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RESEARCH ARTICLE

**An ethical committee approval and/or legal/special permission has not been required within the scope of this study.*

INVESTIGATION OF BOAT MOTION ON OCCUPANT IN PATROL BOATS*

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ABSTRACT

Occupants in high-speed patrol boats are subject to impact forces due to various boat motions. These impact forces should be precisely calculated and accounted for when designing seats for occupants. Hull design and cruising speed are the most critical parameters that cause shock and impact on the boat during the journey. In addition, seat design and material also have a major effect on the impact level sensed by the occupant. In this study, Altair software (Hypermesh and Radioss) is used to build a sample Computer Aided Engineering (CAE) seat and occupant model for patrol boats. The occupant CAE model (50th percentile, Hybrid III) used in our study is already available in the software library and has been verified based on physical testing. During investigation, accelerations coming from reference studies are applied on the model and CAE results are investigated to understand occupant kinematics better. Different accelerations, seat foam thicknesses, and seat foam materials are tested numerically in CAE models. Based on the CAE results, strong relation between boat accelerations and impact level on occupant body regions are compared and verified. Acceleration levels and dummy kinematics was investigated with updates in seat foam design and materials. This study has been conducted in order to avoid injuries for patrol boat occupants and to shed a light on the importance of seat design.

Keywords: *Patrol Boats, Occupant Movement, Impact Forces, Interior Design.*

DEVRİYE BOTLARI KOLTUK TASARIMINDA TEKNE HAREKETİNİN İNCELENMESİ

ÖZ

Yolcular, yüksek süratli devriye botlarında, teknenin hareketi sırasında oluşan ani darbe kuvvetlerine maruz kalabilirler. Oluşan bu darbe kuvvetleri yolcu üzerinde detaylı olarak değerlendirilmesi gereken yüklemeler oluşturabilmektedir. Tekne tasarımı ve teknenin seyir hızı, seyir sırasında teknede şok ve darbeye neden olan en kritik parametrelerdir. Bunların yanında, koltuk tasarımı ve malzemesi de yolcunun maruz kaldığı darbe seviyesi üzerinde önemli bir etkiye sahiptir. Bu çalışmada, Altair yazılımları (Hypermesh ve Radioss) ile devriye botları için koltuk ve yolcu içeren örnek bir Bilgisayar Destekli Mühendislik (CAE) modeli oluşturulmuştur. Oluşturulan modelde yazılım kütüphanesinde bulunan ve ölçüm kabiliyeti ve doğruluğu fiziksel testlere göre korelasyonu yapılmış Hybrid III serisi %50'lik manken kullanılmıştır. Analizler doğrulanmış olan bir manken ile yapıldığı için farklı tasarım parametreleri arasında karşılaştırma yapmak için yeterli seviyede güvenilir sonuçlar vermektedir. İnceleme sırasında, literatür çalışmalarında da kullanılan devriye botlarında oluşabilecek ivme profili modele uygulanmış; analiz sonuçlarında oluşan yolcu kinematiği ve maruz kalınan ivmeler detaylı olarak incelenmiştir. Yapılan CAE analizleri ile farklı ivme profilleri, sünger kalınlıkları ve sünger malzemelerinin yolcu üzerindeki etkileri incelenebilmiştir. CAE sonuçlarına göre tekne çarpma kuvveti ile yolcunun vücudu üzerinde farklı bölgelerde oluşan ivme seviyesi arasında güçlü ilişkinin olduğu gözlemlenmiştir. Ayrıca, koltuk sünger tasarımı ve sünger malzemesindeki değişikliklerin yolcuyu etkileyen kritik iç tasarım unsurları olduğu gözlemlenmiştir.

