有人安全性の定量的評価技術

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Efficient Risk Control based on QRA with considering various uncertainties
QRA based on physics-based simulations
- Physics model, Accuracy and Practicality
- UQ based on limited test and field data
Ultimate Robust Design of Space Systems
Challenges to establish Risk Control based on QRA

- Overcome difficulty of modeling complicated hazard physics to control risk by design and operation.

Reliability
Reliability Challenges – Efficient Reliability Control

1: Overrun of development cost & schedule
- Design is empirical deterministic MOS-based
- MOS is validated in later-phase tests
- Even after certification, failure occurs

2: High cost reliability & life certification
- Large number of system firing test is performed and reliability is evaluated by failure numbers
- Efficient accelerated test is not established

Reliability = \( f(\text{success count}, \text{failure count}, \text{level of confidence}) \)

In H2A rocket development, 140 firing tests is performed in 10 years.

<Estimated human-rated engine certification cost>
3000 firing tests (few billion dollars) is required, means twice of whole cost of HII-A & HII-B development.

Elimination of failure modes
[A] Unknown failure modes
[B] Design consideration

Overrun of development cost & schedule
[C] Development rework by failure modes in later phases
[D] Efficient system reliability evaluation method is not established
[E] Strong dependency on high cost testing

Reliability Challenges – Efficient Reliability Control

▶ Even in later development phase, failure due to design can be happen.
▶ In the worst case, large amount of additional cost and time is required for the failure cause investigation, re-design, and re-certification.

LE-7 Firing Test
Force of JEDI: Quantitative Risk Assessment (QRA)

- Risk is evaluated quantitatively and minimized by appropriate actions.
- All Risk Approach in which all of the failure mode is considered, and both probabilistic and deterministic (rule-base) approach are used.

1. **All failure modes identification**
2. **Design reliability evaluation mainly by numerical simulations**
3. **Uncertainty quantification mainly by low-cost experiments**
4. **Risk mitigation & control based on parameter sensitivity**
   - Redesign
   - Inspection requirement

\[ \text{Risk} = \text{Probability} \times \text{Consequence} \]

Force of JEDI: High Fidelity Simulations

- Rarefied Gas Dynamics
- Reentry Risk Analysis
- Spacecraft Engine
- Propulsion System
- Lattice Structure
- Acoustics
- Rocket Engine
Quantitative Risk Assessment (QRA)

Elimination of Failure Modes
[A] All failure mode identification
[B] Design for each failure modes

Development cost & schedule over-run prevention
[C] Prevent later phase failures to reduce additional tests
[D] Reliability certification mainly by lower cost tests
[E] Reduction of high-cost system tests

Safety
Safety Challenges for Human Space Flight

Catastrophic Hazards ( Explosive )

- Pad Explosion during static firing (Atlas C Abie, 1959)
- Falls back (Atlas-Centar, 1965)
- Loss of Control, Aerodynamic breakup (Ariane 5, 1996)
- Success of crew rescue by LAS Pad Fire (Soyuz T-10-1, 1983)
- Pad Explosion during static firing (Atlas C Abie, 1959)
- Loss of Control, Aerodynamic breakup (Ariane 5, 1996)
- Failure of crew rescue (All crew fatal accident)
- SRB Explosion (STS, 1986)

Crew Safety Improvement

Both reliable launch vehicle and crew rescue system are essential.

Space Shuttle QRA Result

<table>
<thead>
<tr>
<th>Flight Sequence</th>
<th>Loss of crew probability</th>
</tr>
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<tbody>
<tr>
<td>Challenger</td>
<td>1/12</td>
</tr>
<tr>
<td>Columbia</td>
<td>1/90</td>
</tr>
<tr>
<td>1/10</td>
<td>1/10</td>
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<tr>
<td>1/5</td>
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<tr>
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Safety Challenges for Cargo and Crew Transfer

Cargo Transfer
Ground Safety:
Flight Termination
Destructive Reentry

Crew Transfer
Crew Safety:
Rescue System
(LAS, Evacuation System)
Ground Safety:
Flight Termination

Launch Abort System (LAS)
Destructive Reentry
Evacuation System

Improvement in reliability
Vehicle Failure Rate [-]

