Optimal Forces for the Deceleration of the ES-2 Dummy

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Abstract

The purpose of this project is to improve the development process of vehicle safety systems by introducing a new analytic approach. Today, the development of vehicle safety systems, especially the airbag design process, requires many iteration loops via simulations and experiments. In this process, parameters are changed, a new simulation is conducted and the injury values are evaluated. We have a different, two folded approach: First we calculate the optimal forces to decelerate a dummy or human body. In a second step, these optimal forces can be used to design vehicle safety systems.

Here, a generic side impact setup is presented, which allows for a controlled deceleration. Optimal trajectories for the deceleration of a second generation European Side Impact Dummy (ES-2) are developed. Controllers are implemented which apply forces to the body regions depending on their specific injury criteria. Energy distribution across different body parts is presented.

1 Introduction

The occupant safety of a vehicle is tested in a number of precisely defined crash setups in which anthropomorphic test devices (ATD), commonly known as crash test dummies, are used to determine the effects on the human body. These ATDs are mechanical models of the human body that are designed for specific impact types, e.g. frontal, side or rear impact. Measurement devices included in the ATDs measure certain forces, accelerations and deflections that were found to have a statistical relevance with respect to injuries of the human body. The development of thoracic injury and protection criteria for side impacts is explained in [1]. The performance of a vehicle is then assessed in the European New Car Assessment Program (Euro NCAP) Criteria with a rating between zero and five stars, see also Table 1.

In the development of vehicle safety systems, designs are developed and tested in simulations or real crash tests. If the injury values breach the limits, the design is improved and tested again. To enhance this development process an optimal deceleration of the ES-2 dummy in a generic side impact is performed here. This optimal deceleration is carried out as fast as possible without exceeding the critical injury values. The resulting optimal forces for the deceleration can in turn be used as a reference for the design of vehicle safety systems. The optimal deceleration can be seen as a limit to how fast a deceleration can be carried out and how much space is necessary for the protection of the occupant. This optimal deceleration is achieved through a controller implemented in LS-DYNA v8.0 with a combination of `*DEFINE_CURVE_FUNCTION` and `PIDCTL`.

In the first section, the second generation European Side Impact dummy (ES-2) and the generic side impact setup is presented. Then optimal trajectories for the deceleration of the ES-2 dummy in a side impact scenario are developed. Finally, results are shown and discussed. A good overview of optimal protection and injury biomechanics is given in [2] and the limiting performance in frontal impacts is explained. In this paper, the limiting performance in a side impact for a state of the art dummy model is derived.

2 Test Setup

To be able to study the deceleration of side impact dummies across various simulation tools, a generic side impact setup was designed which can easily be set up in a finite element or multibody code. The setup is inspired by [1] and shown in Fig.1. It consists of a Heidelberg type seat, on which the dummy is sitting, respectively moving laterally with its initial velocity.

A ES-2 dummy, shown in Fig.2, is an ATD developed for side impacts, and is the standard dummy used worldwide in almost all side impact crash test. With its weight of 72 kg and a sitting height of 909 mm, it represents a 50th percentile male adult. Furthermore, the lower arms are not included to avoid contact with for example the steering wheel; this improves the repeatability of crash test results. A metal skeleton, different foam and rubber parts are used to model the body parts of the dummy. Multiple sensors are built into the ATD to measure the influences of the crash test onto the model of the human body. The most important body part regarding injuries is the thorax. Therefore, it is the body part modelled with most detail in the ES-2. The thorax of the dummy consists of three independent ribs, which are connected to the central spine box through a combination of springs and dampers. Aside from deformations of the ribs, a guiding system allows only lateral movement of the ribs.

The regulations that will be obeyed are the 2014 Euro NCAP Criteria and the goal is to receive the highest, well-known 5-star rating. This means not breaching the protection criteria listed in Table 1. To rate traumatic injuries, the Abbreviated Injury Scale (AIS) is used. The limits given in Table 1 are based on the probability of the occurrence of serious and severe injuries (AIS 3+). Complying with the higher performance criteria means the risk of serious or severe injuries is expected to be very low, which then results in a high NCAP rating. Comparing the lower and higher performance limits for the thorax, the risk of severe injuries caused by rib deflection is reduced from 17.8 % to 3.3 % according to the US NCAP risk curves.

