Coupling feedback control loop-based model in Simulink to finite element model in LS-Dyna: Application to reposition forward leaning occupant to upright posture

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1 Introduction

Forward leaning postures have been observed for current car passengers [1] and are expected to occur even more frequently in future autonomous vehicles [2]. For existing restrain systems a strategy to provide optimized protection is to deploy mechatronic belt pre-pretensioner (MBPPT) before the crash targeting to maintain or better prevent possible forward leaning postures, mostly induced through pre-crash vehicle maneuvers [3 - 5]. Where for future restraint systems in highly automated vehicles [6 - 9] an additional load case for MBPPT might become important. Here the airbag restraint system is mounted into the seat, enclosing the upright occupant during deployment. If the occupant is out-of-position, the enclosure of the restrain system might not function optimally. Hence, a pre-triggered MBPPT can be used to bring the occupant back to the upright position before the crash.
Repositioning simulations can be carried out by modelling the MBPPT effectively using imposed force-time characteristics with assumed maximum force and ramp-up time in LS-Dyna [10]. In a more advanced approach, a Matlab/Simulink MBPPT feedback control loop model can be coupled to interact with the occupant model in LS-Dyna. However, research needs to be conducted to show the superior predictability using the advanced Matlab/Simulink MBPPT modelling approach over the conventional imposed force-time characteristic approach.
Using a UN R16 mannikin [11] in 50° forward bent posture, the objective is to compare and rate two modelling methods against physical tests. The MBPPT is modelled first by defined force-time characteristics and second by a coupled Matlab/Simulink feedback control loop model. For the mannikin repositioning load case, two types of MBPPT were used and the belt forces, belt pay in and repositioning time were compared. The results of both modelling methods are rated against physical tests using CORA rating.

2 Method

2.1 Passive safety environment in LS-Dyna

The describing right-handed coordinate system has the X-axis points in the reverse driving direction and the Z-axis in an upwards direction. The passive safety environment consists of a rigid UN R16 steel seat with a UN R16 mannikin in 50° forward bent posture as illustrated in fig. 1.

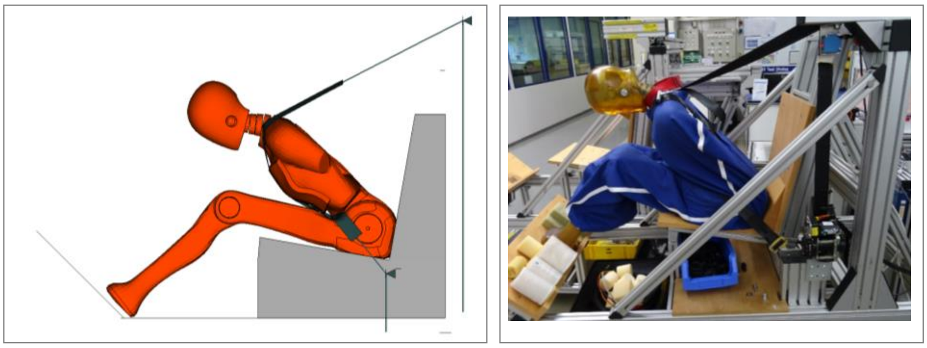

Fig.1: Passive safety environment consisted of UN R16 mannikin in 50° forward bent posture, in CAE (left) and physical (right) representation.

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It had a seat pan angle of 10° with respect to the YX plane and a seat backrest angle of 10° with respect to the YZ plane. The seat belt layout consisted of an anchor plate and a semi-flexible buckle on wire, with wire length of 90 mm. The seat belt geometry was derived from a common b-pillar layout, where the pillar loop location was significantly above the shoulder of the mannikin.
The UN R16 mannikin simulation model was developed in-house and validated with respect to sled test data. It was brought in a 50° forward bent posture by pre-simulation. The environment was in static conditions and hence, no pulse nor initial velocity was applied. The passive safety environment was modelled in the explicit code environment of LS-Dyna R9.3.1 SVN version 141945. Shoulder belt force and seatbelt pay-in were evaluated.