Anahtar Kelimeler: *Devriye Botu, Yolcu Hareketi, Darbe Kuvvetleri, Tekne İç Dizaynı.*

1. INTRODUCTION

A patrol boat is a moderately small marine vessel generally designed for coastal defense, border protection, search duty, and rescue operations. There have been many designs for patrol boats operated by the navy, coast guard, marine police, coastal safety and customs protection. Most modern patrol boat speeds are generally in the range of 25–45 knots. Their small size and relatively low cost make them one of the most desirable type of high speed crafts in the world (Figure 1).

Figure 1. Fast patrol attack boat (Ekber Onuk).

Occupants in high-speed patrol boats are subjected to impact forces due to boat motion which should be investigated in detail. If the impact force applied on occupant is higher than a threshold value, injuries can be observed. To avoid injuries for patrol boat occupants seat design has the utmost importance. Normally, a boat is exposed to acceleration in six directions: heave, surge, sway, yaw, roll and pitch. The most critical motion which has the highest acceleration on occupant is slamming motion. Several investigations are available in the literature which focuses on boat strength, motion, and acceleration. Golwitzer and Peterson (1995) worked on the development of an injury/performance prediction method for high-speed planning boats. Data recorded from various sea tests are presented and applicability of computer simulation or model testing is investigated in their report. Townsend et al. (2012) published a paper which focuses on flexible hull design to isolate the occupants from external disturbance. They investigated the effect of the hull stiffness on motion. Compared to a regular hull design, both suspended and elastomer hull designs transferred smaller acceleration levels to the occupants. Ullman (2014) worked on the slamming standards and creating awareness to injuries caused by the impact. His paper specifically mentioned that hull design is not enough to endure extreme slamming motion. Crew and passengers should also be considered to eliminate possible injuries. Besides hull design, seats with suspension, posture, standing up, driving and handling are other parameters which effect the acceleration subjected to the occupants. Riley et al. (2015) published laboratory requirements for marine shock isolation seats. They presented a test criterion for shock isolation seats used in 7 to 30-meter planning craft. In their setup, steel plates or Anthropomorphic Test Devices (ATD) can be used as a payload to represent the occupant as seen in Figure 2.

ATD are developed to represent a human for several test scenarios: aircraft development, vehicle crash, etc. While these test dummies are developed, their sizes are defined based on the weight and height distribution in population. Specifications are defined for three different dummy types: 5th, 50th and 95th. 5th and 95th dummies represent to 5% percent of the population which are in the upper and lower limit (BOSTONtec, 2021). The size of the 50th dummy is based on the average size of the population. Sample view of the distribution is given in Figure 3. Demir and Barlas (2017), analyzed the impact forces on a boat in a towing tank. They used a planning boat model in their study to examine acceleration and shock. Even though the study was completed using a model scale, the results are applicable to full scale using the method given by the authors in the paper. Avcı et al. (2016) experimentally investigated the shocks and hydrodynamic accelerations of high speed inflatable boats at sea. An inflatable boat of 4.7 m was instrumented and a series of tests were conducted regarding vibration. There are also several standards available which consider acceleration or vibration in boat environment. European Union Directive 2002/44/EC, ISO2631-1 and ISO2631-5 focus on vibration in boat exposed on occupant and IMO HSC 2000 focuses on the acceleration on boat. Based on IMO HSC 2000, passenger seats should not detach during severe impacts. (Ullman, 2014).

