Research on the Particular Risk Analysis Model of Sustained Engine Imbalance on Civil Aircraft

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Abstract. In order to demonstrate the aircraft continued safe flight and landing after fan blade out (FBO), Sustained Engine Imbalance Particular Risk Analysis, as part of the civil aircraft safety assessment, is seriously required to implement. Under the guidance of AC25-24 “Sustained Engine Imbalance”, the specific analysis model are given, combined with engineering application experience on civil aircraft development and certification. The model and methods presented herein provide a valid approach and guidance for safety design requirements capturing in aircraft design and certification demonstration regarding Sustained Engine Imbalance.

1. Introduction

Particular Risk Analysis (PRA) has been difficulty in civil aircraft safety assessment, which is also highly interested by authority during civil aircraft certification compliance demonstration. Sustained Engine Imbalance (SEI) listed in SAE ARP4761[1], which need to be verified in civil aircraft certification, required multi-knowledge, long period continuous analysis and high standard qualification. There is still no matured SEI PRA method for civil aircraft development and verification in China.

Based on the engineering practice, it is certainly necessary to capture safety design requirements derived from SEI at the beginning of the aircraft design, and implement these requirements in aircraft structure, strength and system equipment design. During the verification and certification phase, to conduct the planned verification activities, including aircraft structure and strength assessment, system critical equipment qualification test, cockpit flight crew human factors assessment and aircraft level safety assessment could contribute efficiently to final aircraft type certification. Meanwhile, the re-work risk would be minimized to save aircraft development milestones.

2. Sustained Engine Imbalance

SEI is an event caused by a complete or partial engine fan blade out event (FBO), as shown in Fig.1. It shall be demonstrated that after FBO the airplane is capable of continued safe flight and landing. Both wind-milling and high power imbalance conditions shall be considered [2].
2.1. High Power Condition
The high power imbalance condition occurs immediately after blade failure but before the engine is shut down or otherwise spools down. This condition addresses losing less than a full fan blade which may not be sufficient to cause the engine to spool down on its own. This condition may last from several seconds to a few minutes.

2.2. Wind-milling Condition
The wind-milling condition results after the engine is spooled down but continues to rotate under aerodynamic forces. The wind-milling imbalance condition results from shaft support failure or loss of a fan blade along with collateral damage.

3. Safety Requirements
The section 3.4.2 “Blade Out/Engine Vibration Assessment” of Example Safety Program Plan given by SAE ARP4754A requires: “An assessment of engine vibration following a single blade loss and its possible effects on the aircraft will be developed to ensure the aircraft remains capable of continued safe flight and landing. Particular focus will be on whether the flight crew can perform their functions and maintain adequate control of the aircraft during high vibration scenarios.”[3]

According to CCAR25-R4[4], the airplane safety requirements regarding SEI particular risk are listed in Table1.

| Regulations | Safety Requirements |
|-------------|---------------------|
| 1 25.901(c) | For each powerplant installation, it must be established that no single failure or malfunction or probable combination of failures will jeopardize the safe operation of the airplane. |
| 2 25.903(c) | There must be means for stopping the rotation of any engine individually in flight, only where continued rotation could jeopardize the safety of the airplane. |
| 3 25.903(d) | Design precautions must be taken to minimize the hazards to the airplane in the event of an engine rotor failure. |

4. Sustained Engine Imbalance PRA
Normally, aircraft safety team will lead SEI PRA and make specific work plan. Structure, strength, system design and cockpit flight crew team will conduct those activities under this work plan. The specific activities shall include design and assessment, qualification test, human factors assessment, etc. Fig.2 shows the analysis model regarding SEI PRA. The following chapters describe each main activity.
4.1. **SEI PRA Work Proposal**

Aircraft safety team shall derive the design requirements from SEI event at the early stage of aircraft design, directly based on CCAR25-R4 applicable regulations and AC25-24. Structure design, system integration and equipment supplier shall capture these requirements to ensure the design. Safety team also shall make the entire SEI compliance demonstration working plan and activities for each development phase of aircraft. The main activities for each team are listed as following:

- **Strength team** to define the aircraft vibration spectrum regarding both SEI high power condition and wind-milling condition.
- **System design team** to define the critical equipment, whose failure (loss or abnormality) could cause a catastrophic or hazardous failure condition.
- **Equipment supplier** to conduct the critical equipment vibration qualification test according to the mechanical environmental conditions required by aircraft.
- **Structure team** to assess the impact on aircraft structure caused by SEI particular risk.
- **Strength team** to assess those critical equipment vibration qualification test reports to decide approval or not.
- **Cockpit flight crew** to implement human factor assessment regarding SEI particular risk.
- **Aircraft safety team** to conduct final round safety assessment, based on the structure result, critical equipment test report, human factor result, combined with aircraft functional hazard analysis and fault tress analysis.