2.2 Modelling MBPPT in Matlab/Simulink

The MBPPT was modelled in Matlab/Simulink R2020B by implementing the relevant physical properties of the respective mechatronic parts. For the modelling four main categories were considered. 1) The mechanical properties of electrical motor, gear stage and retractor. 2) The electronic circuit unit (ECU) characteristics and 3) the electro-mechanical interaction. 4) Pyrotechnical pretensioning of the retractor for in crash belt slack reduction was not considered further on in this work. Standard Simulink block building methodology was applied by accounting switches, time integration and differentiation, adds, gains and lookup table blocks.
Mechanical and electrical behavior was modelled by solving the respective differential equations. Along with the time dependent mechanical and electronical behavior, the ECU of the motor was modelled, e.g. voltage and power control, voltage booster or speed limitation. PID-Controller blocks with optimized parameter sets were used for this and a multi-rate system was considered by accounting different clock rates in the system (chipset-, software- and vehicle CAN-Bus clock rate). The complete Matlab/Simulink model consists of 1587 blocks and is numerically solved by explicit Euler-Cauchy method.

2.3 Coupling Matlab/Simulink with LS-Dyna

The coupling of two systems can be interpreted as exchanging kinematic (e.g. velocity) and kinetic (e.g. force) information. To enable the exchange of information between Matlab/Simulink and LS-Dyna a third-party software (model.connect R2020.2) was required. Along with the graphical user interface (GUI) of model.connect, interfaces to LS-Dyna and Matlab/Simulink were supplied.

For LS-Dyna a user-defined material was supplied which was assigned to beam element 500262. A special feature of the LS-DYNA R9.3.1 SVN version 141945 used in this study enables defining a curve 200610 which is filled with values during the runtime of the simulation. For this the x-y relationship in the curve definition was left empty.

```
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
*DEFINE_CURVE
$    label      sidr       sfa       sfo      offa      offo    dattyp
    200610         0       1.0       1.0       0.0       0.0         0
$
$ no values - will be calculated by model.connect
$
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
```

This feature was used to provide belt pay in velocity information from Matlab/Simulink to LS-Dyna, where the velocity was embossed to node 500106 of the beam element 500262 connected to the seat belt.

```
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
*BOUNDARY_PRESCRIBED_MOTION_NODE
$       id       dof       vad      lcid
    500106         3         0    200610
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
```

The MBPPT Matlab/Simulink model interface to LS-Dyna expects forces as input parameter. The current software release of model.connect does not support reading beam forces from element 500262 directly during LS-Dyna runtime. On the other side, reading nodal velocities is supported. Hence, a workaround

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was developed. The current seat belt force in element 500262 was extracted within LS-Dyna using the keyword ***DEFINE_CURVE_FUNCTION** as defined below.

```
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
*DEFINE_CURVE_FUNCTION_TITLE
LSDyna calculated response
$     LCID      SIDR
    200602         0
$     FUNCTION
BEAM(500262,1,2,-1)
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
```

The beam element axial force was embossed to a node of a sled model independent defined beam element 200211 as velocity.

```
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
*BOUNDARY_PRESCRIBED_MOTION_NODE
$       id       dof       vad      lcid        sf       vid     birth
    200112         1         0    200602       0.0         0       0.0
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7
```

This velocity was read by model.connect and further sent to Matlab/Simulink, where the velocity was interpreted as force. With such workaround the required force information was transferred as scalar value between Matlab/Simulink and LS-Dyna.
This coupling method was modularly developed to integrate smoothly in the retractor model concept from Autoliv. This enabled the easy exchange of conventional retractor models in the existing LS-Dyna environment model to retractor models which were coupled to Matlab/Simulink or other software.