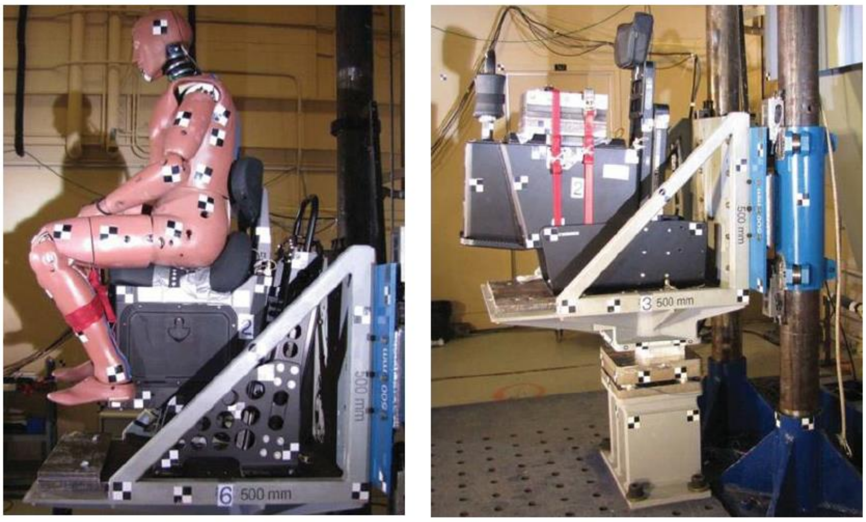

Figure 2. Test setup defined by Riley et al. (2015).

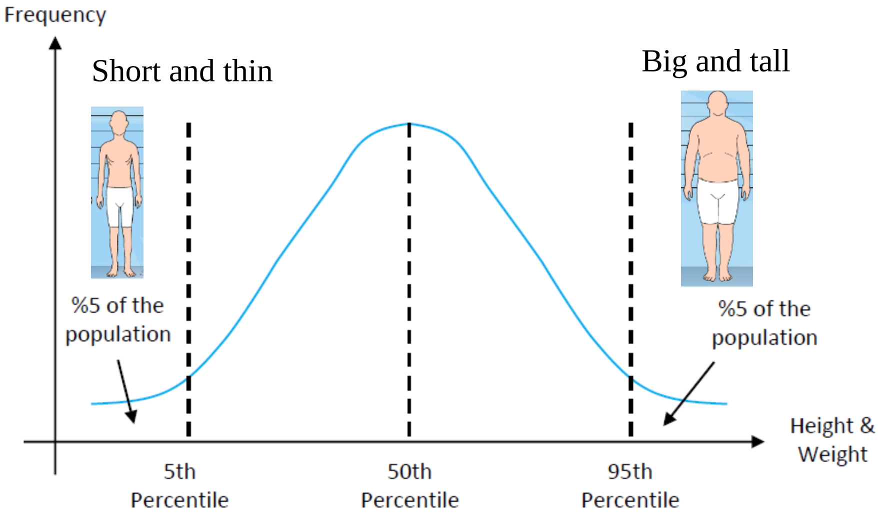

Figure 3. Height and weight distribution of population.

2. METHODOLOGY

In this study, accelerations on the different body regions due to motion of the high-speed marine boat are investigated with computer aided engineering (CAE) tools. Altair software (Hypercrash and Radioss) is used to make detailed investigation with simplified CAE models.

2.1. CAE Modelling

CAE models include seat structure and the 50th percentile Hybrid III occupant model. The CAE setup is given in Figure 4. Model details like nod and element quantity and details of the analysis like CPU and time step are given in Table 1. One dimensional elements used in this study are beams and springs, two dimensional elements are shells and triangular elements, three dimensional elements are bricks and tetrahedral elements, etc. An Intel Xeon 96-core processor is used for all the computations.

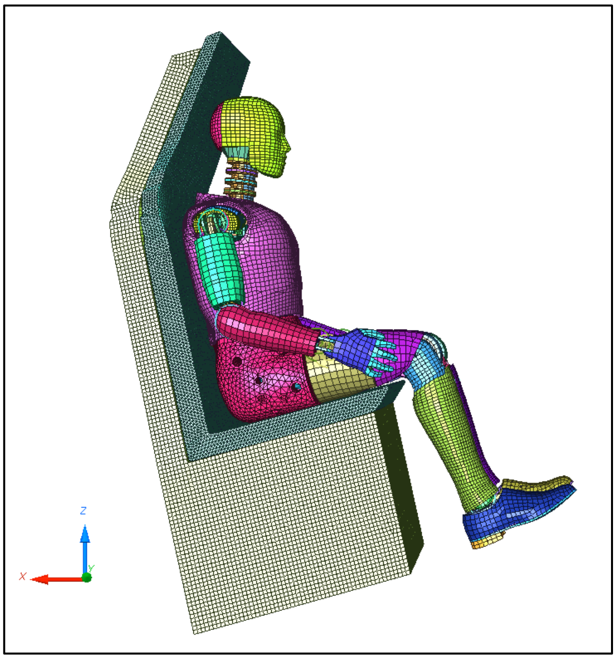

Figure 4. The CAE setup.

