Implementation of Reliability Analysis of an Aircraft System

Conference Paper · May 2013

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IMPLEMENTATION OF RELIABILITY ANALYSIS OF AN AIRCRAFT SYSTEM

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SUMMARY: Reliability analysis of selected aircraft system is performed at different levels of detail. In each case appropriate reliability analysis technique is applied (failure mode and effect analysis, reliability block diagrams or fault trees, dependence modelling). Model quantification is based on accident and incident report databases, service difficulty reports, generic component reliability databases and expert judgement. Finally, the results are compared and discussed in the context of the needs of the risk analysis, maintenance requirements determination and in-service occurrences safety classification and analysis.

Keywords: Reliability Analysis, SDR, Reliability Diagrams, Aircraft Systems.

Introduction

"Enhance global civil aviation safety" is one of the three strategic objectives of International Civil Aviation Organization (ICAO), together with security and sustainable development of the global civil aviation system. Accidents, incidents and other occurences data are collected by the ICAO, The European Aviation Safety Agency (EASA), Federal Aviation Administration (FAA), UK Civil Aviation Authority and other regulatory bodies and private organizations, like aircraft manufacturers, Ascend's World Aircraft Accident Summary (WAAS), etc. These data are used for assessment of the current level of aviation safety and identification of particular safety issues.

The reliability of the aircraft systems has important contribution to accidents and incidents in the overall aviation system. Aircraft system or component failure (SCF-NP) is the third accident category by number of fatal accidents (6), after "Loss of control in flight (LOC-I) (9) and "Controlled Flight Into Terrain" (CFIT) (7) and the second by total number of accidents (62), after "Abnormal runway contact" (ARC) (66) (EASA member states operated aeroplanes for the period 2002 – 2011 [1]). In addition to the direct loss of primary function, less severe system/component failures/malfunctions could contribute to accident propagation, e.g. loss of control, abnormal runway contact, etc. System failures could be related to design errors, manufacturing and maintenance issues. Included are errors or failures in software and database systems.

Performance of reliability analysis of an aircraft system is complex problem. Different techniques, assumptions and simplifications are used to achieve specific purposes. We will consider possible reliability analyses based on service experience at different level of details and corresponding limitations and applications (risk analysis, maintenance requirements determination and in-service occurrences safety classification).

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Reliability analysis at different level of details

Reliability analysis could be performed at different level of details in terms of system structure modelling and causes of failures (or infliences). We could define the following levels of details.

Level 0: Top level functional failure probability assessment

It is based just on accident and incident statistics. Different influencing factors could also be accounted, e.g. system type, aircraft generation, type of operation. The number of functional failures (only critical) is needed and the number of departures/flight hours (utilization information). Therefore available records should be categorized and only applicable counted. In the general case this is slow process because available databases are not specially developed for this purpose. The text description in combination with other structured (coded) information for each record should be considered. Utilization information is also difficult to compile, and it becomes more difficult as more specific cases are considered.

This level is applicable for safety and risk analysis. Only the orders of magnitude of hazardous events are important and low level details of system specifics are irrelevant. Example application of this approach could be found in [2,3]. It provides causal model of air transport system safety. Initiating and pivotal events are modeled top-down using accident and incident statistics.

Level 1: Sub-system and major components level reliability block diagrams

This level of details includes development of simple model of the structure of the system and quantificaton of failure rates of system elements. The model of the system includes only major components and relations. Reliability of system elements (sub-systems and major components) can be estimated based on service experience. FAA collects mechanical reliability reports of US airlines [6] – service difficulty reports (SDRs). Occurence reporting (including technical and maintenance problems) is mandatory in Europe (ECCAIRS) [7] and UK (MORS) [8]. The quantity of information is significant and part of it is freely available. Therefore this approach allows more detailed modelling of the reliability of the system. It could be applied for system architecture selection at design stage, occurence analysis and categorisation, risk analysis for patricular aircraft type. However, at this level many internal dependancies are masked (hidden). In addition, new technologies with little or no service experience could not be assessed.

