DEVELOPMENT OF A HIGH ENERGY SIDE IMPACT DUMMY

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ABSTRACT

A high energy side impact dummy (HE-SID) was developed for special vehicle development used for law enforcement and VIP protections subjected to improvised explosive device (IED). MIL-SID, i.e. ES-2 ATD with Hybrid III head/neck and MIL-LX design, was used to develop the test rig and define inputs to mimic the IED test conditions. It was found that the MIL-SID shoulder and rib modules were not durable enough to survive the impact during the testing. In addition, the shoulder biofidelity was lacking and requires improvement. A new shoulder structure was designed to improve the shoulder biofidelity. Finite element analysis was conducted to optimize the shoulder design according to the target biofidelity as defined by a series of 12 PMHS shoulder impacts. The MIL-SID shoulder cam design was replaced with a single shoulder rib integrated with damping materials. A 3D deflection measurement system was developed to measure the shoulder deflections. The 3D deflection measurement system consists of a linear potentiometer and two rotary potentiometers. An algorithm was developed to calculate the deflections at its shoulder joint attachment location. Hardware was fabricated and retrofitted in a MIL-SID for verification and validation. The preliminary test shows that the thorax durability issue was addressed. The ATD was able to withstand numerous tests without any damage. The new shoulder design demonstrated good biofidelity under high energy test conditions.

INTRODUCTION

Mines have been a major threat for military vehicles and their occupants since World War I [Radonic, 2004]. Improvised Explosive Devices (IEDs) were one of the major threats in Mideast conflict in the last two decades. In peacekeeping and peace-enforcing, occupant safety has the highest priority. Military and law enforcement personnel are becoming more aware that, apart from vehicle integrity, personnel safety is crucial in operations where IEDs pose a threat. In the past 15 years, national and international projects for the improvement of the mine protection of several military vehicles have been performed to study the injury mechanisms under the IED. To systematically approach the issue, HFM-090/TG25, a team of experts developed an injury assessment methodology for light armored and logistic vehicles landmine protection systems [RTO TR-HFM-090]. Hybrid III anthropomorphic test devices (ATD) and ES-2RE were specified for the injury assessment surrogates [RTO TR-HFM-148]. ES-2RE is used for lateral loading test conditions. MIL-SID is an ES-2RE design with the Hybrid III 50th percentile ATD head, neck and MIL-LX lower extremities. The MIL-LX leg provides superior biofidelity and instrumentation capability for under-body blast test.
Shoulder injury is one of the major injuries for occupant injuries from side impact. The most common injury in low-speed automotive impacts is distal clavicle fracture [Bolte et al 2003]. The Post Mortem Human Subjects (PMHS) tests conducted in the Bolte study are conducted at 4.4 m/s for majority of the tests. Two of the tests were conducted at 7.6 m/s velocity. The duration of the impact was slightly over 60 milliseconds. In loading conditions generated from IED detonation in the lateral direction, the impact velocity can be as high as 27 m/s [Lebarbe et al 2013], and the duration of the impact is near 10 milliseconds. Clavicle fracture was rare in high speed tests. Instead, it was found that humerus, coracoid process and scapula fractures were present frequently. Lebarbe observed that there was a good correlation between the force, impact speed and injury. It was observed that the force alone was not sufficient to predict the injuries. He also noticed the shoulder deflection was associated with the humerus and scapular fractures. In the current MIL-SID design, the ATD shoulder structure does not have the capability of measuring the shoulder deflection. There is a need to develop an ATD that has the ability to measure shoulder deflection for injury prediction. In this paper, a new shoulder design was developed and can be retrofitted into the MIL-SID dummy. The revised ATD is named High Energy Side Impact Dummy (HE-SID). HE-SID has a shoulder design that provides motion with a degree of freedom in vertical direction. It also has a 3D linear potentiometer in the shoulder structure to provide deflection measurement in x, y and z directions.

METHOD

HE-SID Design

The design of HE-SID was developed from MIL-SID. Three major changes were conducted in the design: 1) the thoracic rib durability improvement, 2) the shoulder complex, 3) arm flesh thickness.

The existing MIL-SID was tested using a high rate loading condition (20 m/s, 50 mm deflection) to determine a baseline response. For the thoracic rib module, several durability issues were found from the high rate testing. The potentiometer shaft for the rib module was pulled out of its housing during the rib rebound. The rib module rubber stops were sheared off during the initial loading phase. The housing bracket for the rail bent during testing. Under such loading conditions, the thoracic rib model spring was bottoming out. The strong rebound requires a large travel distance to damp out the energy. This additional travel distance exceeded the travel range of the potentiometer and caused damage. The strong rebound also generated higher force and sheared off the rubber stops.

