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Investigations on the Crew Injury Biomechanics and Spaceship Seats Safety Design for Human Space Flight

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Abstract

Quantitative crew safety assessment method was proposed, and continuous research efforts had been made to maximize the crew safety to keep sustainability of the challenging human space flight missions. Key physics-based models to predict the water landing accelerations and the crew injury risk for the transient dynamic loads were developed. Two hazardous scenarios are considered, the one is the large dynamic loads due to the off-nominal excessive water landing speed and the unfavourable crew module attitude and the other is due to the blast-wave over pressure generated by the launch vehicles' failures. At first, these dynamic loads were predicted and selected as the reference conditions for the crew injury risk predictions. Multi-body dynamics and finite-element models of Hybrid III anthropomorphic test device (ATD) were validated by the comparison with the sled test with including the lateral impact, which is the specific conditions of the human space flight. Crew injury risk was evaluated for the reference dynamic load conditions, and the injury mechanisms were investigated based on the numerical and the sled test results. Quantitative crew injury risk assessment was carried out for the water landing loads of the capsule-type crew module concept. Water landing accelerations under wide range of landing conditions were obtained based on the fluid and structure interaction analysis based on Arbitrary Lagrangian Eulerian (ALE) solver and the penalty coupling method of LS-DYNA®. Corresponding crew injury risk distributions were also predicted by using the multi-body dynamics model of Hybrid III ATD for the rigid seat. Key findings of the crew injury mechanism to improve the crew safety were obtained and presented. Finally, the design for safety studies on the spaceship seat were conducted to maximize the crew safety. Large magnitude accelerations were successfully reduced by the design optimization of the lateral and axial dampers. It was confirmed that the resulting injury metrics values even for the most severe landing condition are within the NASA's acceptance risk level for the off-nominal cases. It was found that the design for safety strategies such as the zero-gap concept and the adapted seat liner with the soft padding are key elements to achieve higher-level of crew safety.

1. Introduction

Humans have been continuously expanding frontier into the space with remarkable progress both in the space sciences and the engineering. In the field of the human space flight missions, more than 50 years have been passed from the first human spaceflight of Yuri Gagarin in 1961. The first humans landing on the moon by Neil Armstrong and Buzz Aldrin in the NASA Apollo program in 1969 is another remarkable achievement. International Space Station (ISS) project has been initiated from its first on-orbit construction in 1999. The ISS is not only an in-space platform for demonstrating technologies and capabilities and performing the research, but it is currently focused as the destination of the human space flight program of most countries.

New era is going to be opened toward the moon, Mars and beyond based on the international collaborations. Since the destination and the mission goal are getting challenging, further innovations in the engineering to minimize the risk should be achieved. In terms of the crew safety, the crew transportation to the orbit is still one of the dominant

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risk drivers. In order to continue the sustainable human space missions and also to eventually establish accessible space travel, it is essential to enhance crew safety beyond its current level. Further improvements in both the space transportation system's reliability and the crew rescue success rate are crucial to maximize the crew safety. Therefore, the efficient risk control methodologies to realize ultimate robust system has been proposed and investigated in this study [1][2]. One of the promising approaches to innovate risk control is the system development based on the quantitative risk assessment (QRA), in which the likelihood and the consequence of the failure mode are quantitatively evaluated mainly by the physics-based models such high-fidelity numerical simulations. Main cause of the space system failures are the poor understanding of the relevant physics and the lack of the physics model accuracy, the less consideration of the uncertainty of product and the environmental parameters. Such uncertainties are considered in the probabilistic design analysis based on the high-fidelity numerical simulation, the design and operation change effect on the risk can be evaluated as well. Therefore, the appropriate design margin can be considered, and the strategic planning of the uncertainty quantification experiment based on the sensitivity analysis becomes possible. Detailed and appropriate understanding of the relevant physics mechanism is also the key to establish the robust system.

Most difficult challenges to establish QRA-based development methodology are simply the development of the physics models required for the high-fidelity numerical simulations, the reduction of the time for the probabilistic analysis, and the establishment of the uncertainty quantification process. In terms of the system reliability especially for the liquid rocket vehicles, various aspects of the research efforts have been made and the practical applications to the rocket development or risk assessment activities have been carried out [3][4]. Development of the next-generation rocket H3 is under the way at Japan Aerospace Exploration Agency (JAXA), herein the high-reliability development process based on the QRA has been proposed and applied for the booster engine LE-9 development [4]. LE-9 is the expander-bleed cycle engine which has the advantages such as the low cost due to the small part numbers and the inherent safety to prevent the catastrophic failures. Fundamental process and its supporting tools have already been developed and applied to the real development process, and its effectiveness will be reported after finishing development and the initial phase of the operations.

In terms of the crew rescue success rate improvement, the quantitative crew safety assessment method has been proposed and the continuous research efforts to establish the methodology have been made [2][5][6]. Most of the recent human-rated space transportation system is based on the spaceship located top on the rocket core stages, and the spaceship is equipped with the launch abort system (LAS) for the crew rescue in case of the catastrophic failures. Success rates of the failure detection, the spaceship evacuation from the hazard source, the transition maneuver going back to the ground, and the descent and recovery are evaluated for each possible failure scenario [5]. Schematic overview of the quantitative crew safety analysis models for the spaceship evacuation from the explosive hazard is shown in Figure 1 [2]. There are two physics-based models to predict the crew rescue success rate, the one is the probabilistic trajectory analysis for the maneuver and the descent and the other is the evacuation success limit model from the hazards. Explosion hazard is one of the dominant risk drivers, since its likelihood is relatively higher, the required time to be the hazardous state is very small, the propagation speed and the extent of impact are larger. If the blast-wave overpressure level is still large when it reaches the spaceship, the spaceship can be the loss-of-control due to the large aerodynamic characteristics change, the structure failure and the crew injury or fatality. Excessive speed or unexpected attitude at the landing are also dominant risk factors those can be resulting in the spaceship turn-over and the crew injury or fatality. Most of the physics models such as the aerodynamics, the trajectory, and the structural dynamics have already been developed and applied to various design problems of the rockets and the re-entry vehicles. It is apparent that the crew injury risk prediction models are important for the decision make based on the quantitative safety assessment not only for the nominal end-of-mission but for the launch abort scenario. Since the safety assessment and related decision making are essential to support the current JAXA's astronaut missions, the quantitative crew safety analysis has significant advantages to quantitively assess crew safety with including the correct understanding of the physical mechanisms. Most of the design and operation considerations for the human transportation vehicles are carried out mainly for the US standards, and the averaged body size and mass properties of the Japanese astronauts are different from the US standards. Furthermore, Japanese astronauts would have the opportunity to be transferred by the commercial companies such as the Dragon spaceship serviced by SpaceX, and thus it is important to have the predictive crew injury risk analysis tools to investigate the injury mechanisms and the expected risk based on the limited design data. In addition to these JAXA's aspect, there is growing interest by the aerospace ventures to conduct the conceptual design and the feasibility studies of the human space flight in Japan. Establishment of the quantitative crew safety analysis methods and providing validated analysis tools would be the significant contribution to promote the Japanese aerospace ventures' activities.

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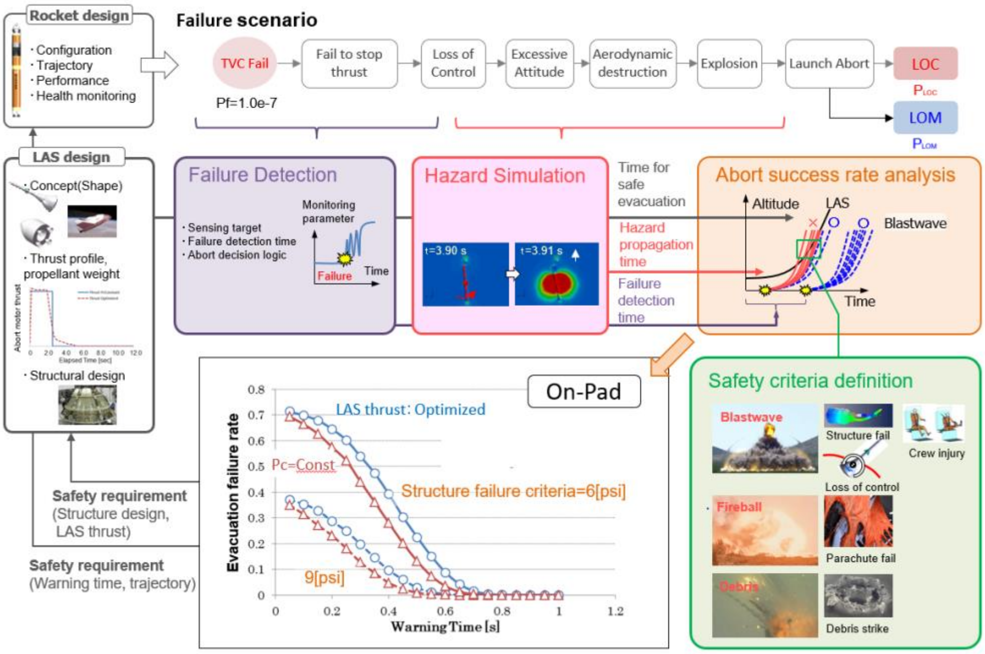

Figure 1: Quantitative crew safety analysis method for the evacuation success rate of LAS [2].

2. Research Objectives

Research needs to establish the quantitative crew safety analysis are significant, so that the one of the main objectives of this study also lies in the establishment of the physics model to predict the crew safety. In order the establish quantitative crew safety analysis models to support the human space missions by JAXA's astronauts, this joint research activity has been initiated in 2013. Research objective is generally to develop the high-fidelity numerical simulation models and those validations to establish the quantitative safety assessment. Based on the assessment of the failure scenario developed in the QRA activity at JAXA, the dominant physics-based models have selected for the joint research items. Those are 1) the destruction and explosion model for the liquid rocket tanks, 2) the water landing load model, and 3) human injury risk model for the dynamic loads. Model development results and the key findings are described especially for the water landing impacts and the human injury risk model for the dynamic loads in this report.