Table 1. Model and analysis details.

Model Details		Analysis Details	
Node	165129	Solver	Radioss 12.0.226
1D elements	558	CPU	96
2D elements	688823	Runtime (ms)	350
3D elements	329913	Time step (ms)	0.004
Model size (MB)	40	Number of cycles	851789
		Elapsed time (hour)	2.53

The seat model used in the analysis is created using a Computer Aided Design (CAD) environment first. The CAD model is meshed, and material properties are applied from the library. For seat structure, composite material PP-LGF30 is chosen. PP-LGF30 is formed using a polypropylene polymer matrix and reinforced with long glass fibers. Fiber content in the material is 30%. Mechanical properties of the seat structure material are given in Table 2. Polyurethane foam which has 60g/l density is used as cushioning on the seat. CAE investigations on cushion density and shape are completed. 50th percentile Hybrid 3 occupant model available in the CAE library is used.

Table 2. Mechanical properties of seat structure (PlastiComp, 2021).

	SI Metric	Test Method
Specific Gravity	1.12	ASTMD-792
Tensile Strength	107 MPa	ASTMD-638
Tensile Modulus	6207 MPa	ASTMD-638
Tensile Elongation	2-3%	ASTMD-638
Flexural Strength	157 MPa	ASTMD-790
Flexural Modulus	5517 MPa	ASTMD-790
Notched Izod Impact	214 J/m	ASTMD-256
Un-notched Izod Impact	828 J/m	ASTMD-4812
DTUL @ 264 psi (1820kPa)	149^{o}C	ASTMD-648

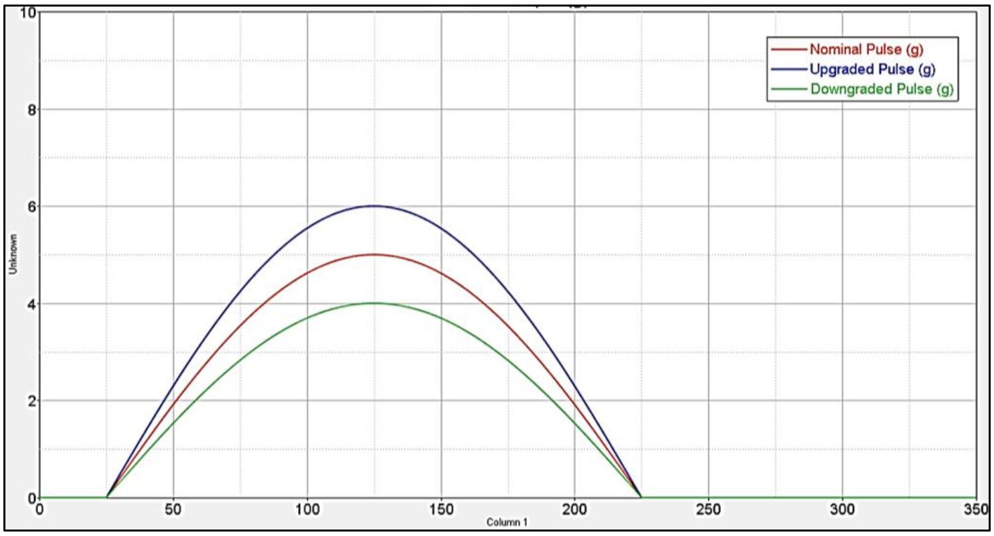

Figure 5. Acceleration profiles used in CAE.