To avoid head injuries, the head accelerations need to stay below a certain level, therefore an accelerometer is mounted in the head's center of gravity. The head injury criterion (HIC) is an integral criterion defined by

$$HIC_{36} = \max_{t_1,t_2:t_2-t_1\leq 36\,\mathrm{ms}} \left\{ \left[\frac{1}{t_2-t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2-t_1) \right\},$$

it takes into account the severity and the duration of the impact. The second criterion is simply the average acceleration over 3 ms. For the thorax, it was found that on the one hand, injuries depend on the deflection of the ribs, like e.g. fractures. On the other hand, injuries to the internal organs occur when an impact happens at high speed and the thorax is already compressed [4]. Therefore, besides the simple rib deflection criterion (RDC), the viscous criterion (VC) is defined as

$$VC = \frac{RDC(t)}{140\,\mathrm{mm}} \cdot \frac{d}{dt} RDC(t),$$

with 140 mm being half the width of the thorax of the ES-2. The deflection of the ribs is measured by linear potentiometers which are mounted at the side of the dummy opposing the impact. The abdomen of the ES-2 dummy consists of several foam parts. Three force sensors measure the lateral forces transmitted onto the lumbar spine. The maximum of the sum of the three forces is the Abdominal Peak Force (APF), which is limited by the Euro NCAP Criteria. The injury criterion for the pelvis is the pubic symphysis force (PSPF). In the ES-2, the pelvic bone is modelled with a left and a right half, which are connected with a load cell at the pubic symphysis. Most of the lateral impact forces applied to the pelvic region can be measured via this sensor.

Table 1: 2014 Euro NCAP Protection Criteria for Side Impact.

	Higher performance criteria	**Lower performance criteria**
Head	$HIC_{36} < 650$; $a_{3\,ms} < 72$ g	$HIC_{36} > 1000$; $a_{3\,ms} > 88$ g
Thorax	deflection < 22 mm; VC < 0.32 $\frac{m}{s}$	deflection < 42 mm; VC < 1.0 $\frac{m}{s}$
Abdomen	abdominal peak force < 1.0 kN	abdominal peak force < 2.5 kN
Pelvis	PSPF < 3.0 kN	PSPF > 6.0 kN

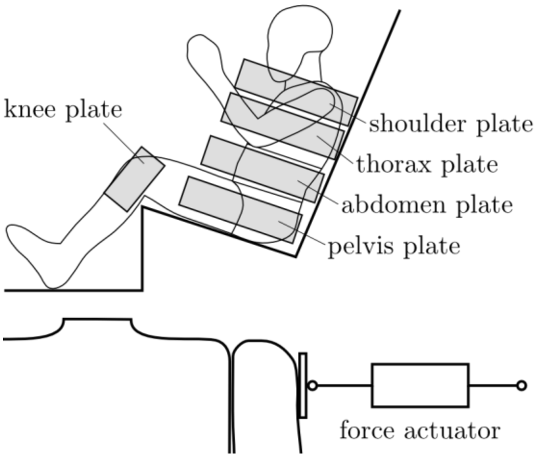


Fig.1: Generic side impact setup designed for evaluation of models of the human body and method of force application.

Fig.2: ES-2 Side Impact Dummy, shown here with a transparent jacket.

To decelerate the ATD in an optimal way, five plates are used to apply forces separately to the different body regions; the knee plate though is coupled rigidly with the pelvis plate. In Fig.1 the setup and the method of force application is depicted. This allows for an independent control of the forces applied to each body region depending on the injury criteria. It was decided not to apply force directly to the head for two reasons. First, safety systems for head protection, such as windows or curtain airbags, are deployed and designed separately from side airbags, and second, these safety systems are designed to protect the head from all possible impacts, but not to apply additional forces, as this implies high risks for head and neck injuries.

In the 2014 Euro NCAP regulations, no injury criteria for the shoulder of the ES-2 dummy are defined. This is mostly due to the design of the shoulder, which features a clavicle which rotates to the front when loaded with lateral forces. As a result of this, the sensitivity to lateral forces measured by the sensor between arm and clavicle decreases significantly. Since a criterion is needed in our setup, it was decided to use the shoulder force criterion for the new World Side Impact dummy (WorldSID) defined in the 2015 Euro NCAP regulations. There a maximum force of $F_{shoulder,max} = 3$ kN is defined. Similar limits where found in experiments and simulations with finite element human body models in side impact scenarios, see [5] and [6].