Identified research items to be reported in this paper are as follows,

a) Development of the water landing acceleration and the crew injury risk model for the dynamic loads
c) Design-for-safety analysis to investigate the relevant physics mechanism and to obtain the key findings

Some of the research results have already been reported in the present author's literatures as follows,

- Validations of the multi-body dynamics for Hybrid III anthropomorphic test device (ATD) on the rigid seat by comparing with the sled test [7]
- Crew injury risk prediction, investigation of the injury mechanisms and the uncertainties on the brain injury risk metrics BrIC for the launch abort systems [8]
- Overview and status report of the crew injury risk prediction model development [9] [10]

Since the present research activity in last 5 years has been concluded in the fiscal year 2017 of Japan, the major research results and the key findings are overviewed, and the additional research results especially for the water landing acceleration model and the design-for-safety studies are presented and discussed. In addition, the design optimization of the spaceship seat and the feasibility studies to meet the NASA's safety criterions including the validation by the sled tests are also presented and discussed in detail. It is important note that the design optimization study for the lateral and axial dampers has been carried out under the joint research between the TS TECH Co., Ltd and OILES Co., Ltd. Safety design optimization of the spaceship seat and the preliminary certification sled test are carried out as the in-house research of TS TECH Co., Ltd.

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3. Quantitative crew safety analysis

Main purpose of this study is to establish the crew safety analysis method especially for the transient dynamic loads such as the blast-wave overpressure and the water landing impacts, those are dominant key risk drivers as already shown by the launch vehicles failures and the accidents in the human space flight missions. Research items identified and tackled in the present research activity are as follows,

(1) Discussion on the crew injury risk prediction methods
(2) Development of the water landing acceleration and the crew injury risk model
(3) Design-for-safety studies and the feasibility study to satisfy the acceptable risk level

Overview, research results and discussions are given for each research items in the following sections, respectively.

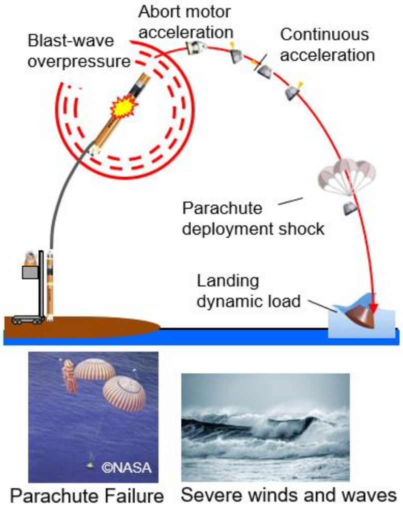

Figure 2: Dynamic loads during the launch abort.

3.1 Crew injury risk prediction methods for human space flight

General process to predict the crew injury risk from the expected spaceflight dynamics loads employed in this study is completely based on the NASA's recommended methodology [11][12], which is similar to the injury risk prediction methods applied to the automobile, the aircrafts and so on. Overview of the crew injury risk prediction model for the dynamic load during the launch abort and the nominal end-of-mission re-entry is shown in Figure 3. At first, the transient dynamic loads induced by the blast-wave overpressure and the water landing are predicted by the numerical simulations with the variation in the key parameters. Key parameters for the blast-wave overpressure are the explosive yields and the warning time to activate the launch abort system, those for the water landing are the capsule's attitude and the velocities. Dynamic response of the human body is evaluated for each dynamic load, then the injury metrics values are obtained by the post-processing the dynamic response results. Finally, the injury probabilities are predicted based on the obtained injury metrics values and the risk curves. This process is generally the same as the safety analysis for the automobile and the aircrafts.

Application-specific research items are shown as follows,
1) Identification of the critical injuries induced by the dynamic loads
2) Identification of the ATD to be used to predict the dynamic response and the injury metrics
3) Identification and the specification of the injury assessment reference value
4) ATD bio-fidelity validations to predict the human's dynamic response

Most of the crew injury prediction method is same as the NASA's recommended approaches, which is developed by the intensive research efforts with including the discussion in the expert panels [11][12].

Crew injury prediction framework is summarized for each item listed above as follows,

1) Injuries related to head, brain, internal organs, neck and spines are the critical risk drivers, those should be considered in the crew safety assessment. Critical injuries identified for the human space flight are as follows, head injury, facial trauma, cervical spine trauma, blunt trauma, lung contusion, rib fracture, hemopneumothorax, upper extremity joint injury, upper extremity fracture, femoral head fracture, thoracic spine trauma, lumber spine trauma, lower extremity joint injury, and lower extremity fracture.

2) Hybrid III, THOR and the world SID are selected for the ATD.
Most of the ATD is designed for the specific direction, Hybrid III is mainly designed and validated for the frontal impact (eye-ball in/out direction) and it should be modified for the lateral impact. THOR ATD is designed to have superior advantages of the multi-directional applicability, but further research efforts should be made to complete the validation. World SID is selected for the side loads.

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3) All possible accident scenario, the critical injuries and the injury process should be considered by the combinations of the ATDs and the injury metrics. Definitions of the injury metrics to be focused in the present study are shown in Figure 4. Injury metrics is designed to be evaluated by the human body's dynamic response characteristics such as the total impulse and the accelerations as shown in Figure 4. HIC is the head injury criterion which corresponding on the translational total impulse evaluated based on the head acceleration. BrIC is the criteria for the brain injuries, which is evaluated by the maximum head rotation rate. Axial compression and tension neck loads are the criterions for the neck related injuries such as the neck fractures and the neurological disorders at neck part. Chest deflection is the criterion for the thoracic injuries such as the lung contusion. Spine axial load is the criterion for the spine related injuries such as the thoracic spine trauma and lumber spine trauma. More detailed descriptions on the mapping process and its results can be referenced in the NASA's literatures [11] [13].

4) Hybrid III is established ATD especially for the frontal impact problems (X direction), which is widely used for the automobile field. Injury criterions are readily available. Since Hybrid III is not suitable for the dynamic response against the side loads (Y direction), World SID is applied. For the lateral load problems (Z direction), modified version of the Hybrid III or THOR are used. THOR has the multiple joints are used to build the spine and the neck for the higher bio-fidelity [14].

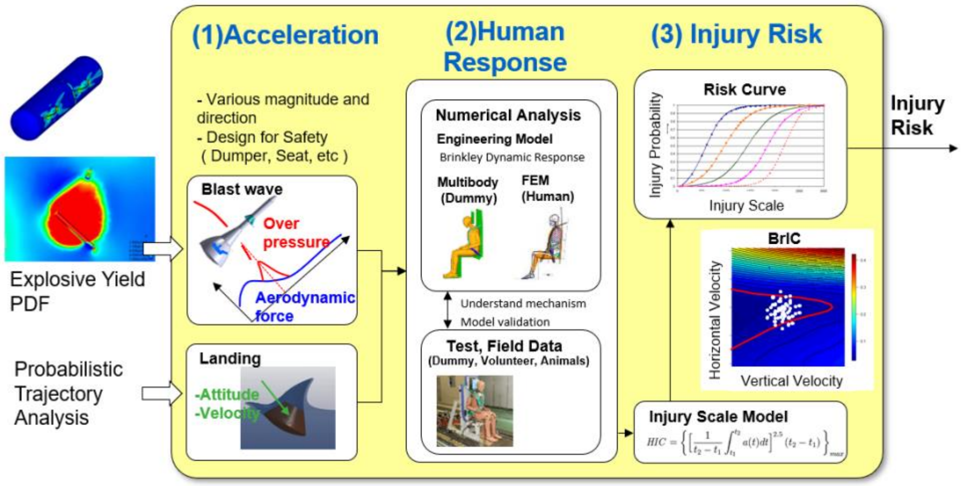

Figure 3: Crew injury risk prediction model for the transient dynamic loads [10].

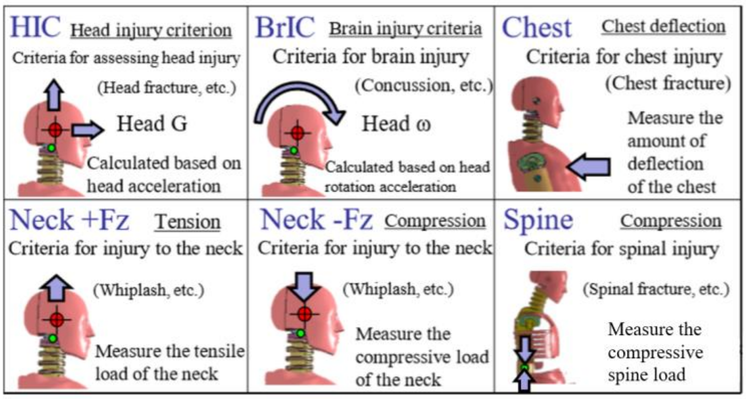

Figure 4: Definitions of major injury metrics.

Various injury scales have been developed to evaluate injury severity and outcomes in other fields such as automobile. The most widely used injury scale is the AIS developed by the Association for the Advancement of Automotive Medicine. In the occupant safety requirements for the human space flight, the crew is required to operate and conduct the task after the accident. While, this is not required in the automobile field. In the case the crew should be evacuated from the spacecraft immediately, the self-egress capability without the any assistance is required. Even if the disability due to the injury has little impact on daily life, it may have the significant impact on the return-to-flight health status. Injury classification score metrics has been developed with considering the original AIS's score, the self-egress

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capability, and the return-to-flight status. Injury classification mapping and the acceptable risk level [11] are shown in Table 1. Landing condition logic diagram is developed to identify the possible scenario and to evaluate the probability of the consequent events based on the initial event probability and the scenario branching probability. Initial event probability is evaluated based on the probabilistic risk assessment (PRA) for Orion project. By linking the landing scenario with the required crew's task, the acceptable risk level for each injury class can be allocated to meet the acceptable mission risk level. Resulting acceptable risk levels for each injury class are shown in Table 1. Those are allocated based on some assumptions such as the off-nominal landing condition can happen 25% probability. Those are also validated by checking the consistency with the field data of Soyuz vehicle. This injury classification and the acceptable risk level are referenced in the present study.

Then, the acceptable probabilities for each injury metrics are allocated based on the acceptable probability of the injury classes as shown in Table 1. To satisfy the desired probabilities of injury associated with all four AIS levels, the minimum values of the injury metrics, injury assessment reference values (IARV) for nominal and off-nominal conditions are selected as shown in Table 2. Since the BrIC was developed for AIS≥4 injury levels and then scaled to other AIS levels, the investigation and its validation are still under the way. There have been some research efforts on the uncertainty quantification of BrIC based on the injury probability field data [15]. IARVs for BrIC are selected to be 0.27 for nominal condition and 0.43 for the off-nominal condition based on the risk curves proposed by Laituri et al [15] and the required probability to satisfy the crew safety requirement.