![Figure 1. Thoracic rib module design changes - 4 inch potentiometer and stronger rail mounting bracket](image)
To address the above durability issues, design changes were made accordingly. A 4-inch (101.6 mm) stroke potentiometer was chosen to replace the 3-inch (76.2 mm) stroke potentiometer, shown in Figure 1. The 4-inch potentiometer had a longer barrel, which required a slot cutout on the guidance bracket to accommodate the additional length and allow enough space for cable exit. When installed, the 4-inch potentiometer shaft was compressed back by 25 mm more to allow additional motion for the rebound. The rubber stops were shifted laterally toward the struck side by 20 mm to allow more energy dissipation before the rail stop knob engages with the rubber stop. The design was proven to effectively address the durability issue in testing.

Test results show the MIL-SID shoulder stiffness is much higher than that of PMHS shoulder. It was desired to improve the ATD shoulder biofidelity. The MIL-SID shoulder structure limits the range of motion in its horizontal plane. The shoulder has a leaf spring and a shoulder cam. When the shoulder is impacted, it rolls inboard. No vertical or posterior range of motion is allowed in the design, shown in Figure 3. In addition, the MIL-SID shoulder design does not provide the ability to measure the shoulder deflection and acceleration in the shoulder joint.

It was desired to have a new shoulder design that was able to provide a long range of motion not only in the lateral direction, but also in the vertical and posterior directions. Due to the budget and time limitation, the project would not permit the exploration of a more complex design, such as the THOR-SD3. It was proposed to develop a simple
solution similar to the SID-II design – a steel shoulder rib with damping material. 3D shoulder deflection measurement was also desired to develop deflection based injury criteria. Considering the constraints above, a shoulder girdle was designed as shown in Figure 4. The design consists of a spring steel rib with the blue damping material developed in the WorldSID program, an interface bracket for the MIL-SID arm, a linear potentiometer and two rotary potentiometers system to provide 3D calculation of the shoulder joint motion, and a triaxial block for 3 linear accelerometers to measure the acceleration in X, Y and Z directions.

The linear potentiometer range of motion was designed to allow ±32° rotation in the transverse plane (rotation along z axis), and ±90° rotation in coronal plane (along the x axis). The design is shown in Figure 4.

Arm flesh provides damping to the skeletal structure of the shoulder. The flesh plays an important role to mitigate the load. It is important to have a representative flesh in the ATD design. To gain knowledge of the flesh thickness, 8 PMHS MRI images were evaluated; the average flesh thickness at the glenohumeral joint was measured to be 14.3 mm with a standard deviation of 4.8 mm. The MIL-SID arm flesh thickness, shown in Figure 5, is between 27-35 mm, which is much thicker than that in human beings.
In order to bring the flesh thickness closer to human thickness values, a nylon insert was designed and attached to the existing MIL-SID arm bone in proximal humerus, which brought the thickness to approximately 15 millimeters, shown in Figure 6. In addition, the edges of the block were rounded to provide a smooth profile in order to minimize the potential damages to the ATD flesh during the impact.

Shoulder Joint Location

The MIL-SID shoulder joint is defined by where the shoulder is located in driving posture, which is in a forward (anterior) position relative to that of a (passively seated?) human. HE-SID was designed to represent the impact scenario of a passenger occupant. The shoulder joint center was aligned with the thorax to reflect the real shoulder joint position of the occupants. The HE-SID arm position is shown in Figure 7. The distance between the two
positions is 46.5 mm. The HE-SID shoulder position allows the arm to have more realistic arm/thorax engagement during the impact.

Figure 7, ES-2 and HE-SID arms overlayed for position comparison

**Shoulder Deflection Calculation**

In the HE-SID shoulder design, a linear potentiometer and two rotary potentiometers were designed in the shoulder to provide the capability for the shoulder joint motion calculations in all three directions. The initial position is aligned with the ATD shoulder local coordinate system, shown in Figure 8.
The calculation can be carried out with the following formula

\[ d_x = (d_0 + d_{pot}) \cdot \sin(\theta_x) \]

\[ d_y = (d_0 + d_{pot}) \cdot \cos(\theta_x) \]

\[ d_z = (d_0 + d_{pot}) \cdot \sin(\theta_z) \]

Where:

- \( d_0 \) is the initial distance (pre-impact condition) between the rotary pot pivot center to the linear pot rod end pivot center.
- \( d_{pot} \) is deflection at the rod end pivot center of the linear potentiometer attached to the rib.
- \( \theta_x \) and \( \theta_z \) are the rotation angles of the two rotary potentiometers from their initial (pre-impact) positions.

For a brand new rib assembly, the rib was very close to the designed orthogonal planes. \( d_0 \) is very close to the designed dimension of 129.66 mm. If the rib is off the orthogonal planes due to small permanent deformation, the rotary potentiometer offset from its orthogonal position and \( d_0 \) at the deformed condition can be measured and taken into consideration in the calculation for better calculation accuracy.
After the above calculation, the data can be filtered according to SAE J211 filter class recommendation if appropriate. The absolute deflection time history in X, Y and Z directions can be calculated by subtracting its pre-impact values from \( d_x, d_y \) and \( d_z \).