2.4 Parameterization of Matlab/Simulink and simplified MBPPT model

The physical tests were conducted using two types of MPBBT. Those two types differed mainly by gear ratio, resulting in the first configuration with approximately 400 N (C_{400}) and second configuration resulting in approximately 250 N (C_{250}) of shoulder seat belt force level measured before the pillar loop. These force levels were derived from static pre-tensioning tests. Both MBPPT configurations were deactivated after 500 ms, irrespective of the achieved repositioning process.
Based on those characteristics, the simplified MBPPT model was specified. For the modelling of C_{400} it was further assumed that the force level was reached after 140 ms, whereas for C_{250} the force level was reached after 56 ms. The ramp-up and force level of both types was bi-linear. For modelling the deactivation of the physical MBPPT, the force level was reduced at 500 ms from the respective level to 50 N.
For the MBPPT modelling using Matlab/Simulink the direct physical properties were defined using the available parameter. Hence, the electrical parameter set (e.g., available power, current and voltage) and the mechanical properties of the motor, gear stage and retractor (e.g., friction, inertia, motor- and torque constant, gear stage ratio, efficiencies) were defined.

3 Results

The mannikin in the physical test shows a saturated 238 mm belt pay-in level at 650 ms using the C_{400} configuration. This position is a nearly upright position. To accomplish this, the seat belt force peaks to 350 N at 150 ms and shows a regressive characteristic afterwards. The belt force is reduced from 234 N to 67 N after the MBPPT is switched off at 500 ms.
The Matlab/Simulink modelling method shows 241 mm of seat belt pay in at 500 ms. This position is a nearly upright position. To accomplish this, the belt force peaks to 350 N at 100 ms and shows a regressive characteristic afterwards. The belt force is reduced from 231 N to 0 N after the power supply is switched off in the simulation model.
The simplified MBPPT modelling shows 406 mm seat belt pay in at 447 ms, where the mannikin is brought into full upright position. The seat belt force follows the defined input characteristic, where the force level of 354 N is reached after 140 ms. After the thorax of the mannikin closes contact with the seat backrest a seat belt inertia driven peak up to 720 N in shoulder belt force occurs. For the shown

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time history metrics, the belt force data is filtered according to SAE J 211 with CFC 60 [12]. The results are illustrated in fig 2.

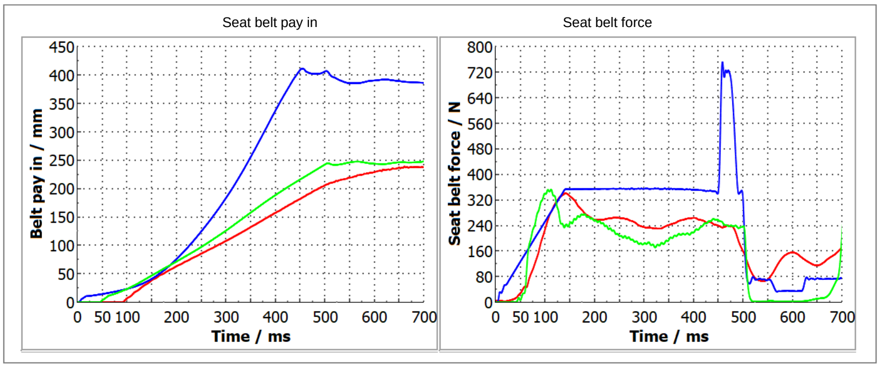

Fig.2: Webbing pay in (left) and seat belt force level (right) for C_{400} configuration. The simplified MBPPT model in blue, the Matlab/Simulink model in green and the physical test data in red.

The mannikin in the physical test shows a saturated 64 mm belt pay in at 250 ms using the C_{250} configuration. The C_{250} lifts the mannikin only slightly and fails to bring it into upright position. To accomplish this, the seat belt force peaks to 316 N at 60 ms. After the peak the belt force shows a constant characteristic of approximately 210 N until MBPPT is switched off at 500 ms.
The Matlab/Simulink modelling method shows saturated belt pay-in level of 58 mm at 410 ms. The belt force degressively increases to approximately 190 N at 100 ms to achieve this. These pay in and belt force characteristics achieve a similar final upright position as the physical test.
The simplified MBPPT modelling shows 137 mm belt pay in at 500 ms. The seat belt force follows the defined input characteristic, where the force level of 212 N is reached after 60 ms. These pay in and belt force characteristics lead to a more upright final position compared to physical testing. These results are illustrated in fig. 3.