Table 1: Injury classification mapping and acceptable risk level [11].

Injury Class	Definitions	Acceptable risk level [%] *3	
		Nominal	Off-nominal*1
Class I (AIS1+)	[Minor] Minor injury that would not impede performance or egress, no long-term health risks	4.8	19.1
Class II (AIS2+)	[Moderate] Moderate injury that may delay self-egress, possible short-term health risks	1.0	3.9
Class III (AIS3+)	[Severe] Significant injury that would require assisted egress and subsequent survival operations; possible long-term health risks	0.03 (0.27) *2	0.11 (1.1) *2
Class IV (AIS4+)	[Life-Threatening] Severe injury and possible threat to life, probable long-term health impacts	0.03	0.11

*1 Off-nominal recommendations based on up to a 25% incidence of off-nominal landings
*2 Acceptance of recommendations in brackets assumes SAR forces will get access to the crew members within 30 minutes of the mishap occurrence.
*3 NASA recommendation are consistent with the results of Soyuz vehicle.

Table 2: NASA recommended injury assessment reference values [11].

Injury Assessment Reference Values (IARV)	Nominal	Off-Nominal
HIC15	340	470
BrIC	0.27*1	0.43*1
Neck axial tension force [N]	760	860
Neck axial compression force [N]	500	950
Maximum chest deflection [mm]	25	32
Thoracic spine axial compression force [N]	5000	5600

*1 Since BrIC is still in the development and validation, IARV by Laituri et al [15] is used.
*2 Decondition effects are also considered.

3.2 Development of the water landing acceleration and the crew injury risk model

In the present study, the injury risk due to the dynamic transient loads during the human space flight is focused. Possible dynamic acceleration causes are the dynamic load at the landing, the parachute deployment shock, the abort motor acceleration, and the blast-wave over pressure as shown in Figure 2. Since the acceleration characteristics of the LAS can be controlled by the optimization of the abort motor thrust profile, which is already discussed in the present author's study [16]. Key uncertainty factors on the LAS acceleration are its activation altitude and the abort motor's temperature. Although effect of these parameters on the crew injury should be considered based on the probabilistic trajectory analysis, the acceleration level can be reduced to the acceptable level. Dynamic loads due to the parachute

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deployment are depending on the parachute system such as the parachute type, the size, porosity and the reefing availability, and the dynamic pressure. Dynamic loads due to the parachute deployment can be relatively easily controlled by the design as well. Although it is needless to mention, however the landing should be performed in every mission including the nominal end-of-mission re-entry and the launch abort case, and the occurrence of the off-nominal landing conditions is not small. Therefore, the resulting crew injury or fatality risk related to the landing load becomes larger as comparing with the others. Explosion related consequences such as the blast-wave overpressure, fire-ball's radiation, and the debris strike are the typical catastrophic hazards, whose likelihood is not small and those should be considered as the worst-case scenario in the design of the LAS [17]. From those reasons, dynamic loads due to the landing impact and the blast-wave overpressure are focused in this study.

In the present research project, the following research plan was proposed and adopted.

(1) Setting the reference accelerations for the blast-wave over pressure case and the water landing case
(2) Hybrid-III ADT sled test on the rigid seat and the validation of the multi-body dynamics model
(3) Crew injury risk prediction by the validated model for the reference accelerations
(4) Water landing acceleration prediction under the wide range of landing conditions and the crew injury risk prediction for those conditions

As is already discussed in the previous sections, the dynamic loads due to the water landing and the blast-wave over pressure are important and thus focused in this study. In such conditions, wide range of the three-dimensional dynamic acceleration of the vehicle should be considered in the crew injury risk predictions. Water landing dynamic load is depending on the terminal velocity vector of the crew vehicle, the heat shield angle with respect to the sea surface, and the wave height. Terminal crew modules' velocity vector can be changed dynamically depending on the vehicle's status such as the number of the successfully deployed main chutes and the environmental conditions such as the side wind level and the stochastic wave conditions. Dynamic angular motion of the vehicle is another cause of the water landing loads. Dynamic load induced by the blast-wave over pressure is depending on the overpressure level and the crew vehicle's attitude with respect to the propagating direction of the overpressure. The over pressure level is highly depending on the resulting explosive yields and the warning time for the LAS evacuation start. In order to evaluate the crew injury risk including variations in these uncertainty factors, the efficient probabilistic analysis method is essential. In addition, the safety-related experiment cost is significantly expensive and thus it is unpractical to cover all possible combinations of the uncertainty parameters. Apparently, the high-fidelity numerical simulation is essential to predict the important physics process accurately with limited numbers of the uncertainty quantifications by the comparison with the experiments.

At first, the fundamental understanding of the dynamic acceleration for the water landing and the blast-wave over pressure is conducted. Since the geometry of the lifting re-entry crew module is generally similar, and thus the experimental data of the dynamic acceleration on the water landing for the quarter scale Apollo command module is investigated [18]. Its condition is corresponding to the toe-in splash down. Vertical velocity is 9.1 m/s, the horizontal velocity is also 9.1 m/s and the heat shield angle with respect to the sea surface is 11, 21 and 38 degrees. Resulting accelerations for the normal direction A_x and the longitudinal direction A_z are shown in Figure 5. Resulting maximum normal (eyeball-in) acceleration is 17.5 G, the axial (eyeball-down) acceleration is 6.9 G and those duration is roughly 20 milliseconds for CaseWL2 $\theta = 21°$. When the angle between the heat shield and the sea surface θ becomes smaller, the normal acceleration A_x becomes larger as comparing with A_z. Then, the dynamic accelerations for the blast-wave over pressure are evaluated and investigated to understand the relevant physics process. To evaluate the accelerations induced by the blast-wave over pressure, the 6DoF CFD analysis was carried out in the present author's previous research [19]. Single core liquid hydrogen and oxygen rocket with the tractor-type LAS is considered, which is designed to have 15G acceleration by the abort motor under the vacuum conditions. Blast-wave over pressure level is depending on the released energy depending on the explosive yield and total amount of the propellant, the altitude and the velocity of the rocket at the LAS activation, and the crew module's distance from the exploded launch vehicle. These parameters effect on the induced accelerations were evaluated by the 6DoF CFD analysis. 6DoF CFD analysis conditions for the LAS blast-wave evacuation behaviour are shown in Table 3. Predicted accelerations induced by the over pressure are shown in Figure 5 only for dominant axial direction. Duration of the strong over pressure is ranging from 0.01 to 0.04 seconds. For the larger explosive yield cases, the maximum acceleration level can be even over 80 Gs. If the larger warning time to activate LAS is available, the resulting propagate distance until the over pressure reaches the crew module becomes larger. In that case, the over pressure level can be dramatically reduced. Therefore, the maximum acceleration and the total impulse for CaseBW2 are significantly smaller than that for CaseBW1.

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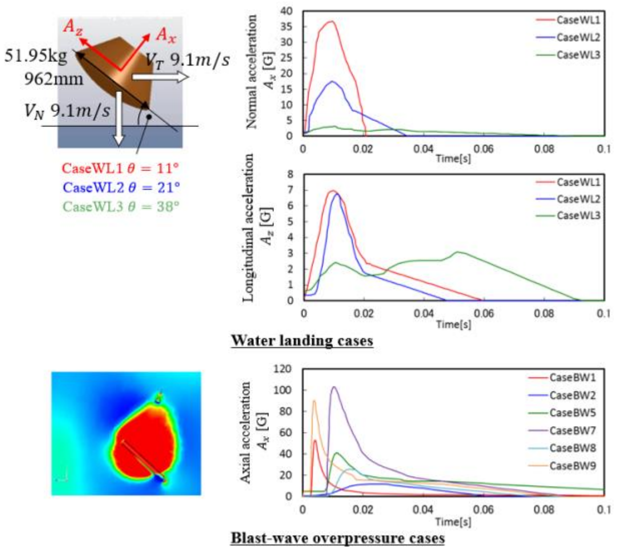

Figure 5: Dynamic accelerations for the water landing and the blast-wave overpressure [19].

Table 3: 6DoF CFD analysis conditions for the LAS blast-wave evacuation behaviour [19].

Case	Explosive Yield [%]	Freestream Mach number	Angle of attack at abort initiation [degrees]	Crew module distance from the explosion center [m]
BW1	4	0.7	0	20
BW2	4	1.4	15.5	40
BW5	12	1.4	31.0	20
BW7	20	0.7	31.0	40
BW8	20	1.4	0.0	60
BW9	20	2.1	15.5	20

At second, Hybrid III ATD sled tests had been conducted to obtain the dynamic response data to validate the numerical analysis model and to investigate the crew injury mechanism in the present author's previous study [7]. Since the frontal or rear impact accident is the important research area to maximize the occupant safety in the automobile fields, the dynamic response of the human body and the crew injury mechanism have already been investigated for many years. However, the lateral load in the eye-ball down direction induced by the vehicles' bottom impact has not been investigated in the automobile field. Therefore, there should be more research efforts to understand the key physics and to maximize the occupant safety. In this reason, the lateral impact to represent the water landing case is considered in the sled test. As shown in Figure 5, the maximum lateral acceleration reaches its limit with θ. Then, CaseWL2 is selected from the water landing cases as the reference accelerations for the sled test. It is technically difficult to consider accelerations in both directions at the same time. In addition, it is preferable to make the crew injury mechanism simpler by considering the acceleration in the single direction. The lateral accelerations whose maximum is 7.0 and 15.0 are considered to represent the water landing conditions as shown in Table 4. Those duration is roughly 20 milliseconds as shown in Figure 6. In terms of the acceleration induced by the blast-wave over pressure, two accelerations for CaseBW1 and BW8 are selected as the reference acceleration case. Dynamic acceleration for CaseBW1 is corresponding to the larger peak and less duration time case, and CaseBW8 is corresponding to the smaller peak and longer duration time case, respectively. Sled tests of Hybrid III AM 50 are conducted at the HYGE^{TM} impact test facility at Japan Automobile Research Institute (JARI). Resulting accelerations for the sled test are compared with the reference accelerations in Figure 6. Difference is smaller for the initial increasing profile before reaching the peak, however those difference is larger in the decreasing phase. It is mainly due to the capability limitations of the used facility. Rigid spaceship seat and the restraints are designed and prepared at JARI by considering the requirements for civil aircraft SAE AS-8043B for such as the restraint type and its pretension [13]. 90 degrees of the angle between seat and seat back is the exceptions to make the injury mechanism simpler to be understood. Configurations of the ATD seated on the rigid seat are shown in Figure 7 with the corresponding numerical analysis results.