3 Optimal Deceleration Trajectories

The dynamic behavior of the body parts of the ES-2 dummy and the respective deflection, velocity and force criteria form the basis for the optimal deceleration trajectories.

For the determination of the dynamic behavior of the rib, a model identification is performed. For the model identification, the rib is extracted from the ES-2 dummy and fixed with a constraint. By examining the structure of the isolated rib as seen in Figure 3, it can be seen that the rib consists of a linear mass-spring-damper system and a rib arc with nonlinear behaviour. Therefore the response characteristic of the isolated rib is similar to a PT-2 transfer function.

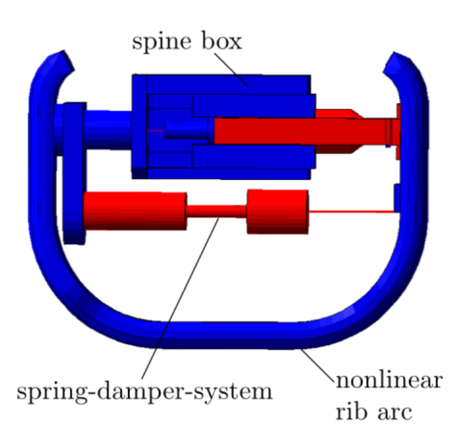


Fig.3: A rib of an ES-2 dummy.

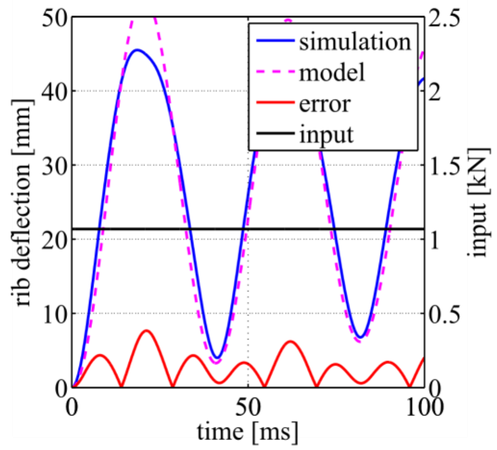


Fig.4: Step response of an ES-2 rib.

Thus a state space model of second order with the corresponding differential equation

$$m\ddot{q} + d\dot{q} + cq = F$$

is chosen to approximate the dynamical behaviour of the rib, where m is the mass, d damping, c stiffness, F is the input force and q the rib deflection. To determine the model parameters the step response of the rib is simulated and a parameter identification is performed. The step response of the rib and of the identified model can be seen in Fig.4.

To determine the force to be applied by the plate, a controller based on the identified model is developed. To control the rib, a closed loop control in combination with an open loop control is used, see Fig.5. A PI state space controller is used for the closed loop control of the rib. For the PI state space controller, the model of the rib must be transformed into the state space model

$$\dot{\mathbf{x}} = \mathbf{A} \cdot \mathbf{x} + \mathbf{b} \cdot u \,,$$

where $\mathbf{A}$ is the system matrix, $\mathbf{b}$ is the input vector, u is the control and

$$\mathbf{x} = \begin{bmatrix} q \\ \dot{q} \end{bmatrix}$$

is the state vector. The state feedback

$$u_{\text{closed}} = -\mathbf{k}^{*} \cdot \mathbf{x}$$

with the feedback vector $\mathbf{k}^{*}$ stabilizes the system while the corresponding PI controller ensures that the steady state error due to disturbances is zero. The corresponding open loop control can be written as a combination of the inverse dynamics and the state feedback:

$$u_{\text{open}} = m\ddot{q}_t + (d + k_2^{*})\dot{q}_t + (c + k_1^{*})q_t \;\; .$$

The control parameters can be calculated by deciding on a characteristic polynomial for the closed loop control, see [7].