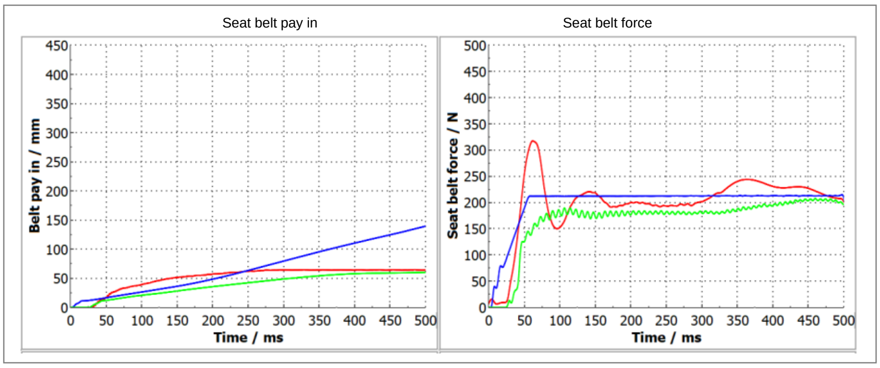

Fig.3: Webbing pay-in (left) and seat belt force level (right) for C_{250} configuration. The simplified MBPPT model in blue, the Matlab/Simulink model in green and the physical test data in red.

The initial and final positions of both configurations and the respective modelling methods are illustrated in fig. 4. For C_{400} the difference in the final upright position is obvious, as the simplified MBPPT is in fully upright position. The Matlab/Simulink MBPPT is in a nearly upright position. The nearly upright position of the Matlab/Simulink model visually correlates to physical testing.
For C_{250} simplified and Matlab/Simulink MBPPT fail to bring the mannikin into upright position, where the simplified MBPPT is more upright compared to Matlab/Simulink. Pictures of the physical test are not available, but belt pay in results expects the mannikin to be also only lifted slightly.

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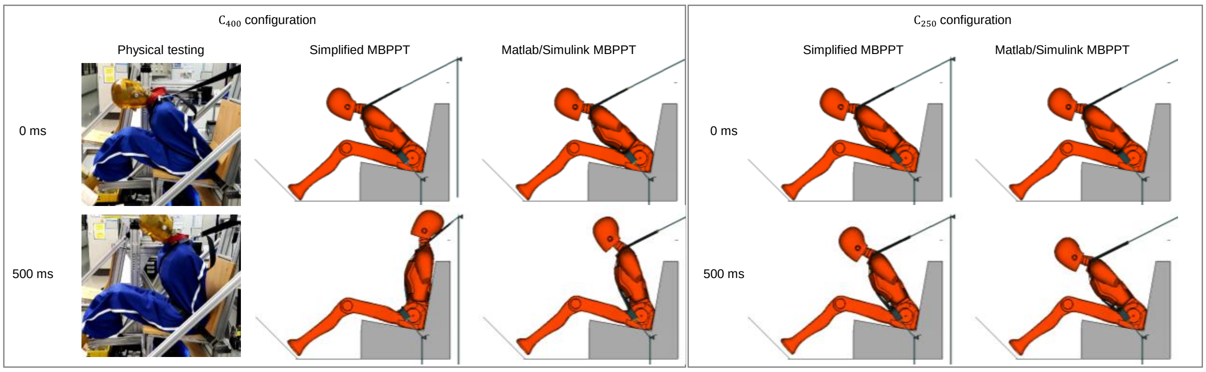

Fig.4: Kinematic comparison of C_{400} (left) and C_{250} (right) for both modelling methods showing the initial position (top row) and position at 500 ms (bottom row). For C_{400} the physical testing is given as reference.