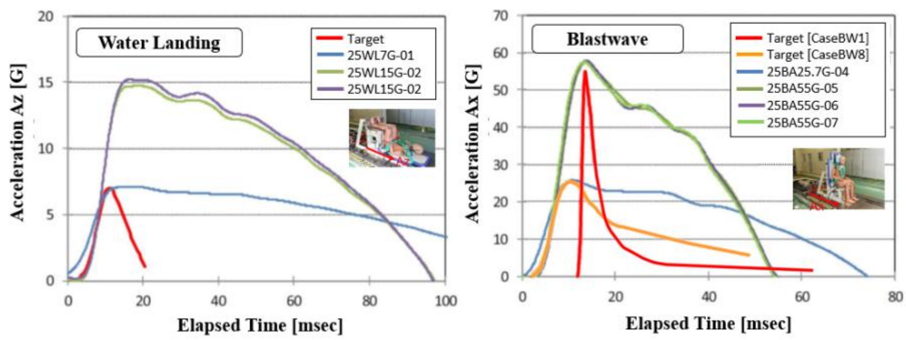

Figure 6: Hybrid III dummy sled test accelerations for the rigid seat [7].

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Table 4: Hybrid III sled test accelerations for the rigid seat.

Scenario	No	Case ID	Acceleration Ax [G]	Az [G]
Water landing	1	25WL7G	0.0	7.0
	2	25WL15G-02	0.0	15.0
	3	25WL15G-03		
Blast -wave	4	25BA25.7G-04	25.7	0.0
	5	25BA55G-05	55.0	0.0
	6	25BA55G-06		
	7	25BA55G-07		

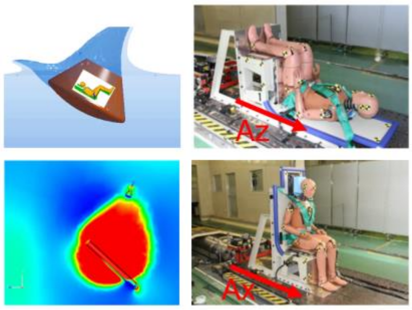

Figure 7: Hybrid III sled test configurations for the rigid seat.

For the efficient parametric study on the crew injury risk, the multi-body dynamics human response analysis is employed. Mathematical dynamic model (MADYMO) of TASS international [20] is applied. Standard ellipsoid model for the Hybrid III AM 50 is employed. Pre-tensioning of the restraints and pre-positioning of ATD to be same as the measured position are conducted in advance, those are important for the accurate predictions. Finally obtained predicted dynamic response characteristics are compared with the corresponding experimental measurement data as shown in Figure 8.

Dominant uncertainty parameters influence on the accuracy of the dynamic response are as follows,

1) Parameters of the contact force model whose explaining variable is the penetration depth of the ATD's contacting surface into the seat structure wall
2) Parameters of the contact force model for the head and the shock absorbing head rest
3) Initial position of the restraint belt
4) Initial position of the ATD

It can be concluded that the predicted dynamic response of Hybrid III ATD by the multi-body dynamic is agree well with the sled test results as shown in Figure 8. It is important to be noted that the this is not the discussion on the ATD's bio-fidelity, there should be further research effort on the advanced ATDs such as the THOR to achieve more bio-fidelity to predict the real human body's behavior accurately.

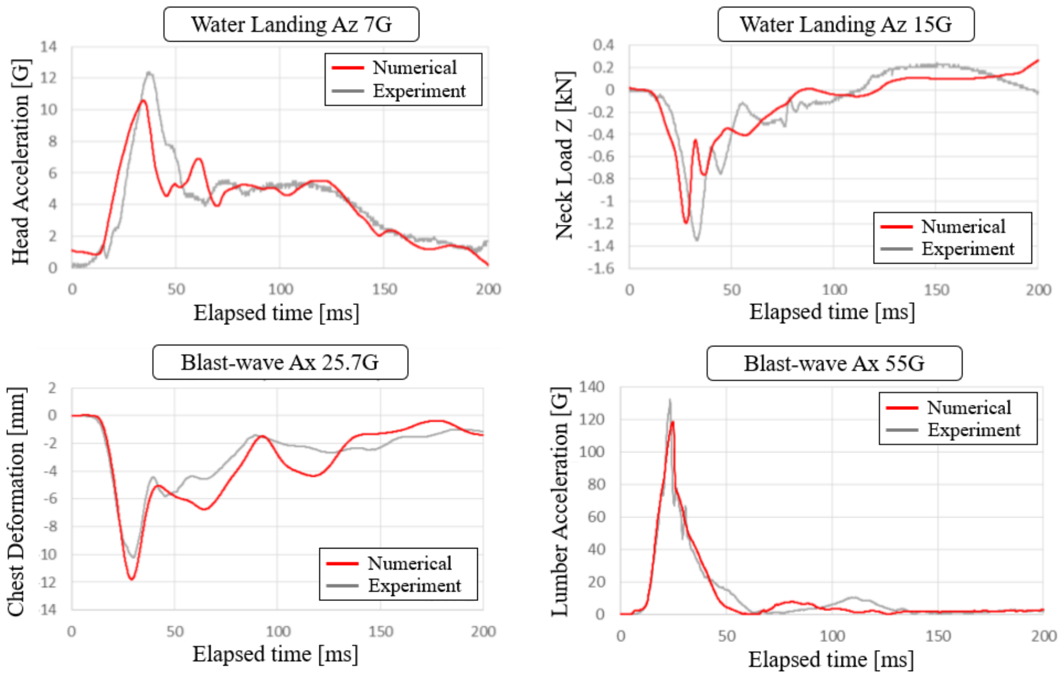

Figure 8: Comparisons of the experimental and predicted dynamic response of Hybrid III with the rigid seat [7].

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At third, the crew injury analysis is carried out by using the validated multi-body dynamics model for the reference accelerations including the water landing and the blast-wave over pressure shown in Figure 5. Crew injury metrics values are evaluated for the Hybrid III AM 50 with the rigid seat. It should be noted that the any soft padding and the designed seat linear are not considered in this study, considered conditions are corresponding to the worst cases in terms of the seat design. All predicted injury metrics values are shown in Table 5. In case of the large maximum acceleration cases such as the CaseBW5, 7, 8 and 9, most of the IARVs are violated. Furthermore, even life-threatening injury ($AIS \geq 4$) risk related to the neck tension becomes larger. Due to the strong axial impact, the head is directly pushed by the head-rest or pushed up by the neck due to the lateral force coming from the lower body part. Then, strong translational or bowing pitching motion are generated. Consequently, the neck tension becomes significantly large since the neck is pulled by the head. Neck compression force IARV for CaseWL1 is also violated. Head moves downward due to the impact from the head rest, then the neck is pushed down ward by head. At the same time, the thoracic spine pushes neck upward due to the lateral load propagating through the spine. Then, the neck is significantly compressed from the both sides. It is the main reason of the increase in the neck compression in CaseWL1. It implies that the appropriate head rest design is essential to achieve the crew safety under various impact conditions. Since the magnitude and the directions of the acceleration change significantly depending on the external impact conditions, there should be intensive research and development efforts to achieve the robustness. Generally, the margins of the injury metrics values for the lumber and the neck are smaller as comparing with that for the HIC15 and chest deflections. This is because that the lateral load propagating through the lumber and spines is dominant for the human space flight problems.

Table 5: Injury risk comparisons for the Hybrid III ADT on the rigid spaceship seat [7].

	IARV	Water landing cases			Blast-wave overpressure cases					
		WL1	WL2	WL3	BW1	BW2	BW5	BW7	BW8	BW9
Maximum acceleration	---	36.7	17.5	3.1	55	11.7	41.3	103.2	25.7	90.2
HIC15	470	165.7	16.9	0.3	33.4	45.5	301.8	**2437**	134.2	**513.1**
BrIC	(0.43)*1	0.379	0.159	0.04	0.165	0.152	0.244	**0.449**	0.201	0.32
Neck tension [N]	860	727	298	39	495	611	**1309**	**2964**	**903**	**1675**
Neck compression [N]	950	**1513**	691	180	651	560	**1404**	**3672**	**973**	**1919**
Chest deflection [mm]	32.0	14.1	6.3	1.5	7.3	3.1	14	31.3	9.9	18.7
Lumbar Fz [N]	5600.0	5270	2748	883	3601	2906	**5731**	**10429**	4377	**7104**

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At fourth, the crew injury risk assessment for the realistic capsule-type crew module at the water landing is conducted. Considered crew module dimensions are diameter of 4.2 m, total height of 3.28 m and the total mass is 4900 kg as shown in Figure 10. Wide range of the water landing conditions are considered as shown in Table 6, which results in 64 cases in total. The conditions are selected based on the cumulative probability functions of the Apollo command module [21] as shown in Figure 11. In order to obtain the dynamic load characteristics, the fluid and structure interaction analysis by the ALE solver [22][23] and the penalty method of LS-DYNA® are applied. Computational grid used for the water landing load analysis is the equi-spaced structured grid as shown in Figure 9. Model validation study of the water landing dynamic load analysis by LS-DYNA® was carried out by comparing with the quarter-scale Apollo capsule experiment [18] and 6.8% HTV-R capsule experiment, which is the preliminary research work of JAXA. Prediction results are generally in good agreement with the experimental data, which can be concluded that the accuracy is sufficient for the objective of the present research. It should be noted that the prediction based on the rigid body spacecraft often underestimated the actual structural responses [24][25][26].

Dynamic loads and the pitch rate during the water landing of the crew module under the realistic conditions are shown in Figure 12. When the attitude θ is smaller, the sensitivity of the horizontal velocity V_T on the acceleration peak becomes very small as comparing with that of vertical velocity V_N as shown in Figure 12. Maximum acceleration level is observed at $\theta = 15°$ and $V_N = 13\ m/s$, whose magnitudes are over 70 Gs. Predicted pitch rate is ranging from -200 to 200 deg/sec. It is clear that the pitch rate becomes large when the horizontal velocity becomes large, so that the horizontal velocity has strong effect on the occurrence of the turn-over of the crew module.