Occupant CAE models in the library are verified using physical tests, so the kinematics and the outputs from the sensors are trustworthy. Acceleration due to patrol boat motion is applied in the CAE model to investigate occupant kinematics and acceleration. Sinus curve is used for imposed acceleration curve characteristics. Ullman (2014) shared accelerations which are measured on platform and seat separately. The paper prepared by Ullman is used as a reference to define maximum acceleration levels in CAE investigation. 5 g is defined as the maximum acceleration level for the reference model. 200ms is used as the duration of the acceleration curve. During CAE investigations, the maximum acceleration level is changed in order to understand the effect of the acceleration on occupant response. Acceleration curves which are used in this investigation is given in Figure 5. In CAE studies, the seat motion is restricted in the X and Y directions. So, the defined acceleration is imposed only on the Z direction. The occupant who is positioned on the seat can freely move as there is no boundary applied on the occupant model. Gravity is also applied on whole model to make the CAE environment more representative.

3. RESULTS

The CAE investigation covers three main areas based on the reference condition. Occupant kinematics and acceleration on the occupant is measured from the head, chest and pelvis area for each condition. The first investigation area is the acceleration levels due to boat motion. Reference acceleration is scaled up and down by %20 to represent different boat motion characteristics. Difference in the occupant kinematics and acceleration in different body regions are given in Figures 6 and 7. As can be seen in Figures 4 and 5, there is a correlation between boat acceleration and occupant response. Increased boat kinematics cause occupant movement and acceleration levels to also increase. Likewise, head and chest acceleration measured on the occupant is higher compared to pelvis and imposed patrol boat acceleration for each case. Movement of the occupant led these phenomena during motion. Pelvis movement can be reduced by the seat better compared to the upper body. Thus, acceleration levels are lower in pelvis area. Rotation observed in the upper body leads to an increase in the final acceleration level on the chest and head. Foam design is the other investigation area of this study. Foam thickness is increased by 50mm and results are compared with the reference model. Design difference between the new and the reference model is given in Figure 8. Difference in the occupant kinematics and acceleration on different body regions are compared in Figures 9 and 10.

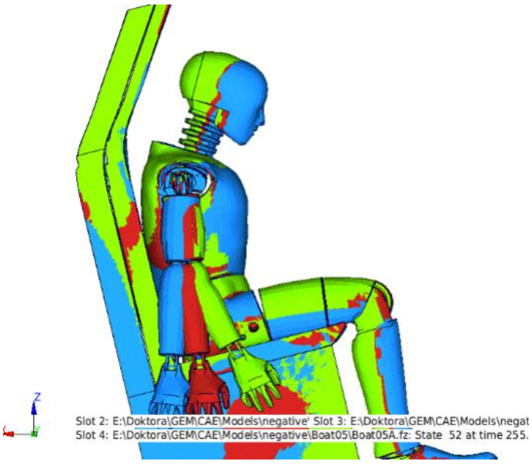

Figure 6. Occupant kinematics in different boat motions.

