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Monte Carlo simulation based time limited dispatch analysis with the constraint of dispatch reliability for electronic engine control systems

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ABSTRACT

Time Limited Dispatch (TLD) allows a degraded redundant system to operate for a limited length of time before repairs are required. Existing TLD analysis methods do not consider the requirement of dispatch reliability as a constraint, thus unacceptable flight delays or cancellations may occur when aircraft are dispatched following the intervals determined by existing methods. In this paper, an improved TLD analysis method with constraints of both dispatch reliability and average safety levels is proposed for Electronic Engine Control System (EECS) based on Monte Carlo simulation. Dispatch strategies for multiple fault TLD models are presented, maintenance strategies for multiple fault TLD models are discussed, and a step by step procedure of Monte Carlo simulation based TLD analysis is proposed. Finally, a case study illustrates the effectiveness of the proposed method, and a TLD analysis of an EECS is given to show the application of our method to a practical system.

1. Introduction

The concept of time limited dispatch (TLD) originated during the development and certification of Full Authority Digital Electronic Control (FADEC) systems used on the turbine jet engines of the Boeing 767 airplane. Aircraft and engine manufacturers recognized that redundancy features could provide means for reducing aircraft delay and cancellation events by enabling redundant systems to dispatch with faults. The concept of TLD is one wherein a redundant system with faults is allowed to operate for a predetermined length of time before repairs are required [1]. TLD operation has been applied to FADEC systems equipped engines used in multi-engine aircraft applications, particularly those engines used in large transport aeroplanes. Once the TLD operation has been approved, maintenance actions can be scheduled at specific time intervals. Not all faults are required to be rectified prior to the next flight. Therefore, flight delays or cancellations can be avoided or reduced [2,3].

TLD operation is conditional upon that average safety levels of Electronic Engine Control Systems (EECS) can be maintained, and the safety of the degraded system operating with faults can be adequate to satisfy the requirements of certification authorities [3].

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In a TLD analysis, the average safety level of EECS is denoted by $\bar{\lambda}_{\mathrm{LOTC}}$ [1], whose accurate definition is the frequency of Loss of Thrust Control (LOTC) events [4]. It must be noted that when the frequency of LOTC events increases, the safety level will decrease. The safety of the degraded EECS operating with faults is measured by the instantaneous LOTC rate [1,4–9], which indicates the significance of the faults present. The average safety level of EECS used in large transport aeroplanes should be better than or equal to 100 000 hours for faults that result in one LOTC event, namely, $\bar{\lambda}_{\mathrm{LOTC}}$ should be less than 10^{-5} failures per hour. In the case that $\bar{\lambda}_{\mathrm{LOTC}}$ is less than 10^{-5} failures per hour, dispatch strategies are decided by the instantaneous LOTC rate which is treated as a constant value in most literature. We usually have four dispatch categories [1]:

1) No Dispatch (ND), the EECS is not allowed to be dispatched if its instantaneous LOTC rate is greater than 100 failures per million hours;

2) Short Time Dispatch (ST), the EECS should have a short time dispatch interval T_{ST} if it has suffered a significant loss in redundancy or its instantaneous LOTC rate is between 75 and 100 failures per million hours;

3) Long Time Dispatch (LT): the system could have a long time dispatch interval T_{LT} if the instantaneous LOTC rate is less than 75 but greater than 10 failures per million hours. We have $T_{\mathrm{LT}} > T_{\mathrm{ST}}$;

Nomenclature

Acronym

BSV	Burner Staging Valve
CCDL	Cross Channel Data Link
EASA	European Aviation Safety Agency
ECU	Engine Control Unit
EECS	Electronic Engine Control System
FAA	Federal Aviation Administration
FADEC	Full authority digital electronic control
FMV	Fuel Metering Valve
FU	Full-up
HMU	Hydro-Mechanical Unit
HPTCC	High Pressure Turbine Clearance Control
LPTCC	Low Pressure Turbine Clearance Control
LOTC	Loss of thrust control
LT	Long time dispatch
MTTF	Mean Time to Failure
N1	Lower Pressure Rotor Rotational Speed
N2	High Pressure Rotor Rotational Speed
ND	No dispatch
P0	Ambient Static Pressure
PS12	Fan Inlet Static Air Pressure
ST	Short time dispatch
T3	High Pressure Compressor Discharge Air Temperature
T12	Fan Inlet Total Air Temperature
T25	High Pressure Compressor Inlet Air Temperature
T49.5	Exhaust Gas Temperature
TBV	Transient Bleed Valve
TLA	Thrust Level Angle
TLD	Time limited dispatch
TWA	Time weighted average
VBV	Variable Bleed Valve
VSV	Variable Stator Valve