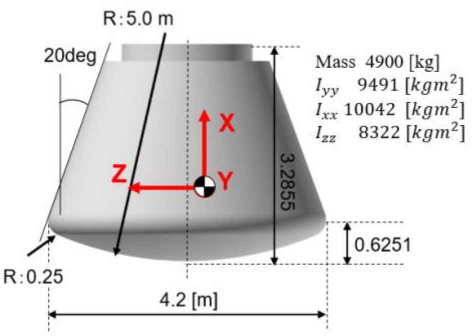

Figure 10: Crew module configuration.

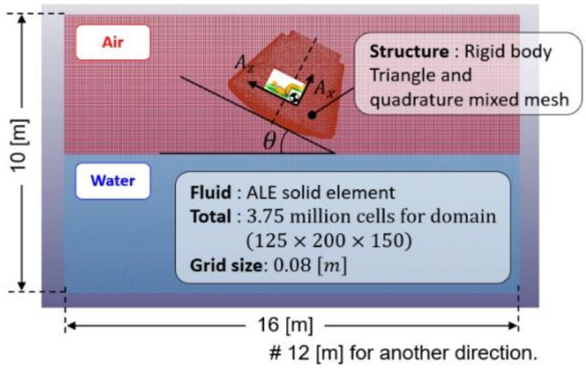

Figure 9: Computational grid for the water landing load analysis.

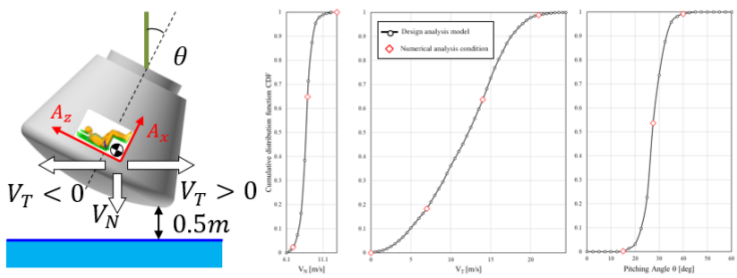

Figure 11: Cumulative distribution function for the water landing condition [21].

Table 6: Water landing conditions.

Attitude θ [deg]	15, 27.5, 40
V_T [m/s]	-21, -14, -7 0, 7, 14, 21
V_N [m/s]	7, 9, 13
	64 case in total

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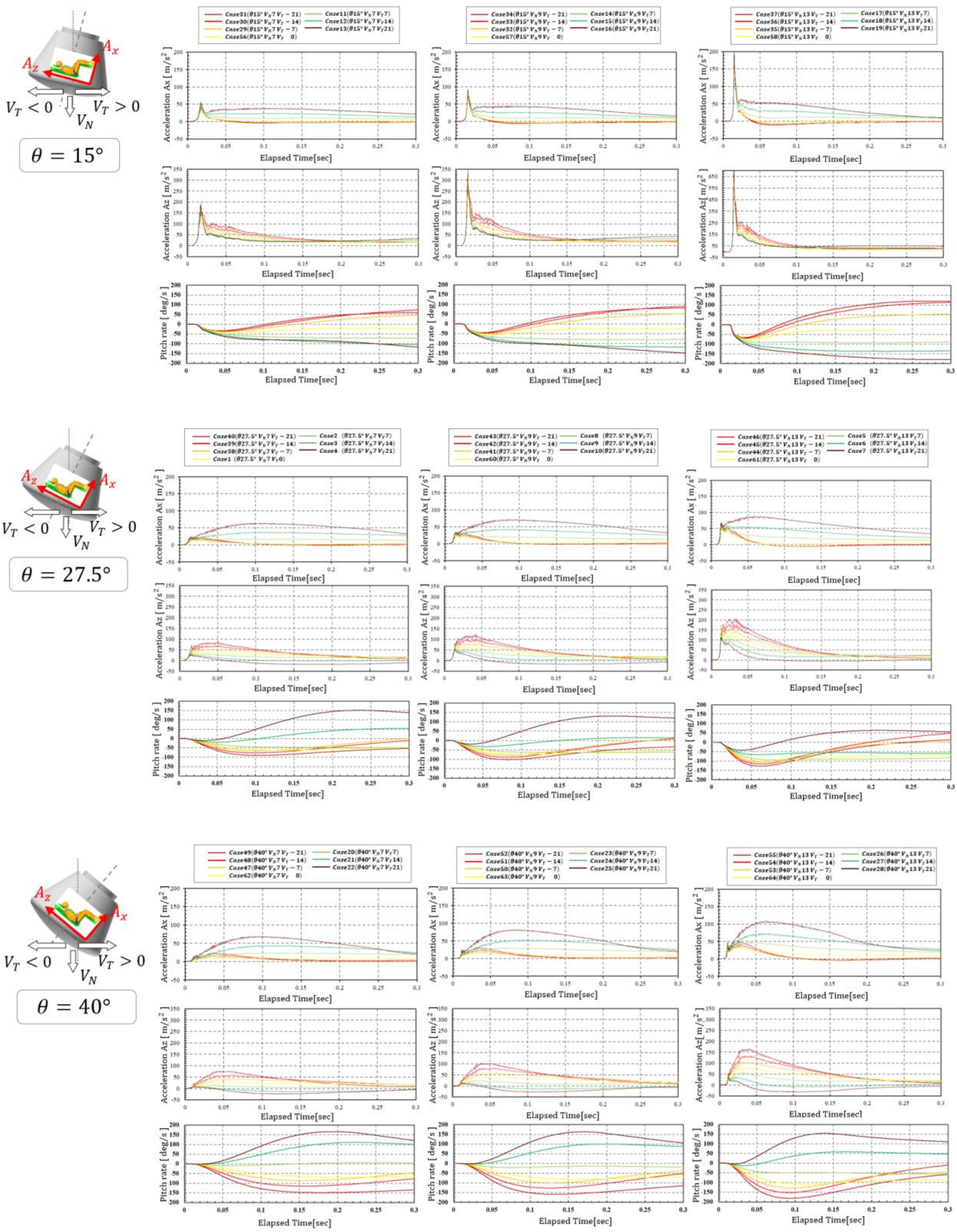

Figure 12: Dynamic loads and the pitch rate during the water landing of the crew module under the realistic conditions.

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Then, parametric crew injury risk analysis is carried out for the predicted water landing loads mentioned above. Multi-body dynamics model of Hybrid III 50 AM on the rigid seat is used for this study, which is validated by the comparison with the sled test data. Contour plots of each injury metrics values over the horizontal and vertical velocities for each θ are shown in Figures 13, 14 and 15 respectively.

- Sensitivity of the horizontal velocity V_T on the acceleration peaks is smaller when the attitude angle θ is small.
- Vertical velocity V_N has strong impact on all the injury metrics, larger V_N results in higher injury risk.
- When the vertical velocity V_N and magnitude of the horizontal velocity V_T is larger on the negative side, the axial load (eye-ball in direction) becomes dominant (Large A_x Case). In this condition, HIC15, chest deformation, BrIC and the neck tension become large. Correlation of these four injury metrices are strong.
- When the magnitude of the horizontal velocity V_T is larger on the positive side, the lateral load (eye-ball down direction) becomes dominant (Large A_z Case). In this condition, BrIC becomes larger as well.

Key findings on the injury mechanisms are shown in Figure 16.

In the Large A_x conditions, the head and the body are initially pushed by the axial road through the head rest and the seat back, then head and the body move forward until those motions are restricted by the restraints. After that, the head rotates, and finally neck is tensioned. This is the reason of the strong correlations between the corresponding four injury metrics.

In the Large A_z conditions, the lateral load is propagated through the lumber and the spine until it reaches the head. Induced lateral load is generated by straighten of the curved spine due to the axial load through the seat back. Both loads are finally resulting in the head rotation. This is the reason of the strong correlations between the A_z and BrIC.

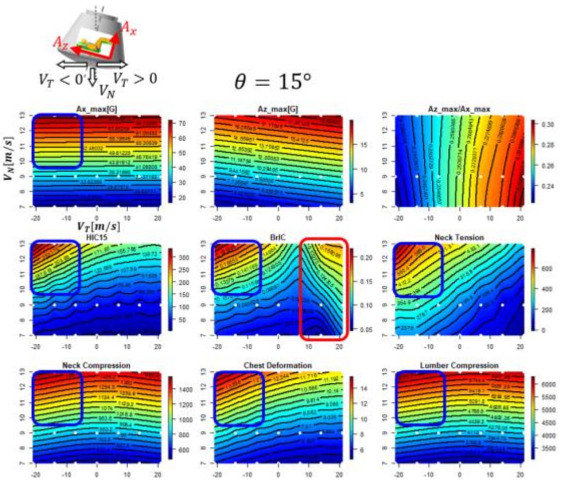

Figure 15: Crew injury risk map over the water landing conditions for $\boldsymbol{\theta = 15°}$.

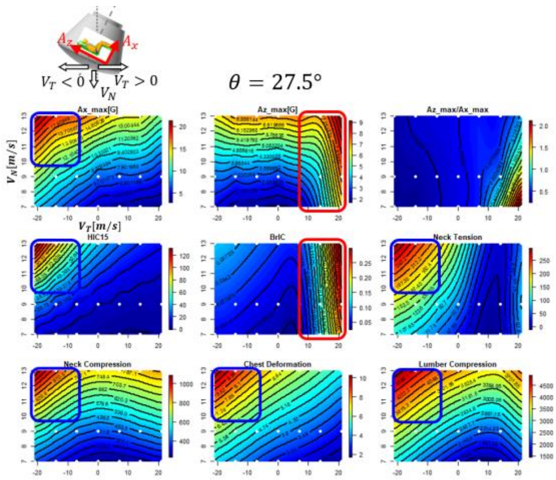

Figure 14: Crew injury risk map over the water landing conditions for $\boldsymbol{\theta = 27.5°}$.