4.2. **Aircraft SEI Vibration Spectrum**

SEI vibration spectrum includes high power and wind-milling vibration spectrum. The tests aim to ensure the critical equipment could maintain its norm function under such kind of environmental conditions. Normally, to define the SEI vibration spectra following the steps:

- **General team** to define aircraft diversion profile. Fig.3 shows the typical aircraft diversion profile for twin-engine mounted aircraft.
- **Engine supplier** to define the engine rotation speed of wind-milling state and durations, and vibration frequency, amplitude for both FBO occurrence and wind-milling state, based on the mechanical interface between engine and pylon.
- **Strength team** to define the aircraft vibration spectrums regarding SEI with the input from engine supplier. Fig.4 shows the typical high power vibration spectrums for each zone. Curve R shall be applied to fuselage, instrument panel, console and equipment rack; Curve P shall be
applied to nacelle, pylon, engine, gear box, wing, wheel well, landing gear, empennage and fin tip. The wind-milling vibration spectrums varies greatly depending on aircraft design configuration.

4.3. Equipment Supplier Qualification Test

Equipment supplier shall capture the SEI vibration qualification test requirements at the early stage of aircraft development. These requirements shall be involved in product design as a part of design requirements. Then supplier shall conduct critical equipment vibration qualification test for both high power condition and wind-milling condition, and submit test report to aircraft for further assessment and approval.

Supplier shall ensure the equipment normal function after SEI vibration qualification test, which means the equipment could provide normal function without loss or abnormality. SEI vibration qualification test could not replace equipment functional vibration test and endurance vibration test.

4.4. Aircraft Structure Design and Assessment

It is required to demonstrate that the aircraft primary structure could endure the combined loads caused by flight and SEI vibration.

Additionally, the aircraft structure endurance assessment shall consider SEI particular risk condition. The cumulative fatigue damage caused by high power condition and wind-milling condition
shall be considered in the “fail-safe” structure endurance assessment. It is required to demonstrate that the aircraft could save adequate residual strength in diversion profile when using “damage-tolerance” method. The assessment shall consider the initial crack expand generated by manufacture. The integer crack expand shall include both normal conditions and wind-milling condition[5].

4.5. Cockpit Human Factor Assessment
The cockpit human factor assessment aim to demonstrate the aircraft safety flight could not be impacted by cockpit vibration from SEI particular risk, the flight crew could maintain the safety flight under each flight phase with proper operation.

Normally, the engineering simulator or flight simulator could be used for SEI cockpit human factor assessment. It is required to simulate the flight crews’ reaction and operation under FBO failure and immediate SEI vibration scenario to confirm the safety flight regarding SEI particular risk.

4.6. Aircraft Level Safety Assessment
Aircraft safety team shall perform the ultimate safety assessment based on critical equipment qualification test result, structure design and assessment result, cockpit human factor assessment result, aircraft level functional hazard analysis. It will be determined whether the aircraft safety could be impacted by SEI particular risk or not. The conclusion will be made to state whether SEI particular risk could cause catastrophic or hazard failure conditions.

According to SAE ARP4761, it is not allowed to have catastrophic or hazard failure condition caused by any particular risk. Otherwise, the aircraft final safety assessment conclusion will be made based on the criteria. In case of non-compliance issues, it is needed to turn back to the beginning of the work flow to find the corresponding step to improve until the issue closure. System equipment design change, structure design change, cockpit human factor improvement might be considered under such cases.

5. Conclusion
The SEI PRA model is given based on AC25-24“Sustained Engine Imbalance” and engineering practice, including main activities generated from SEI PRA plan, work-flow for different team and targets. The main technical activities for aircraft safety, structure, strength, system design and equipment supplier, cockpit human factor assessment were described to consolidate each procedure during aircraft development. Methods presented herein provide a valid approach and practical guidance for safety design requirements capturing in aircraft development and an effective technical solution to certification demonstration regarding Sustained Engine Imbalance.

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