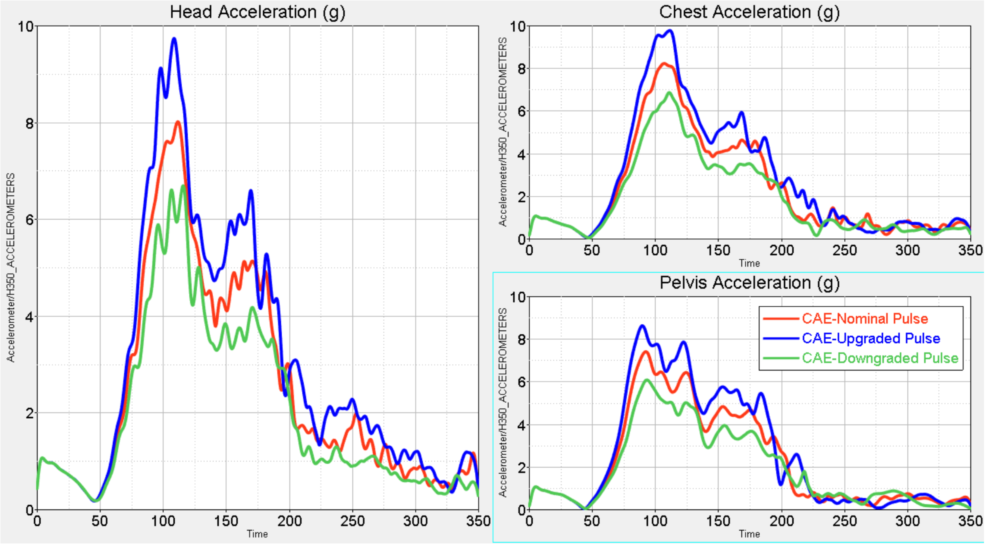

Figure 7. Accelerations in different patrol boat motions.

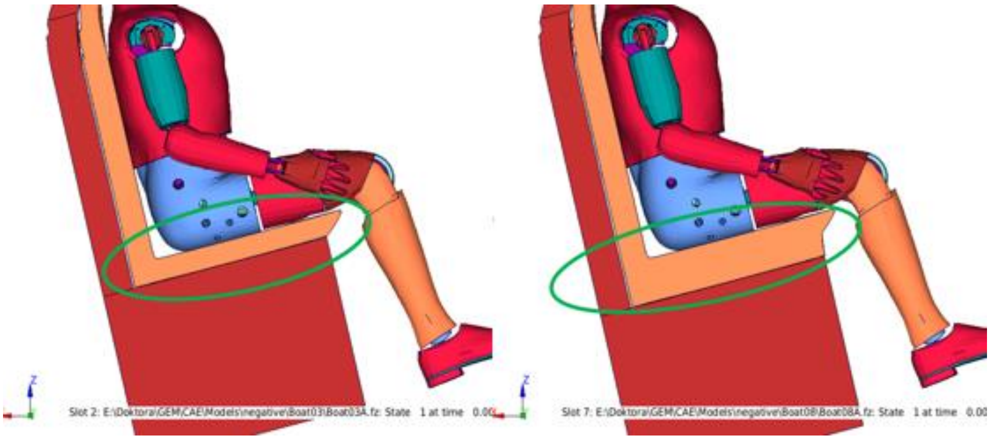

Figure 8. Two different foam designs studied in this study.

When foam thickness is increased, acceleration on the body regions can be reduced until ~100ms. During initial boat loading, less acceleration is observed in each region. Occupant kinematics also show similar phenomena. Effect of the imposed acceleration can be absorbed by thicker foam until the threshold timing. In the animations, the seat can move further with less effect on the occupant, so acceleration is less in the new design. On the other hand, occupant movement increases after the threshold and the occupant rotates more. Foam material is the last investigation topic of this study. Two additional foam material property is used in the CAE analysis to understand the effect of the foam material on kinematics and acceleration.

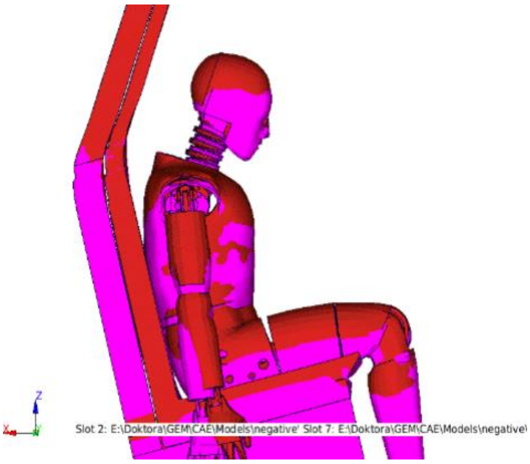

Figure 9. Occupant kinematics in different foam design.