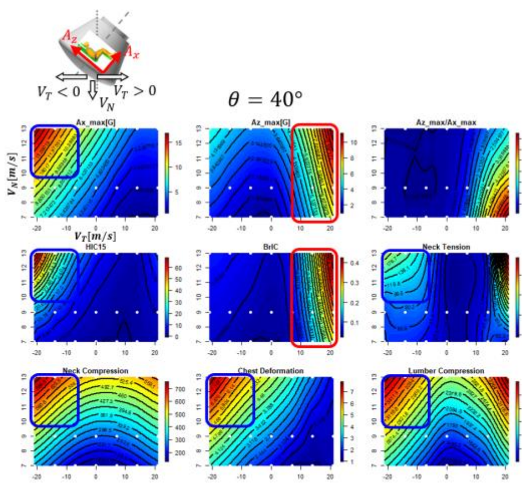

Figure 13: Crew injury risk map over the water landing conditions for $\boldsymbol{\theta = 40°}$.

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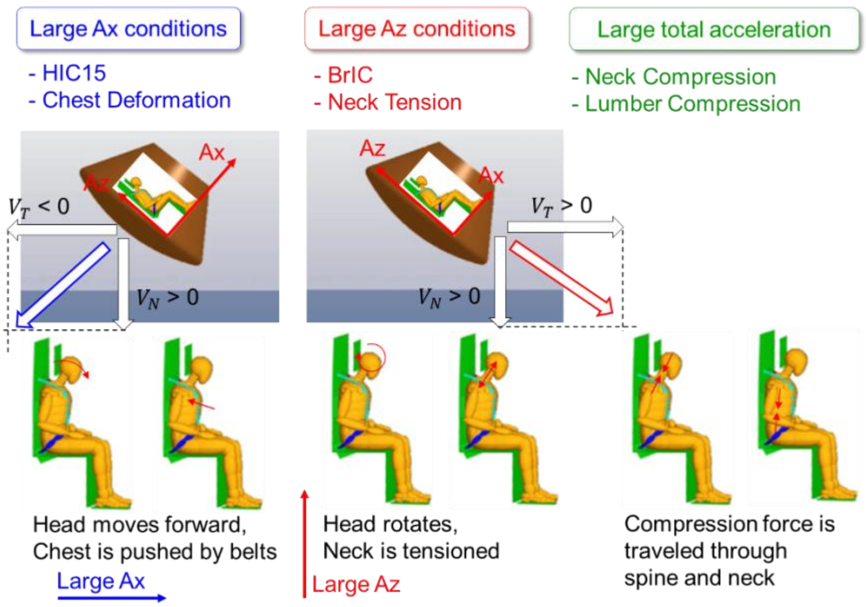

Figure 16: Crew injury biomechanics for the dynamic load due to excessive water landing velocity.

4. Design-for-safety for the spaceship seats

Finally, the design-for-safety for the spaceship seats is carried out mainly by the in-house research of the TS TECH. Sharing all key elements such as the key findings and the knowledge of the injury mechanism, and the sophisticated design technique accumulated in the automobile seat development significantly contributes to realize the ultimately robust spaceship seat. Selected water landing condition is Case19, in which the vertical velocity is 13 m/s, the horizontal velocity is 21 m/s, and the attitude angle is 15 degrees as shown in Figure 17. It is corresponding to large A_z conditions and the worst case whose velocity magnitude is maximum among the considered conditions in this study.

At first, the design optimization is conducted to reduce the acceleration peak and the total impulse, to minimize to be acceptable level for the spaceship seat design. Four lateral dampers, and the four axial dampers are considered as shown in Figure 17. Considered design variables are 10 positions of the 4 dampers and the one friction characteristics parameter and another spring characteristics parameter for each damper. 18 parameters are considered for the half of the configuration for the design optimization. Resulting reduced accelerations by the optimized dampers are shown in Figure 18. Clearly, remarkable reductions in the acceleration level are achieved, original A_z of 20 Gs becomes 4.9 G, and the original A_x of 70 Gs becomes 6.0 Gs by the optimized dampers.

Acceleration profile whose maximum is 10 Gs and the duration is 0.1 seconds shown in Figure 18 is selected for the design-for-safety of the seat. Design analysis and the certification tests are carried out for each direction independently.

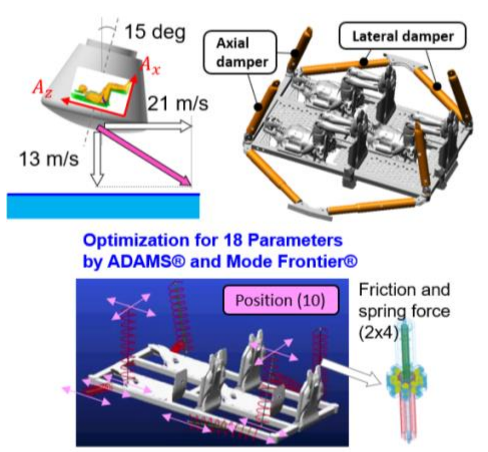

Figure 17: Design optimization for the spaceship dampers to reduce the acceleration level.

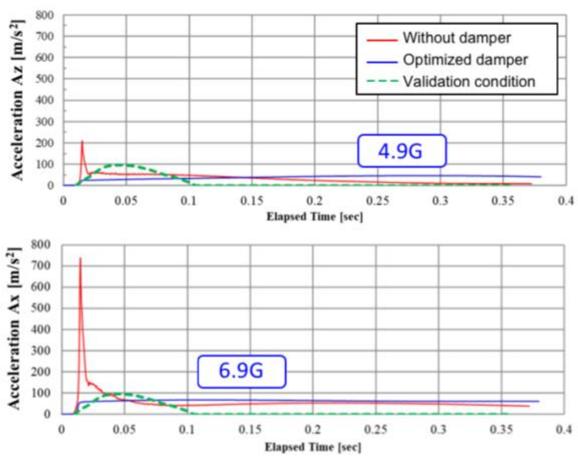

Figure 18: Design optimization result to reduce the acceleration level and the design validation condition.

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Table 7: Design for safety of the spaceship seat.

	IARV	Lateral load (Z direction)				Axial load (X direction)			
		Rigid Seat	Without padding	Final (FEM)	Final (Test)	Rigid seat	Without padding	Final (FEM)	Final (Test)
HIC15	470	68.3	36.9	**31.7**	**29.5**	6.3	47.0	**12.3**	**10.0**
BrIC	(0.43)*1	0.032	0.028	**0.297**	**0.315**	0.042	0.220	**0.036**	**0.052**
Neck tension [N]	860	**1839.0**	**1035.2**	**588.1**	**655.8**	263.0	442.5	**16.3**	**41.2**
Neck compression [N]	950	132.0	465.3	**572.7**	**485.6**	112.6	673.8	**218.3**	**134.4**
Chest deflection [mm]	32.0	4.7	4.0	**1.4**	**0.8**	5.2	4.6	**0.8**	**1.5**
Lumbar Fz [N]	5600.0	**6823.8**	3984.3	**2820.0**	**1923.3**	2694.3	1500.5	**1217.6**	**1335**

*1 Since BrIC is still in the development and validation, IARV by Laituri et al [14] is used.

For the numerical analysis to evaluate the dynamic response, finite element model of the Hybrid III AM 50 of LS-DYNA® is applied. Comparisons of the injury metrics values for the rigid seat, intermediate design with the adaptively-shaped seat liner without padding, final design with the padding are shown in Table 7. In the axial load conditions, all injury matrices are bellow the IARV even for the rigid seat. It is clearly because that the incoming acceleration is significantly reduced by the optimized dampers. Its peak becomes smaller and the increase rate is much slower as comparing with the water landing load acting on the crew module. While, in the lateral load conditions, IARVs of the neck tension and the lumber compression are violated. As is already discussed in the previous sections, the excessive lateral motion of the body generated by the lateral load propagated through the lumbar is resulting in the head's translational motion, then the neck is tensioned by the moving head as shown in Figure 19. To suppress the lateral body motion, the design-for-safety studies have been conducted. Identified key design improvements are 1) the seat linear adaptively shaped to be fit with the body, 2) add the padding for the shock absorption and 3) move the head rest position forward in 30 cm as shown in Figure 19.

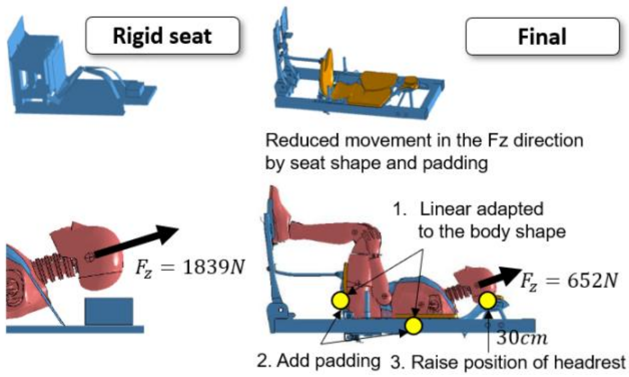

Figure 19: Design-for-safety considerations to maximize the crew safety.

Finally, the designed seat has been fabricated and the sled tests have been carried out by using the impact test facility of TS TECH to obtain the injury metrics values and to confirm the design validity. Injury metrices experimentally obtained for the fabricated seat are also shown in Table 7. It is validated through the sled test that all injury metrices IARV are successfully satisfied by the final design for both lateral and axial directions. Neck tension and the lumber force are remarkably reduced to be half as expected.

Dynamic response characteristics for the final version of the designed seat are obtained numerically and experimentally, those are compared in Figure 20. Corresponding behaviours of ATD are also shown in Figure 21. Predicted dynamic response of Hybrid III ATD with the design-for-safety seat is in excellent agreement with the sled test results. As is discussed in the previous sections, the numerical results obtained by the multi-body dynamics analysis for Hybrid III ATD with the rigid seat is good agreement with the sled test results. It is generally shown that the dynamic response models such as the multi-body dynamics analysis by MADYMO® and the finite element analysis by LS-DYNA® have the sufficient accuracy for the crew safety assessment under the considered human space flight conditions.