Notation

$\bar{\mathbf{0}}$	Vector whose all elements are 0
ε	An arbitrarily small positive real
λ_A	Identical failure rate of component A1 and A2
λ_B	Identical failure rate of component B1 and B2
λ_C	Failure rate of component C
λ_i	Failure rate of the ith component
$\bar{\lambda}_{LOTC}$	Average safety level of FADEC system
$\lambda_{LOTC}(t)$	Instantaneous LOTC rate at time t
λ_{MaxLT}	Maximum value of $\lambda_{LOTC}(t)$ in ST dispatch interval
λ_{MaxST}	Maximum value of $\lambda_{LOTC}(t)$ in LT dispatch interval
$\lambda_S(t)$	Instantaneous failure rate of a system at time t
μ_{FB}	Repair rate from the LOTC state to the FU state
μ_{LT}	Repair rate of LT faults
μ_{ST}	Repair rate of ST faults
μ_{ND}	Repair rate of ND states
N_{ND}	Number of ND states that have occurred
N_{sim}	Number of finished simulations
R_D	Dispatch reliability
$R_i(t)$	Reliability function of the ith component
$\boldsymbol{R}(t)$	Vector whose elements are $R_i(t)$ $(i = 1, 2 \cdots n)$
$R_S(t)$	System reliability function
s_i	State of the ith component
$\boldsymbol{S}$	State vector of components, its elements are s_i $(i = 1, 2 \cdots n)$
t_i	Time when the state of the ith component will change
$\boldsymbol{T}$	Time vector of components, its elements are t_i $(i = 1, 2 \cdots n)$
t_m	Next moment when the state of a component will change, it is also the time when the state of the ith component will change
$t_{rand}^{(m)}$	Random number generated according to the lifetime distribution of the mth component
T_{FL}	Average flight time
T_j	A sample of time between LOTC states determined by the jth simulation
T_{ST}	Short time dispatch interval
T_{LOTC}	Mean time between LOTC states
$T_{LOTC}^{(0)}$	Initial value of T_{LOTC}
$T_{LOTC}^{(N_{sim})}$	Value of T_{LOTC} determined by N_{sim} simulations
T_{LT}	Long time dispatch interval
$T_{ND\text{-}LOTC}$	Mean time between ND or LOTC states
$T_{ND\text{-}LOTC}^{(0)}$	Initial value of $T_{ND\text{-}LOTC}$
$T_{ND\text{-}LOTC}^{(N_{sim})}$	Value of $T_{ND\text{-}LOTC}$ determined by N_{sim} simulations
$E_{LOTC}^{(N_{sim})}$	Absolute value of the difference between $T_{LOTC}^{(N_{sim})}$ and $T_{LOTC}^{(N_{sim}-1)}$
$E_{ND\text{-}LOTC}^{(N_{sim})}$	Absolute value of the difference between $T_{ND\text{-}LOTC}^{(N_{sim})}$ and $T_{ND\text{-}LOTC}^{(N_{sim}-1)}$

4) Manufacturer/Operator defined Dispatch: the dispatch interval for certain faults may be agreed upon between the manufacturer and the operator as these faults do not affect the LOTC rate.

If an approval is sought for dispatch with faults present in an EECS, a TLD analysis must be carried out to determine the dispatch intervals [2]. As T_{ST} used in analysis is usually fixed at 250 hours for an entry level EECS, the objective of the TLD analysis is only to determine T_{LT} in most situations. In the TLD analysis, $\bar{\lambda}_{LOTC}$ is treated as a function of T_{LT}, so T_{LT} can be calculated via the function when the value of $\bar{\lambda}_{LOTC}$ is given [1,2].

In the present TLD analysis, $\bar{\lambda}_{LOTC}$ is the only requirement considered in determining T_{LT}, other requirements such as flight delay rate and flight cancellation rate are not considered. Dispatch reliability (R_D) is defined as “the percentage of scheduled flights which depart without making a mechanical delay of more than 15 minutes or cancellation”. It is an important measure for aircraft design and operation [9]. Low dispatch reliability means that flight delays or cancellations occur frequently; consequently, the operation cost of airlines will increase [10,11]. In this paper, R_D and $\bar{\lambda}_{LOTC}$ are both considered as constraints in the TLD analysis. A Monte Carlo simulation procedure is proposed to get the values of R_D and $\bar{\lambda}_{LOTC}$ according to the assumed T_{LT} value. When a series of assumed T_{LT} values are given, curves of R_D and $\bar{\lambda}_{LOTC}$ can be acquired by regression methods. Therefore, R_D is also a function of T_{LT} just as $\bar{\lambda}_{LOTC}$. When the requirements of R_D and $\bar{\lambda}_{LOTC}$ are given, the corresponding value of T_{LT} can be calculated via the two functions. If aircraft are dispatched following the dispatch intervals determined by our proposed method, $\bar{\lambda}_{LOTC}$ will be accepted by certification authorities, as well as flight delays or cancellations will be acceptable to airlines.

The rest of this paper is structured as follows. In Section 2, the previous work related to the TLD analysis is given and three widely used TLD approaches are discussed. In Section 3, characteristics of multiple fault TLD models are studied, as the ND states which have a close relationship with the dispatch reliability are usually multiple fault states. In Section 4, the solution methodology of the Monte Carlo simulation based TLD analysis is proposed, and the step by step procedure is given to calculate the average