To compare the two sets of simulation results to physical test results, CORA rating according to ISO 18571 [13] is applied to the time history data of the seat belt pay-in. The result of CORA rating ranges from 0.0 (no correlation between curves) and 1.0 (excellent correlation between curves). The rating is conducted from 0 to 700 ms for C_{400} and 0 to 500 ms for C_{250}. The CORA ratings for the C_{400} configuration were 0.80 for the Matlab/Simulink modelling method and 0.48 for the simplified modelling method, respectively. For C_{250} the CORA ratings were 0.46 for the Matlab/Simulink and 0.29 for the simplified modelling methods. The CORA ratings are illustrated in fig. 5.

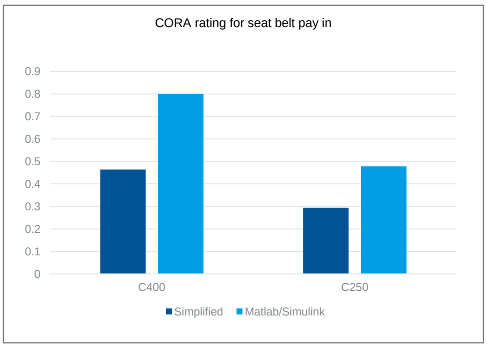

Fig.5: CORA rating of webbing pay in for C_{400} configuration (left) and C_{250} configuration (right) for simplified (dark blue) and Matlab/Simulink (light blue) MBPPT modelling methods.

4 Discussion

In this study two MBPPT modelling approaches were compared to physical test data. The physical test data consisted of two different MBPPT configurations, resulting in different seat belt force level. The physical tests were modelled using two different approaches. The first approach involved the sophisticated method of using a Matlab/Simulink feedback control loop model and the simplified approach using defined force-time characteristics.

The regressive belt force characteristic of C_{400} using Matlab/Simulink modelling followed the working principle of an electrical motor. Maximum force was applied to the seat belt as the mannikin was at rest. As the mannikin was brought into motion, the applied force was reduced as the motor was increasing the rotational velocity. Hence, the applied force to the seat belt was dependent on the resistance acting on the seat belt. This significantly affected the resulting acceleration of the mannikin. In case of the simplified modelling method, the force was held constant as defined. This led to higher acceleration and hence, accomplished the upright position of the mannikin.

In physical testing of C_{250} the mannikin was not brought into significant motion as only 64 mm of seat belt pay-in was achieved. Hence, the motor did not reach a high rotational speed by which the applied seat belt force would have been reduced. Moreover, the motor was applying the static load to the seat belt. This phenomenon was also observed using the Matlab/Simulink modelling approach, where it was not observed with the simplified force-time characteristics approach.

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These two load cases of mannikin repositioning and the CORA ratings show the need of a coupled simulation for MBPPT modelling. As the mannikin or occupant is not expected to be brought into motion by the MBPPT, the simplified approach of assumed seat belt forces can give close enough results. As the occupant is expected to change the position through belt forces applied by the MBPPT, the consideration of the resistance dependent motor characteristics increase predictability. Especially for future restraint concepts, which require the occupant to be in an upright position, it is essential to predict the out-of-position-repositioning time. The coupled approach is fundamental for this analysis.

The Matlab/Simulink modelling of MBPPT gives further insights to devise a future MBPPT configuration. Mechanics and electronics of the MBPPT are analytically resolved and the physical properties can be modified. Hence, the effect of, e.g., different power profiles, scattering in vehicle network data, component exchange or conceptual designs can be directly linked to passive safety analysis. The occupant repositioning process can be further optimized by balancing seat belt load and pay in speed with relevant injury tolerances of human body models.

The coupling offered the advantage of using the best modeling interfaces of each solver and averted the need to translate the models between software environments. This accelerates the development process and reduces the re-engineering work. However, a disadvantage is that two additional simulation tools, other than LS-Dyna, are required.

5 Conclusion

The feedback control loop method modelled in Matlab/Simulink outperforms the force-time characteristic method if compared to physical test as evidenced by CORA ratings. Therefore, feedback control loop modelling could be a better method for designing and evaluating repositioning functionalities of seat belt systems.

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