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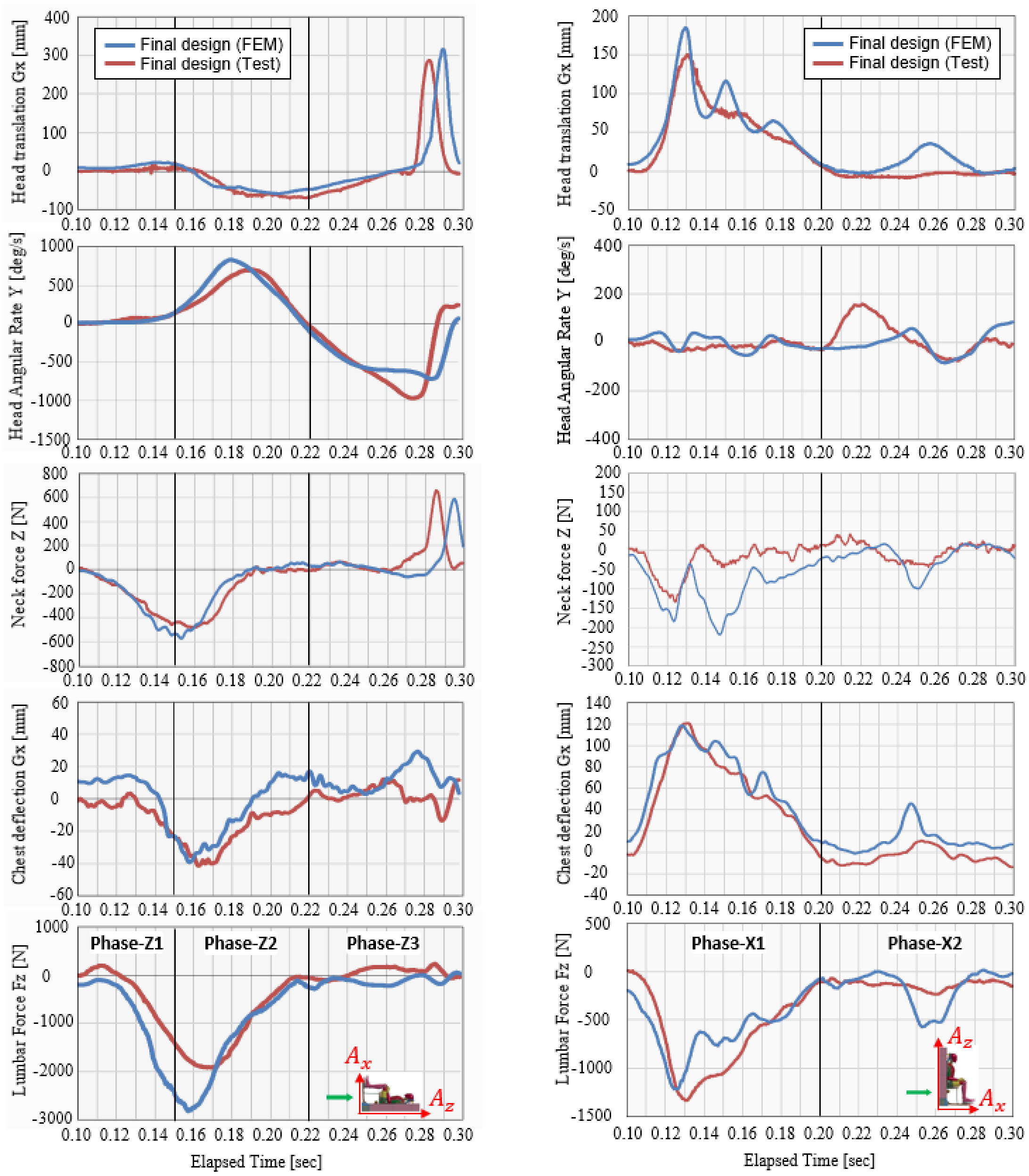

Figure 20: Hybrid III dynamic response for the final safety-designed spaceship seat DCSM-1401.

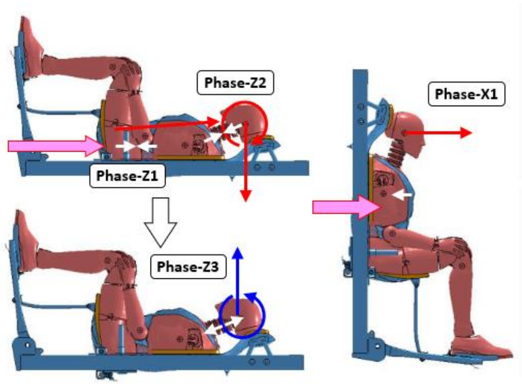

Figure 21: Dynamic behaviour of ATD for the design-for-safety seat.

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Identified design-for-safety strategies to maximize the crew safety for human space flight conditions are summarised in Figure 22. These should have been already identified, and those importance are already confirmed in previous development of the human-rated space launch vehicles. Since Japan has little experience even on the research regarding the human space flight issues, the experience and the knowledge obtained through the present research project would significantly contribute to the JAXA's crew safety assurance.

In the in-house research of TS TECH, the design-for-safety spaceship seat DCSM-1401 is fabricated as shown in Figure 23. Injury metrics values are obtained for Hybrid III ATD seated on the DCSM-1401 by using the impact test facility of TS TECH. Although further robust design considerations should be made in the real development process, as is already shown in the previous sections, all IARVs are satisfied under the considered dynamic load conditions.

Key features of the spaceship seat DCSM-1401 are shown in Figure 23. As already well described in the present report above it is comprehensively designed for the crew safety based on the experience and knowledge accumulated in the advanced automobile field. Weight is designed to be 12.8kg, which is reduced by the shape changes to remove unnecessary structure part and the light weight material applications such as CFRP. Further weight reduction by the application of more advanced materials such as Zylon® would be future research topic. During the present research project, the research status reporting and the technical discussions have been carried out with the JAXA's astronauts and supporting flight surgeons. It is clarified that there exist more demands and expected function in addition to the safety and the low weight. The comfort even for long standby during the launch operations, the compactness to maximize the available cabin space as much as possible for the long cruise toward the long distance destinations such as the moon and Mars, the multi-functionality which enables the further function in addition to the seating, and so on. Such valuable living opinions are adopted as much as possible, significant design improvements are the soft padding made by low resistance urethane, the removal of the unnecessary body-holding seat backs and adding the grip. Most advanced feature of DCSM-1401 is its self-deployability. Since it can be switched to folding and unfolding mode automatically with the latching mechanisms, the available cabin space can be maximized and this capability would contribute to the multi-functionality.

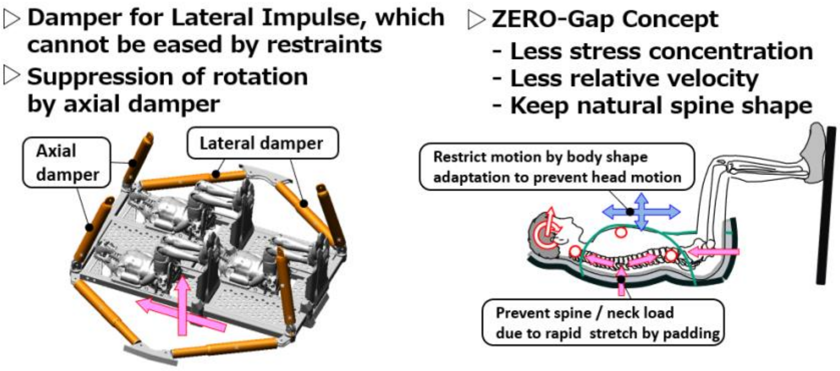

Figure 22: Proposed design-for-safety strategy to maximize the crew safety for the human space flight.

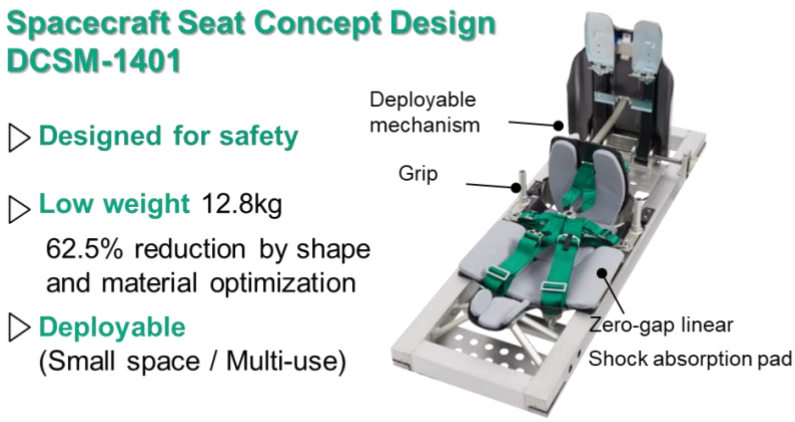

Figure 23: Spaceship seat DCSM-1401 developed in the in-house research of TS TECH.

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In the present research project, the comprehensive research efforts have been made to establish the development process based on the quantitative safety assessment to maximize the crew safety required to accomplish the challenging human space flight missions. Quantitative safety assessment method is proposed for the human space flight including the off-nominal water landing and the launch aborts. Dynamic load environment which threatens the crew's life is characterized by the revisiting the previous studies and the numerical analysis. Crew injury risk prediction method is proposed and the essential physics-based models, such as the water landing load model and the ATD's dynamic response model are developed and validated by comparing with the experimental data. Then, the investigations on the identification of the possible crew injury risk drivers, and injury mechanisms and the design-for-safety are performed. Finally, the design optimizations on the dampers and the spaceship seat are carried out to find the practical and yet robust spaceship system design. Designed spaceship seat DCSM-1401 is really fabricated and the feasibility to satisfy the NASA's recommended safety requirement is investigated. It is confirmed by the sled test that all injury metrics IARVs are satisfied under the considered off-nominal water landing conditions.

As the supplemental research effort to fill the remaining gap to achieve ultimate crew safety, technical discussions and the meetings have conducted with the experts such as the occupant protection team of NASA and the experienced automobile safety assurance specialists. Schematic overview of the design-for-safety process based on quantitative safety assessment for spaceship seats is shown in Figure 24. Technical readiness level regarding on the development of the spaceship seats has apparently increased by this intensive research project.