**Finite Element Analysis**

Preliminary PMHS test results were used to evaluate the biofidelity of the HE-SID design. Finite Element models were built to analyze the design for durability, biofidelity and sensitivity to the shoulder impactor alignment.

Quasi-static analysis was conducted for the rib rail mounting bracket with AutoDesk Inventor 2012 Professional (stress results from LS-DYNA). The MIL-SID design with aluminum 6061-T6 was loaded until it yielded. The stress distribution is shown in Figure 9. The same load was applied to the HE-SID design, which has 5 mm additional thickness with aluminum 7075-T6 material, shown in Figure 10.

![Figure 9, Load to yield for the ES-2 rail mounting bracket](image_url_9)

![Figure 10, HE-SID rail mounting bracket stress distribution with the same load to yield ES-2](image_url_10)

The analysis is summarized in Table 1. HE-SID rib module rail mounting bracket strength was increased by approximately 90%.

<table>
<thead>
<tr>
<th>ATD</th>
<th>Materials</th>
<th>Load</th>
<th>Max Von Mises Stress</th>
<th>Yield Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES-2</td>
<td>Aluminum 6061-T6</td>
<td>5.2 KN</td>
<td>274 MPa</td>
<td>276 MPa</td>
</tr>
<tr>
<td>HE-SID</td>
<td>Aluminum 7075-T6</td>
<td>5.2 KN</td>
<td>264 MPa</td>
<td>503 MPa</td>
</tr>
</tbody>
</table>

Stress analyses were conducted for the shoulder rib to analyze the durability of the rib. For spring steel 1095, the Von Mises stress is well below the yield stress level for 60 mm compression, which is well above the estimated shoulder injury threshold.
In PMHS tests, the center of the impactor is aligned with the glenohumeral joint. Due to the irregular geometry in the shoulder girdle, the alignment is critical for achieving consistent test results. An FEA study was conducted to investigate the sensitivity of the impactor alignment with the ATD shoulder. Two positions were analyzed for comparison – 1) the impactor center is aligned with the ATD shoulder joint pivot center, 2) the impactor center is aligned with the ATD shoulder corresponding to the human glenohumeral joint.

From the kinematics analysis, it was observed that the HE-SID upper torso does not move much at all when the shoulder was maximally compressed (~50 mm). This is consistent with the observation in PMHS impact tests. Due to its impact speed and high energy impact, the PMHS and ATD upper torso remains its position due to its inertia. The deformation happened mainly in the local girdle of the shoulder, shown in Figure 11 and Figure 12. The low reaction of the torso kinematics is also evidenced by the relatively low T1 displacement, less than 3.5 mm in both cases.

Between the two alignment positions, a large deflection difference, up to 14 mm from both skeleton or arm flesh, was observed. It is important to align the impactor with glenohumeral joint for ATD biofidelity validation and verification test so that the results are comparable.
Figure 13. Deflection from ATD linear potentiometer measurement.

Figure 14. Deflections from the exterior arm flesh measurement.
RESULTS

Durability

Upon the completion of the HE-SID design, prototype ATD hardware was fabricated for validation and verification testing. After the first test, it was found that the shoulder rib was bent. The rib was brought to Humanetics for analysis and it was discovered that the spring steel was not properly heat treated. A second rib was treated with the proper heat treat process and the rib survived numerous impact tests without damage. No durability issue was observed for the thoracic rib module. The thoracic rib potentiometer was functioning well without any issue. The analysis and the design successfully addressed the MIL-SID durability issue.

ATD Responses

The prototype HE-SID was tested in the same rig that was developed for PMHS tests to verify the ATD biomechanical response. A series of 12 PMHS were tested to develop a biofidelity guideline and also the injury criteria. The force-deflection relationship of the PMHS tests is summarized in Figure 16, Figure 17 and Figure 18. The ATD demonstrates that the biomechanical parameters are similar to those of the PMHS. Specifically, the third test in the series aligns well with the PMHS corridors. Additional testing will need to be completed to fully characterize the variance shown in the initial test series.
Figure 16, ATD and PMHS shoulder deflection comparison

Figure 17, HE-SID and PMHS shoulder probe force comparison
Figure 18, HE-SID and PMHS force vs deflection comparison

CONCLUSIONS

HE-SID was developed to address the need for a durable and biofidelic ATD in high speed testing for injury predictions. The design is based on the ES-2RE design with improved durability of the rib modules and a new shoulder design. The HE-SID shoulder design allows motion in more degrees of freedom and also offers a 3D deflection measurement ability with a linear potentiometer and two rotary potentiometers. The shoulder joint of the HE-SID is located closer to the anatomical location and the arm skin thickness now resembles that of the human. The testing of the prototype design shows good durability at the high impact speed. Compared to PMHS shoulder response, the ATD shows similar results to human response. Further testing will be conducted to evaluate the HE-SID biomechanical response and injury criteria will be developed accordingly in the future.

REFERENCES