Level 2: Assembly and part/detail level analysis

Recommendations for detailed safety/reliability assessment of aircraft systems during design and certification of aircraft are described for instance in FAA FAR-25 (AC 25.1309) or EASA CS-25 (AMC 25.1309) regulation for aircraft design. These cover applicable reliability data sources and assessment methods, i.e. FMEA, FTA, RBD, etc. Reliability block diagrams at this level are very complex, often with no exact analytical solution and often difficult to verify and validate. Qualitative part of the analysis should not be underestimated.

These analyses should be used for every newly designed and certified aircraft system.

Level 3: Detailed dependancy modelling

These could include common cause failure models, external risks and Bayesian Belief Nets for influencing factors. Quantification is difficult, based on detailed examination of service experience data and mostly on e xpert opinion. Each external risk examination requires development of separate methodology. These analyses need not reach assembly and part level, but should consider many external to the system factors as quality of maintenance, quality of production, operator errors, environmental factors, etc.

Dependancy modelling is good complement to the other levels of analysis. It will foster better maintendnce management, operations management, organization management and risk analysis.

Detailed dependancy modelling is out of the scope of this work and will not be discussed.

Aircraft elevator control system reliability based on accident and incident data

We consider technical failures in the elevator that could cause loss of control if flight crew fails to maintain control by other means. The probability of this critical failure condition will be calculated based on accident and incident statistics.

FAA Accident /Incident Data System (AIDS) database [4] is used as a main source of data, because there is free public access. It contains accident and incident data records for all categories of civil aviation in the US between 1978 and the present (over 200 000 records).

The scope of the analysis is limited to commercial air transport with US registered aircrafts heavier than5700 kg.

First, all records of accidents and incidents are filtered based on the following criteria:

- time period: 1985 – 2003 (97898 records)
- aircraft weight class: over 12500 lbs (5670 kg) or blank (16000 records)
- type of operation: air carrier/commercial or blank (12841 records)

The associated number of flights n_{flights} is 224 million [5].

Next we need to count the number of events caused by elevator control system failure. For the selected database we combine full text search for selected keywords in the event description field (remark field) and filtering by “Primary cause” and “Secondary flying condition” categories:

- full text search for keywords: “elevator” OR “pitch” OR “control column”: 226
- filtering by “Primary cause”: “27” OR text OR empty: 147
- filtering by “Phase of flight”: NOT “Other Ground Ops” AND NOT “Ground Taxi, Other A”: 153
- full text search for keywords: NOT “trim”: 113
- filtering by “Secondary flying condition”: “Weather Not A Factor” OR “Unknown” OR “Other” OR empty: 101

The resulting set of 101 events was reviewed and further reduced to 45 elevator critical failures ($n_{\text{elev-fail}}$).

At this stage it is possible to calculate the probability of elevator control system failure P_{ELEV} per flight for US operated large aircrafts:

$$P_{ELEV} = \frac{n_{elev-fail}}{n_{flights}} = \frac{45}{224 \cdot 10^{6}} = 2 \cdot 10^{-7} \quad (1)$$

Aircraft elevator control system reliability based on simple system model

This level of analysis requires specific component arrangement to be considered. The Boeing 737 longitudinal control design is selectied for illustrative purposes and neither the system structure, nor the quantitative values drawned should be taken for real.

The logitudinal flight control system is hydraulically powered with manual reversion available [9]. Pilot input to the flight control systems is generally through a cable and pulley arrangement connected to hydraulic power control units that position the flight control surfaces. On the -300\-400\-500 series, the "A" hydraulic system is powered by the left engine driven pump and by a three phase, 115-VAC electric motor-driven pump that is powered by BUS No. 2, which is supplied by the right engine. The opposite is valid for hydraulic system "B", that is each hydraulic system is powered by each engine.