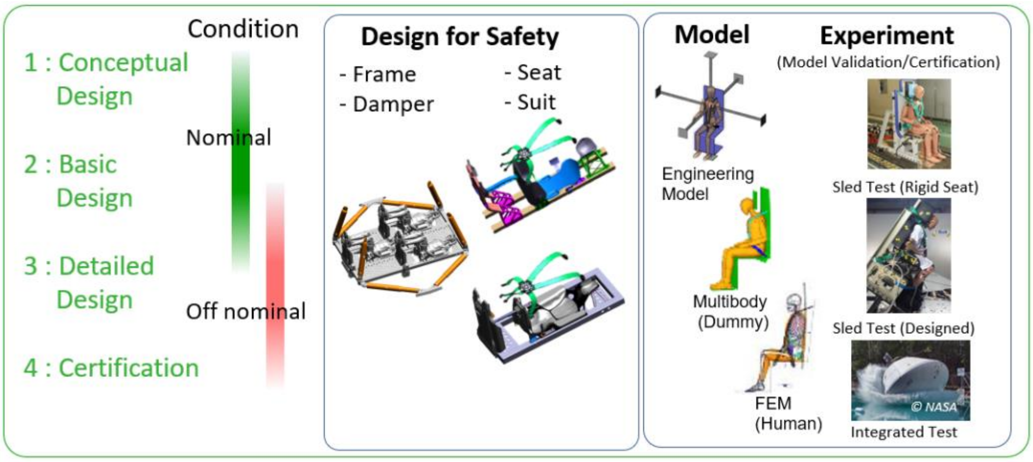

Figure 24: Design for safety process based on quantitative safety assessment for spaceship seats.

5. Conclusion

Quantitative crew safety assessment method was proposed, and continuous research efforts had been made to maximize the crew safety to keep sustainability of the challenging human space flight missions. Key physics-based models to predict the water landing accelerations and the crew injury risk for the transient dynamic loads were developed. Two hazardous scenarios are considered, the one is the large dynamic loads due to the off-nominal excessive water landing speed and the unfavourable crew module attitude and the other is due to the blast-wave over pressure caused by the launch vehicles' failures. At first, these dynamic loads were predicted and selected as the reference conditions for the crew injury risk predictions. Multi-body dynamics and finite-element models of Hybrid III anthropomorphic test device (ATD) were validated by the comparison with the sled test with including the lateral impact, which is the specific conditions of the human space flight. Crew injury risk was evaluated for the reference dynamic load conditions, and the injury mechanisms were investigated based on the numerical and the sled test results. Quantitative crew injury risk assessment was carried out for the water landing loads of the capsule-type crew module concept. Water landing accelerations under wide range of landing conditions were obtained based on the fluid and structure interaction analysis based on Arbitrary Lagrangian Eulerian (ALE) solver and the penalty coupling method of LS-DYNA®. Corresponding crew injury risk distributions were also predicted by using the multi-body dynamics model of Hybrid III ATD for the rigid seat. Key findings of the crew injury mechanism to improve the crew safety were obtained and presented. Finally, the design for safety studies on the spaceship seat were conducted to maximize the crew safety. Large magnitude accelerations were successfully reduced by the design optimization of the lateral and axial dampers. It was confirmed that the resulting injury metrics values even for the most severe landing condition are

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within the NASA's acceptance risk level for the off-nominal cases. It was found that the design for safety strategies such as the zero-gap concept and the adapted seat liner with the soft padding are key elements to achieve higher-level of the crew safety.

Acknowledgement

I wish to thank Eiichi Wada and Naoki Tani of JAXA for the collaborative forward looking investigations on the quantitative crew safety analysis methods, the feasibility studies on the launch abort system, and the crew injury risk prediction model. I wish to thank all students of the university of Tokyo Kazuyuki Kuriyama, Akihiro Ueda, Shusuke Imaizumi, Naoki Saito, Kentaro Miyata, Akira Takahashi, Koudai Nakagawa, Tasuku Nakai, Shunnosuke Inoue, and lecturer Asuka Hatano for the joint investigations on the crew injury mechanisms and developing the crew injury risk prediction model. I wish to thank Professor Mizuno Koji of Nagoya university for advice on the dynamic response analysis of ATD. I wish to thank Takuya Furumoto and associate professor Takehiro Himeno for the investigations on the water landing load modeling. I wish to thank Yoshihiro Sukegawa of JARI to carry out the sled test for Hybrid III ATD on the rigid seat. I wish to thank Jacobo Antona-Makoshi of JARI for advice on the validation study on the brain injury metrics.

References

[1] Fujimoto, K., Kobayashi, T., Okita, K., Sunakawa, H., Kurosu, A., Taguchi, H., Miyoshi, H., Nishimoto, M., Yamanishi, N., Ogawara, A., Kumada, N., Manako, H., "Quantitative risk analysis for next-generation rocket development based on high-fidelity numerical simulations," International workshop on future of CFD and aerospace sciences, 2012.

[2] Fujimoto, K., Wada, E., Tani, N., "Quantitative Crew Safety Analysis for Launch Abort System," 1st International Conference on Computational Engineering and Science for Safety and Environmental Problems: COMPSAFE 2014, 2014.

[3] NASA, "Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners," NASA SP-2011-3421, 2nd Edition, 2011.

[4] Kumada, N., Nakajima, A., Ogawara, A., Manako, H., Taguchi, H., Fujimoto, K., Sunakawa, H., and Kobayashi, T., "Highly Reliable Development Methods for Next Booster Engine LE-X," Space Propulsion 2014, 2014.

[5] Manning, T., Lawrence, S., Mathias, D., Nejad, H., Gee, K., Ramamurthy, B., Gage, P., "Role of Simulation Assisted Risk Assessment in Abort Trigger Recommendations," 10th International Conference on Probabilistic Safety Assessment & Management 2010, Vol. 1, pp. 2446 - 2458, 2010.

[6] "Hazard Analysis of Commercial Space Transportation," Office of Commercial Space Transportation Licensing Programs Division, U.S. Department of Transportation, 1995.

[7] Imaizumi, S., Ueda, A., Fujimoto, K., Hatano, A., Izumi, S., and Sakai, S., "Crew safety evaluation and injury mechanism at Launch Abort System based on multibody simulation," Transactions of the JSME, Vol. 82, No. 838, 2016 (in Japanese).

[8] Ueda, A., Imaizumi, S., Nakagawa, K., Fujimoto, K., Hatano, A., Izumi, S., and Sakai, S. "Safety evaluation and injury mechanism identification in Launch Abort System using Finite Element Method", Transactions of the JSME, No.18-00126, 2018 (in Japanese).

[9] Fujimoto, K., Wada, E., Sakai, S., Izumi, S., Numajiri, H., and Tanabe, J. "Development of Spaceship Crew Injury Risk Analysis Method for Impact Load," 2017 NASA Human Research Program Investigators' Workshop, 2017.

[10] Fujimoto, K., Wada, E., Inoue, S., Sakai, S., Izumi, S., Numajiri, H., and Tanabe, J. "Investigation on the Crew Injury Biomechanics at Water Landing for Human Space Flight," IRCOBI 2017, Short Communication, 2017.

[11] Somers, J.T., Newby, N. J., Lawrence, C., Deweese, R. L., Moorcroft, D., and Phelps, S. E., "Investigation of the THOR anthropomorphic test device for predicting occupant injuries during spacecraft launch aborts and landing," Frontiers in Bioengineering and Biotechnology. 2(4)., 2014.

[12] Jeffrey, T. S., Richard, S., Bradley, G., Jeffrey, J., Nathaniel, N., Michael, G., "Defining NASA Risk Guidelines for Capsule-based Spacecraft Occupant Injuries Resulting from Launch, Abort, and Landing," NASA TM-2014-217383, 2014.

[13] Jeffrey, T. S., Dustin, G., James W. B., "Application of the Brinkley Dynamic Response Criterion to Spacecraft Transient Dynamic Events," NASA TM-2013-217380-REV1, 2013.

[14] Humanetics Innovative Solutions, Inc., "THOR-M Advanced Male Dummy," Parts Catalog, Rev8, 2017.

DOI: 10.13009/EUCASS2019-789

[15] Laituri, T.R., Henry S., Pline, K., Li, G., Frankstein, M., Weerappuli, P., "New Risk Curves for NHTSA’s Brain Injury Criterion (BrIC): Derivations and Assessments," Stapp Car Crush Journal, Vol.60, pp.301-362, 2016.
[16] Fujimoto, K., Tani, N., Wada, E., Nishihara, S. and Okita, K., “Safety Design of Abort Motor Thrust Profile for Launch Abort System,” Space Propulsion 2014.
[17] Mathias, D., Go, S. and Gee, K., and Lawrence, S., “Simulation assisted risk assessment applied to launch vehicle conceptual design,” Reliability and Maintainability Symposium, RAMS.2008.4925773, 2008.
[18] Stubbs, S. M., “Dynamic model investigation of water pressures and accelerations encountered during landings of the Apollo spacecraft,” NASA-TN-D-3980, 1967.
[19] Tani, N., Kawatsu, K., Wada, E., Fujimoto, K. and Yamanishi, N.,” Development of Numerical Simulation Method for Safety Evaluation of Launch Abort during Ascent Phase”, 5TH EUCASS, 2013.
[20] TASS International “MADYMO Human Body Models Manual,” Release 7.4.2, TNO Automotive Safety Solutions, 2012.
[21] Arthur M. Whitnah, David B. Howes, “Statistics Concerning the Apollo Command Module Water Landing, including the Probability of Occurrence of various Impact Conditions, Successful Impact, and Body X-axis Loads”, NASA/TM X-2430, 1971.
[22] Benson D.J., “Lagrangian and Eulerian hydrocodes”, Comput. Methods Appl. Mech. Eng,. 99 pp 235-394, 1992.
[23] Amsden A. A., Ruppel H. M., Hirt C. W., SALE – a simplified ALE computer program for fluid flow at all speeds, Report, 1980, Los Alamos National Laboratory.
[24] Benson, H. E., “Water Impact of the Apollo Spacecraft,” Journal of Spacecraft and Rockets, Vol. 3, No. 8, August 1966, pp. 1282-1284.
[25] Wilkinson, J. P. D., Cappelli, A. P. and Salzman, R. N., “Hydroelastic Interaction of Shells of Revolution during Water Impact,” AIAA Journal, Vol. 6, No. 5, 1967, pp. 792-797.
[26] Wang, J. T. and Lyle, K. H., “Simulating Space Capsule Water Landing with Explicit Finite Element Method,” AIAA-2007-1779, Proceedings of the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, Apr. 23-26, 2007.