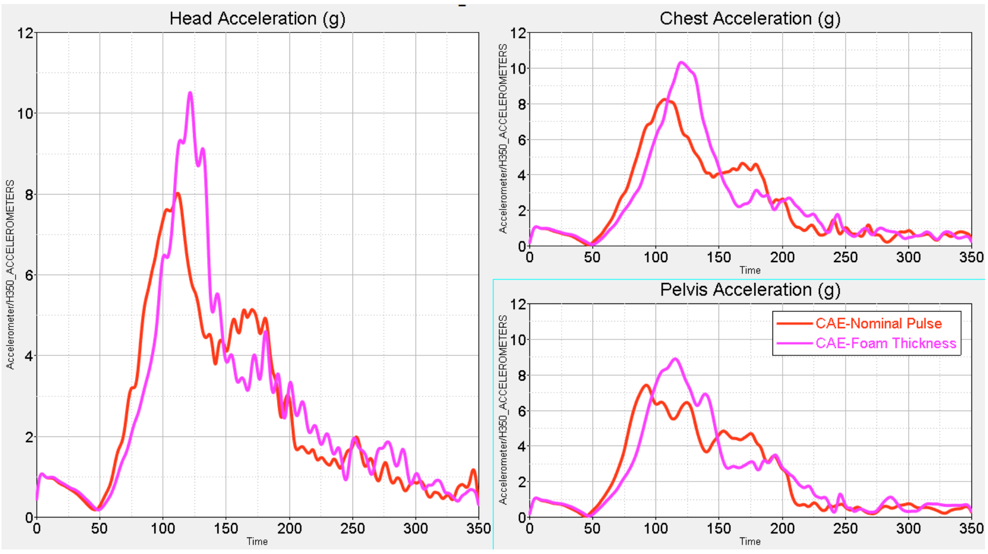

Figure 10. Accelerations in different foam design.

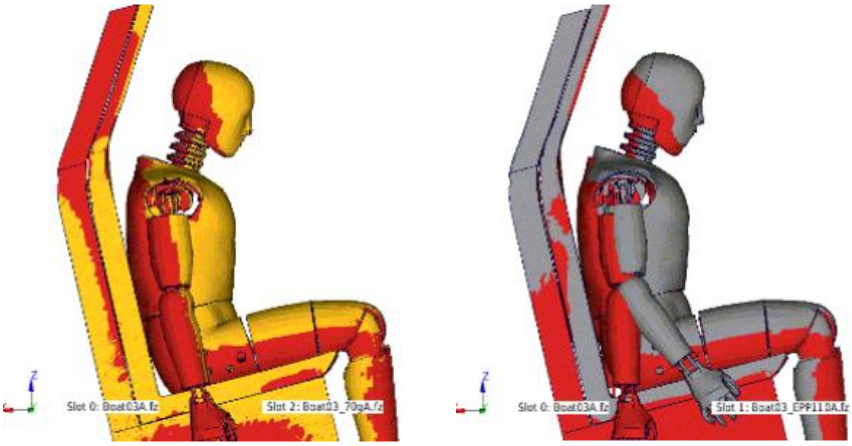

Figure 11. Occupant kinematics in different foam materials.