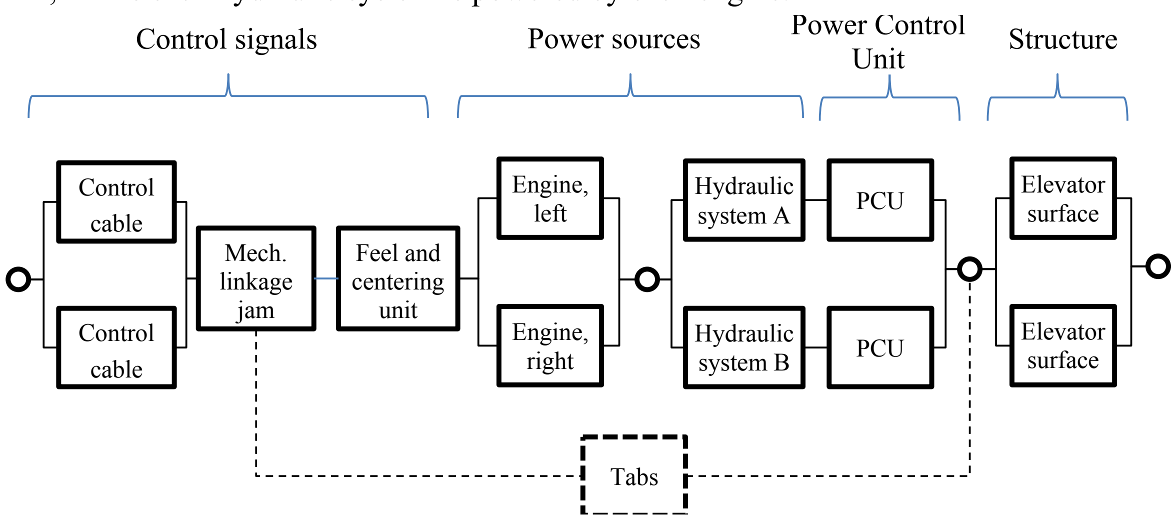

Fig. 1: Simple Reliability Block Diagram of example elevator control system

The probability of failure of each component is calculated using SDR data.

First, all records of air carrier/commercial service difficulty reports are filtered based on the following criteria:

- time period: 1985 – 2003 (over 550 000 records)
- Air Transport Association (ATA) code: 27 (20 048 records)
- Stage of operation: NOT "INSP/MAINT" (14835 records)

Than individual component failures are counted and failure probabilities calculated.

<u>If not specified else, it is assumed that on average there is one component of each type per aircraft.</u>

Power Control Unit (PCU):

- ATA code: 2730 (1 124 records)
- full text search in "Descriptive name of part" for keywords: "actuat" OR "pcu": 97
- full text search in "Location of the defective or malfunctioning part":NOT "trim": 82
- full text search in "Remarks": NOT "trim": 48 records

$$P_{PCU} = \frac{n_{PCU\_fail}}{n_{flights}} = \frac{48}{224 \cdot 10^6} = 2.14 \cdot 10^{-7} \tag{2}$$

Control cable

- ATA code: 2701 OR 2730 (713 records)
- Nature of condition: NOT "FALSE WARNING" (634 records)
- full text search in "Descriptive name of part" for "cable": 30 records
- review of the records → $n_{\text{cable\_fail}} = 28$

$$P_{CABLE} = \frac{n_{Cable\_fail}}{n_{flights}} = \frac{28}{224 \cdot 10^6} = 1.25 \cdot 10^{-7} \tag{3}$$

Mechanical linkage

- ATA code: 2701 OR 2730 (713 records)
- Condition of failed part: jammed, seized, stuck, frozen, locked, etc. (31 records)

$$P_{JAMMED} = \frac{n_{jammed}}{n_{flights}} = \frac{31}{224 \cdot 10^6} = 1.38 \cdot 10^{-7} \quad (4)$$

Feel and centering unit

- ATA code: 2700 OR 2701 OR 2730 OR 2731 (16 records)
- full text search in “Descriptive name of part” for “feel”: 16 records

$$P_{FEEL} = \frac{n_{Feel\_fail}}{n_{flights}} = \frac{16}{224 \cdot 10^6} = 0.71 \cdot 10^{-7} \quad (5)$$

Elevator Tabs

We count records from all stages of operation, including inspections and maintenance (INSP/MAINT), because elevator tab degraded condition could be hidden to the operating crew if hydraulics is operating normally.