To ensure that the deceleration of the dummy is as swift as possible without exceeding the NCAP criteria, an appropriate trajectory for the rib deflection needs to be determined. This trajectory q_t serves as a reference signal for the rib controller and as the desired rib deflection. For an optimal deceleration the trajectory should approach the maximum steady value as fast as possible, so that the maximum stationary force can be used.

Due to model uncertainties, a 5 % safety factor is used to ensure that the NCAP criteria are met. The corresponding boundary conditions for the trajectory are the rib deflection criterion

$$q_{t,\max} = 22\,\mathrm{mm} \cdot 0.95$$

and the viscous criterion with

$$\dot{q}_{t,\max} = \frac{140\,\mathrm{mm}}{x_t} \cdot \frac{0.32\,\mathrm{mm}}{\mathrm{ms}} \cdot 0.95.$$

To ensure a smooth trajectory, it is necessary to put a boundary on the maximum force or the maximum rib acceleration. Therefore, a maximum rib acceleration of

$$\ddot{q}_{t,\max} = 60\ \mathrm{g} \cdot 0.95 = 0.59\,\frac{\mathrm{mm}}{(\mathrm{ms})^2} \cdot 0.95$$

is imposed, in accordance with the thorax injury criteria for frontal crash. Due to the low damping and the unilateral force input, it is important to ensure that the controller can follow the resulting trajectory. By neglecting the damping, this leads to the conservation of energy with

$$E = \frac{1}{2} m \dot{q}^2 + \frac{1}{2} c q^2 \ \text{ and } \ E \le \frac{1}{2} c q_{\max}^2 .$$

With these constraints, the optimal trajectory q_t can be computed. The constraints and the optimal trajectory can be represented and understood best in the phase portrait as shown in Figure 6. As seen in Fig.7 the controller is able to follow the trajectory without exceeding the NCAP criteria. In the first part it follows the trajectory defined by the limit for the rib acceleration, then it follows the limit curve defined by the potential energy to the maximum rib deflection, where it remains until the dummy is decelerated completely. Therefore, the trajectory never gets close to the limit of the viscous criterion.

The other body parts, shoulder, abdomen and pelvis have force based NCAP criteria, which yield more simple trajectories. The optimal deceleration of the abdomen is shown as an example.
The trajectory of the abdomen only needs to ensure that the maximum value of the abdominal force is lower than the limit of the NCAP criterion of 1 kN. Therefore, an exponential signal

$$u(t) = A_{\max} \cdot (1 - \exp(-t/T))$$

with

$$A_{\max} = 1\mathrm{kN} \cdot 0.95$$

is used. The time constant T is chosen, such that the rise time of the trajectory is in the same order of magnitude as rise time of the optimal trajectory for the rib deflection. This ensures that all body parts are decelerated equally fast and avoids tilting of the dummy. The trajectories for the shoulder and the pelvis are chosen with the same time constant but amplitudes corresponding to their NCAP criterion.
For the control a model based PID controller is used. The controller is chosen such that the overshoot is minimal and the NCAP criteria are satisfied.

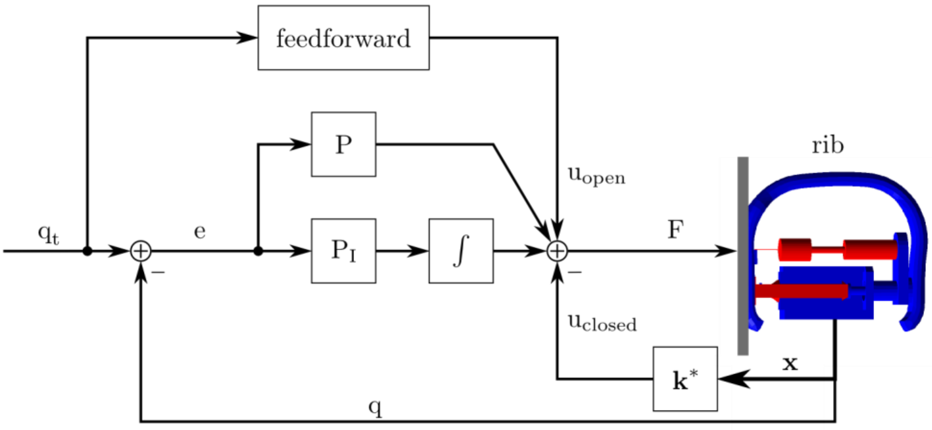
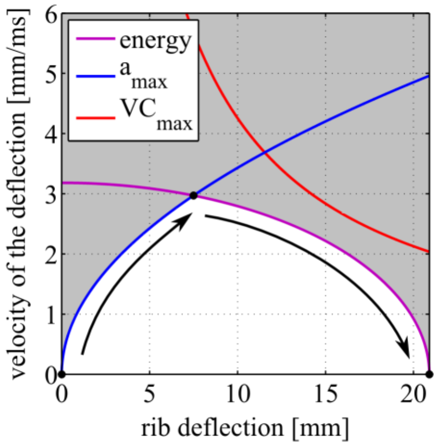