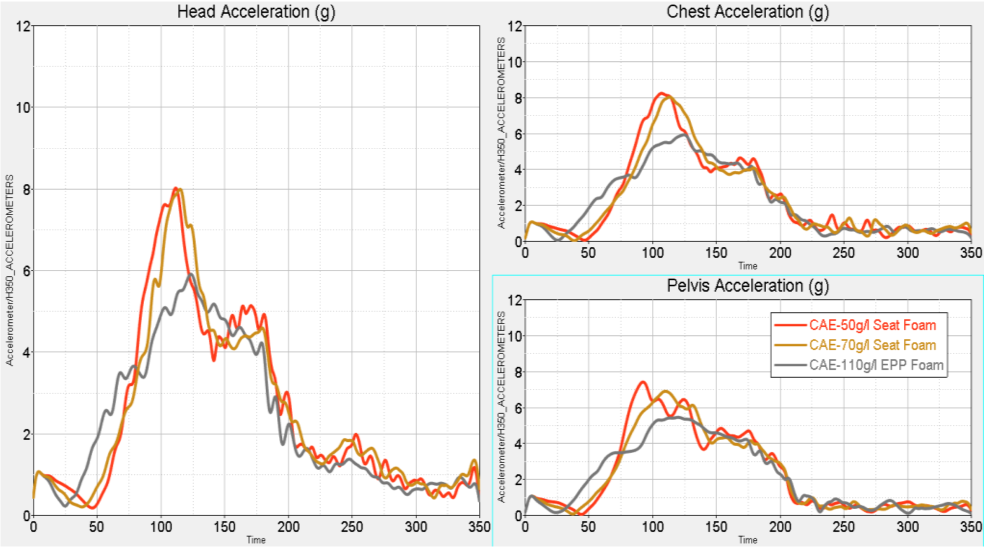

Figure 12. Accelerations in different foam materials.

For the first material iteration, density of the available foam material (60g/l) was increased to 70g/l. Expanded Polypropylene (EPP) foam which has a density of 110g/l was used for the second CAE iteration. EPP foam is stiffer compared to PU foam, which is used in other CAE models. Occupant kinematics and acceleration comparisons are given in Figures 11 and 12. As can be seen, the difference in kinematics and acceleration (red and yellow) are limited to the density difference in same material. On the other hand, major change in kinematics and acceleration is observed after the foam material is replaced to EPP. As 110g/l EPP is stiffer compared to PU foam, acceleration from boat motion is transferred to the occupant earlier. Therefore, the occupant is exposed to higher acceleration in the first ~75ms. On the other hand, peak acceleration level observed in this model is less compared to the model with PU foam material.

4. CONCLUSION

In this study, impact of the acceleration during patrol boat motion on occupant is investigated. As technology develops, more powerful engines and lighter composite structures cause the patrol boat speeds to increase, therefore increasing the hydrodynamic loads and impacts of the patrol boats. Boats running at high speeds in the rough seas experience six degrees of freedom (heave, surge, sway, yaw, roll and pitch) which is highly complex and dangerous. Furthermore, apparent waves make the acceleration and shock problem on patrol boats very complicated. The patrol boat operating at high speeds is exposed to severe repeated shocks. Therefore, if the impact force applied on the occupant is higher than the threshold, injuries can be observed. Hull design is not enough to endure extreme slamming motion. Crew and passenger seats with suspension and posture aid become important and it should be considered to eliminate possible injuries.

CAE analysis is used to understand the effects on occupant kinematics and acceleration which is measured from different body regions. Correlated CAE models are used in this investigation. Material data used in the CAE analysis comes from physical test results. Thus, system CAE results are reliable to make back-to-back comparison between different cases. Based on the CAE results, correlation is observed between boat motion and occupant movements. Higher acceleration on the boat causes higher occupant movement and acceleration. With changes in seat foam design and material, occupant motion and acceleration can also be changed. This shows that besides boat motion, interior design also has an important effect on kinematics and acceleration acting on the occupant.

In future investigations, full system correlation on the CAE model (contact parameters, friction coefficients etc.) can be planned to understand the correlation level of the system and make more detailed design of experiment studies for interior components, especially seat design. To make full system correlation, the system can be tested in a sled environment and acceleration on different occupant body regions can be compared. Besides correlation of the system, boundaries of the study can be extended for future studies. This study is completed with one directional load case (Z) for one occupant (50th percentile) size. Boat motions in other directions can be implemented into full system evaluation. Also, smaller and bigger occupant sizes (5th and 95th percentile) can be used in further studies to investigate effect of interior design changes for all occupant sizes. Moreover, a vibration dose value (VDV) analysis can be investigated by using the patrol boat in-situ shock and acceleration values. This analysis would yield us the dosage an occupant will be receiving.

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