- ATA code: 2731 (723 records)
- Nature of condition: NOT “FALSE WARNING” AND NOT “FLUID LOSS”: 640
- full text search in “Remarks”: NOT “trim”: 220 records

In addition, the structure of elevator tab surfaces hinged to elevators is coded in ATA 5523:

- ATA code: 5523 (46 records)

$$P_{TABS} = \frac{n_{Tabs\_fail}}{n_{flights}} = \frac{640 + 46}{224 \cdot 10^6} = 3.0 \cdot 10^{-6} \quad (6)$$

Hydraulic system A or B:

- Air Transport Association (ATA) code: 28 (8706 records)
- Stage of operation: NOT “INSP/MAINT” (7761 records)
- Nature of condition: “FLT CONT AFFECTED” OR “AFFECT SYSTEMS” (97+320=417 records)

The number of hydraulic system failures to perform its main function is between 417 and 7761. It is hard to classify 7761 records manually or by simple keyword search. Advanced automatic text categorisation tools would be of great help for reducing estimation uncertainty.

$$P_{HYDR\_lower} = \frac{n_{HYDR\_fail\_lower}}{n_{flights}} = \frac{417}{224 \cdot 10^6} = 1.9 \cdot 10^{-6}$$

$$P_{HYDR\_upper} = \frac{n_{HYDR\_fail\_upper}}{n_{flights}} = \frac{7761}{224 \cdot 10^6} = 3.5 \cdot 10^{-5}$$

In addition, review of records coded for “Multiple failures” showed that there is at least one case of multiple failures of both main hydraulic systems. Therefore, automatic text search for multiple failures is needed for appropriate common cause failure modelling.

For further calculations, because $P_{HYDR}=(0.2 \div 3.5).10^{-5}$ and there is multiple failures, we assume:

$$P_{HYDR} = 3.5 \cdot 10^{-5} \quad (7)$$

Elevator surface

- Air Transport Association (ATA) code: 5520 OR 5521 OR 5522 OR 5524: 2271 rec.
- Stage of operation: NOT "INSP/MAINT"
- Nature of condition: "F.O.D." OR "FLT CONT AFFECTED" OR "INFLIGHT SEPARATION": 36 records

$$P_{SURF} = \frac{n_{Surface\_fail}}{n_{flights}} = \frac{36}{224 \cdot 10^6} = 1.6 \cdot 10^{-7} \quad (8)$$

Engine in-flight shut down (IFSD)

The rate of IFSD must be less than 2 per 100 000 engine flight hours for engine approval for ETOPS 180 (Extended Twin Operations). Therefore, for a flight with duration $\tau$of 5 hour we can assume probability of engine failure as follows:

$$P_{ENGINE} = FR \bullet \tau = 2 \cdot 10^{-5} \cdot 5 = 1 \cdot 10^{-4} \quad (9)$$

After the probability of failure of each element of the system have been assessed in formulae (2) to (9), the probability of failure of the whole system could be calculated, based on the selected structure:

In case of no mechanical backup (element connected with dotted line in fig. 1 excluded):

$$P_{ELEV} \approx P_{CABLE}{}^2 + P_{JAMMED} + [P_{FEEL} + P_{ENGINE}{}^2 + (P_{HYDR} + P_{PCU})^2] + P_{SURF}{}^2$$

$$P_{ELEV} = 2.2 \cdot 10^{-7} \quad (10)$$

With mechanical backup:

$$P_{ELEV} \approx P_{CABLE}{}^2 + P_{JAMMED} + [P_{FEEL} + P_{ENGINE}{}^2 + (P_{HYDR} + P_{PCU})^2] \cdot P_{TABS} + P_{SURF}{}^2$$

$$P_{ELEV} = 1.4 \cdot 10^{-7} \quad (11)$$

This simple calculation shows that the primary concern for such system is mechanical linkage jamming and artificial feel unit failure. Elements with reservation like control cables, control surfaces and even hydraulics could be neglected. In reality this is not true. That's why common cause failure modelling should be added to the analysis.

Aircraft elevator control system reliability based on detailed system model

This level of analysis require in depth knowledge of the system modelled. An example model of Boeing 737 c lass elevator control system is included in [10]. It contains one main Reliability Block Diagram (RBD) (see fig. 2) and multiple sub-diagrams. In total, over 130 different elements are used. Element failure rates are based on generic data. The resulting system reliability (3.10^{-4} without and 2.10^{-4} with mechanical backup) however is much lower than operating history of similar aircrafts show (and the above results).

Therefore, lack of detailed design data, as well as neglecting qualitative part of the analysis (e.g. failure mode and effect analysis) could lead to unpredictable results.

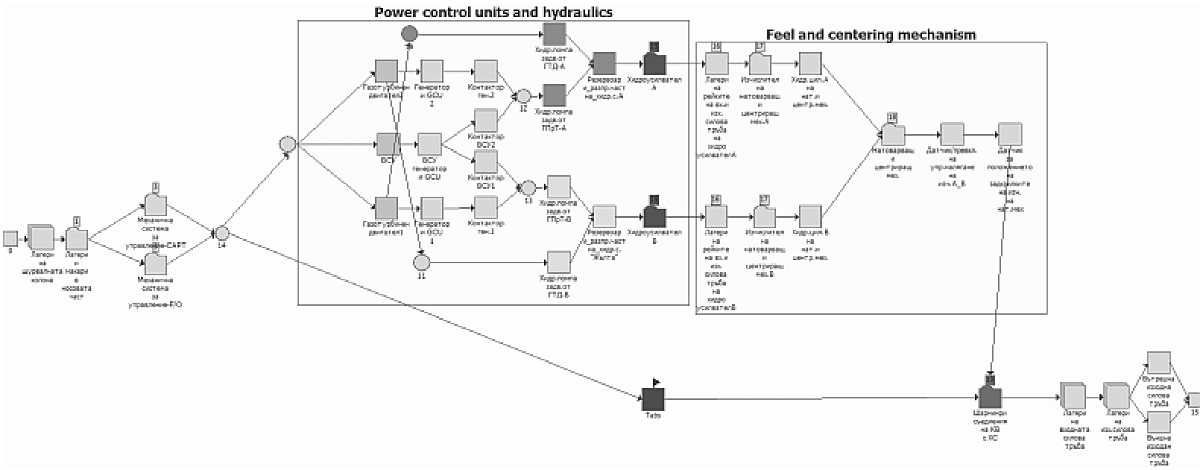

Fig. 2: Detailed RBD of example elevator control system, main diagram

Conclusion

Several approaches for system reliability assessment based on service experience are discussed and two example studies are presented.

The first problem to work out is analysis of operational history of the system/component. When rare events are considered it is important to use all available information. This means searching through a lot of records (not only for the aircraft type under consideration). Manual categorisation of past occurrences is impractical. The approach used in this work is selection of combination of categories and keywords for filtering and full-text search of available databases. Thus, the number of records for manual review is reduced. More advanced methods for automatic categorisation according to the needs of the specific study could improve analysis accuracy and completeness.

Particular attention should be paid to common cause failures of reserved components (multiple failures). Database schema should explicitly allow such information to be included. In addition, database users should be trained to recognise and appropriately mark such events.

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