Fig.5: Structure of the controller used for the rib.



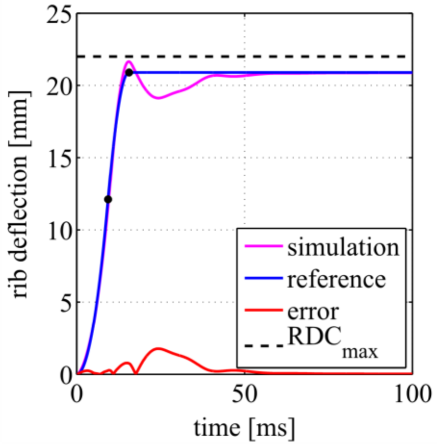


Fig.6: Boundaries for the rib trajectory.

Fig.7: Rib deflection following the trajectory.

3.1 Implementation Details

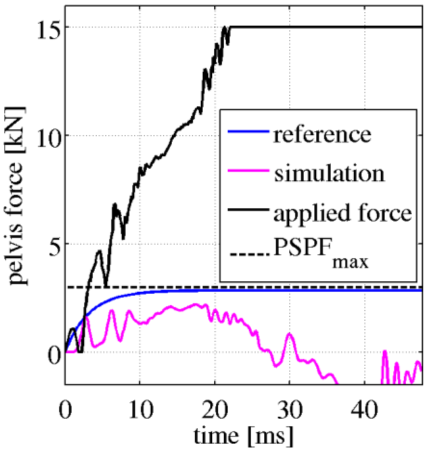
For the implementation of the controller in LS-DYNA two approaches exist: the user loading method and the curve functions. For the implementation of the user loading method, a Fortran function needs to be written and compiled. The controller can then be used with the `*User_Loading` keyword. Since LS-DYNA v8.0, a direct implementation of the PID controller is available, using `PIDCTL` in the `*DEFINE_CURVE_FUNCTION` keyword. More complex controllers can be created through combinations of standard functions in the input file. The curve function method is preferred because it is easier to use and implement.

For the implementation of the controller, the current injury values are needed as an input to calculate the force applied to the plates. Sensors need to be defined that are capable of measurements during the runtime of the simulation. The forces in the pelvis and shoulder are measured through linear springs, so that the current force can be calculated from the distance between the nodes of the spring. The rib deflection is equal to the change in length of the spring connecting the rib to the spine. The abdominal force is the sum of three contact forces, which can be directly computed by using `RCFORC` in the curve function. To calculate the integral part of the input force, a unit mass element is used as an integrator. A force equal to the current error is applied to the mass element, so that the current velocity of the mass element corresponds to the integral of the error.

4 Results

By combining the aforementioned controllers for all body parts, the dummy can be decelerated in an optimal way. However, certain characteristics pose a problem. The pelvis acts like a high-pass filter and therefore relatively high forces can be applied on the pelvis without exceeding the NCAP criteria as seen in Fig.8. Besides being unrealistic as such, these high forces can lead to an undesirable tilting of the dummy. To prevent this, an upper limit of 15 kN is imposed on the pelvis force. With this modification, the optimal deceleration of the ES-2 dummy is accomplished without exceeding the NCAP criteria and without tilting.

In Fig.9 the final results are displayed. The plot shows the velocities of each body part in the sagittal plane. Starting at an initial velocity of $12\frac{\mathrm{m}}{\mathrm{s}}$, the average velocity reaches zero after 54 ms. The total distance for the deceleration is 382 mm, which can be regarded as the limiting performance. The velocities of all body parts remain in a small corridor until 30 ms, after that they start to divert a little. The lower body parts are decelerated faster due to the high pelvic force applied.



