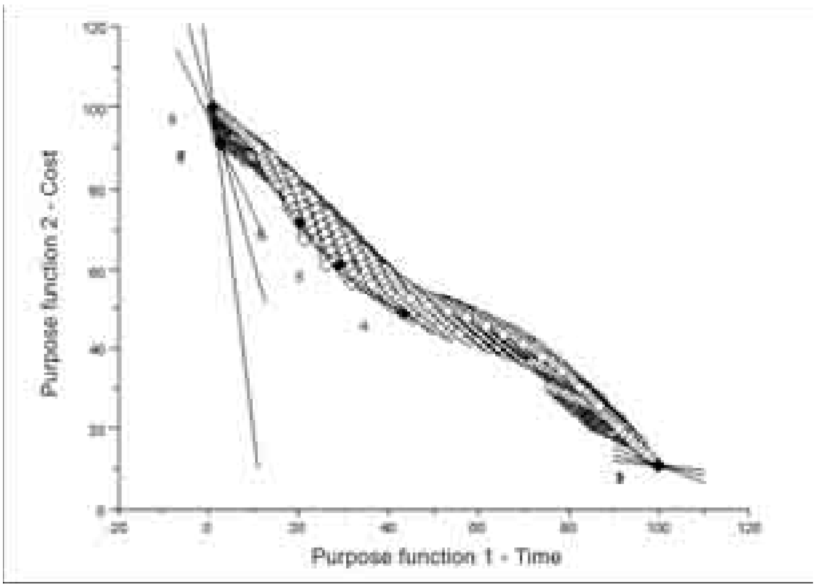

Fig. 6. Achievable (Pareto front) and optimum solution

Two optimisation criteria and three decision variables have been identified in construction of the mathematical model. In the overhaul process, overhaul duration and overhaul costs are functions of the number of personnel, stock of spare parts and equipment of the overhaul base. Two goal functions occur in the task: overhaul duration (Fig. 7) and overhaul cost (Fig. 8). A minimisation of both goal functions is sought, for two criteria that are minimised. On one end of the front the minimum (*fc*_duration) criterion value is obtained at the maximum value of the (*fk*_cost) criterion while a reverse situation is obtained on the other end. There is a whole set of intermediate solutions between these extreme ones.

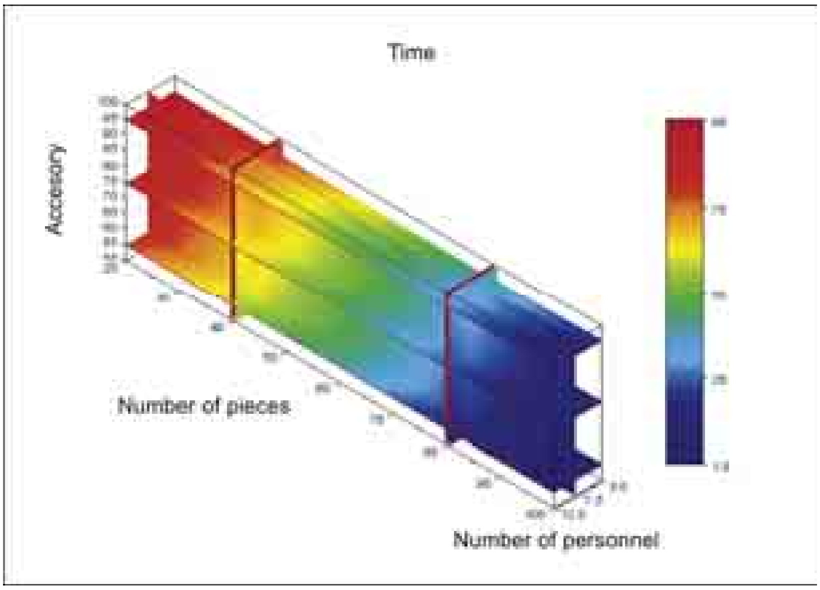

Fig. 7. Goal function – duration minimisation

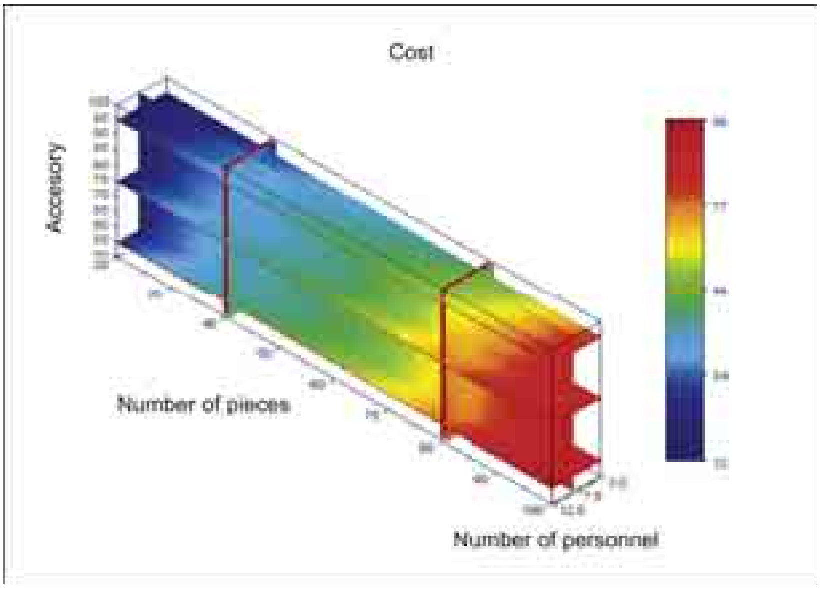

Fig. 8. Goal function – cost minimisation

The generalised overhaul quality indicator, *WJ*, in the time interval used is determined by the following relationship:

$$WJ = \frac{N_r - N_{rn}}{N}, \tag{3}$$

where:

N_r – the number of units reported for overhaul;

N_{rn} – the number of units reported for overhaul due to operational damage (e.g. engine blade damage caused by FOD, bird ingestion, etc.) but not accepted for overhaul;

N – the number of overhauled objects handed over for operation.

5. Summary

A process of field overhaul of aircraft and its assemblies including the propulsion assembly is aimed at restoration of operational potential and providing serviceability. This process is affected by overhaul preparation operations (disassembly, verification of parts and assemblies), preparation of necessary documentation, preparation of properly trained maintenance personnel, etc.).

Deploying a maintenance or overhaul system in the form of a field overhaul system for aircraft and their propulsion assemblies is a very complex operation.

In any case a correct implementation of such a project requires taking into account many factors closely connected with conditions of operation. They refer to both external and internal considerations including project and human resources management, planning and implementation of changes in operation of the system. In any situation an analysis of effect of the field overhaul system's organisation on a time needed to prepare aircraft for combat mission execution should be conducted. This allows for determining directly an effect of the overhaul system on availability of aircraft for individual missions or operations, and also on selection of the right method, adjustment of the overhaul system for operational needs as well as a correct utilisation of the maintenance potential.

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