Improvement in crew rescue system such as LAS

1/10^0 1/10^1 1/10^2 1/10^3 1/10^4 1/10^5
0.0 1/500 1/250 1/167 1/125 1/100

1/5 1/10 1/20 1/100
Quantitative Safety Assessment – Efficient Safety Control

[Objectives]
- Establishment of quantitative safety analysis method
  (Safety design, TRL increase for future decision)
- Feasibility study of LAS (Conceptual design, safety requirement)

[Development of Technology]
Quantitative safety analysis technology based on high-fidelity numerical simulations
1) Safety design in early design phases, 2) Appropriate reliability/safety requirements,
3) Decrease in validation test cost

[Success Criterion]
- Realization of full phase abort feasibility (as conceptual design)

High Fidelity Simulations for Safety

▷ Models for Failure Mode Physics.
▷ Joint research with univs and automobile fields.
**Objective - High Fidelity Simulations for Safety**

**[Crew Injury]**
- Japanese decision making for JAXA’s astronaut missions.
- Establish physics-based injury risk model and investigate mechanism.

**[Explosion Process]**
- Possibility to ease trajectory restriction by accurate safety analysis.
- Additional performance, etc...

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**High Fidelity Hazard Simulations – Contribution to Engineering**

**<Contribution to other fields>**
Establish serious research communities and improve high-fidelity simulation capability.

**Destruction and explosion**
- In the fields of hydrogen automobile, fuel cell, LH2 storage tanks, transportation of nuclear waste, investigation of the hazard mechanism & QSA for rare event is essential.
- Demands for the QSA getting significant.
- Since hazard simulation technology is key to keep the quality of Japanese products, the investigation to establish QSA is meaningful.

**Occupant Safety**
- Safety is the key for the international competitiveness for the automobile and trains.
- Open collaboration framework is employed in this research project to achieve the goal!
Explosion Process Modeling - Motivations

- Motivation to establish explosion process model are
  1. Understand hazard physics
  2. Cost reduction of uncertainty quantification test ( = Less uncertainty )
- In order to achieve goal above, numerical model for destruction and explosion process & efficient risk assessment technique are essential

Explosion Test

Explosive Yield Model
(Uncertainty/Variation)

Blast-wave(BW) Model
(Speed, OP Decay)

Explosion Process Modeling - Destruction

- Constitutive eq. and failure criterion for liquid rocket tank (Al-alloy) were developed.
- Strain-rate and temperature dependencies are modeled to predict destruction process.
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Strain-rate and temperature dependencies are modeled to predict destruction process.
**Explosion Process Modeling - Destruction**

1) Multi-Physics Analysis
   - Structure / Fluid / Heat transfer of Multiple Shape in 6-DoF motion
2) Deforming Complicated Shape
3) Coupling analysis with Fluid Dynamics
   - Condition dependent flow structure
   - Evaporation
   - Reactive Flow (Combustion)

**Explosion Process Modeling - Ignition**

- Ignition delay, its location and energy are key driver of the explosive yield.
- Ignition mechanisms and conditions at which ignition and flame hold were investigated.


Explosion Process Modeling - Fall back failure

Landing Acceleration – Validation study

Analysis: LS-DYNA ALE, CIP-LSM
Approach: Analytical, HTV-R6.8%, Apollo1/4
Condition: Velocity and pitch angle (incl. off-nominal)

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Cell Size [m]</th>
<th>Az Max [G]</th>
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<tbody>
<tr>
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<td>Mesh5</td>
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Work by Shunnosuke Inoue, Shinsuke Sakai (Univ. of Tokyo)

Landing Acceleration – Validation study

Computation Vv=9m/s

Experiment Vv=9m/s

Computation Vv=7m/s

Experiment Vv=7m/s

Work by Takuya Furumoto, Takehiro Himeno (Univ. of Tokyo)
Quantitative Crew Safety Analysis

Physical models have been developed with joint research with universities.

(1) Acceleration
- Various magnitude and direction
- Design for Safety (Dumper, Seat, etc.)

(2) Human Response
- Over pressure
- Aerodynamic force
- Blast wave

(3) Injury Risk
- Injury Probability
- Injury Scale

Design for Safety

FEM-based dummy model has been validated for the design spacecraft seat.

Further crew safety improvements have been achieved by the comprehensive consideration on the design for safety.
To establish practical probabilistic analysis for QRA, efficient design-of-experiment methods have been investigated.