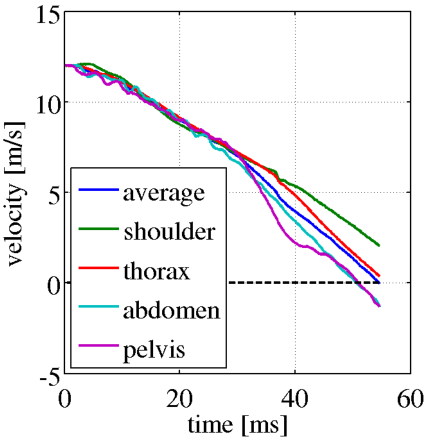


Fig.8: High-pass characteristic of the pelvis.

Fig.9: Velocity of the body regions.

The resulting optimal energy distribution is shown in Fig.10. It can be seen that, even though the force on the pelvis is reduced, the biggest portion of the energy is transmitted through the pelvis. For the upper body, the energy transmitted through the thorax has the highest values. The lowest energy portions are applied to the shoulder and abdominal region. The decline of the kinetic energy over the time is depicted in the upper diagram in Fig.10. The total energy needed for the deceleration of the dummy is bigger than the initial kinetic energy because of energy dissipation by damping and deformation and because rotational energy is not accounted for. The relative accumulated energy applied to each body region is shown in the lower diagram.

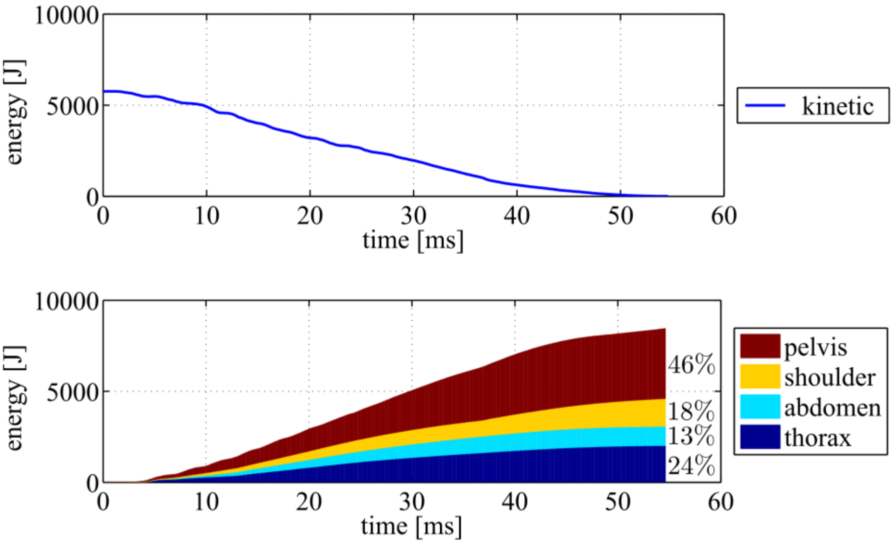


Fig.10: Power of the different controllers.

5 Summary and Outlook

The goal of this paper was to present a setup and method by which one can calculate the optimal forces for the deceleration of the ES-2 dummy. The optimal forces are such that they decelerate the dummy as fast as possible without exceeding the critical injury values. They can be used to aid in the design of vehicle safety systems. This is different from the usual approach of varying parameters based on experience. The advantage of such optimal forces becomes apparent if a new dummy model is introduced and there is no experience available. In this case optimal forces determined as proposed here, can be very helpful in accelerating the design process.

The sensitivity of these optimal forces with respect to perturbations in position or velocity has also been tested and it was found that the variation of the optimal forces under small perturbations is insignificant. This can be seen as a validation of the robustness of the results presented here.

As an addition to the results obtained here for the deceleration of the ES-2 dummy, a similar optimal deceleration of a human model (THUMS) is going to be conducted. This enables us to compare the ES-2 dummy to the human body and can thereby show potential weaknesses in the design of the ES-2 dummy or in the application of the optimal forces to the human body.

6 Literature

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