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Some Ideas on Bag and Belt Control

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CHAPTER ONE

Some Ideas on bag and belt control

1.1 Introduction

The objective is a control design approach to simultaneously control two occupant injury measures by manipulating variables of the safety belt and of the driver airbag. Here, it is essential that during control, constraints on the manipulated variables and on the motion of the crash dummy are to be taken into account.

The crash under investigation is the frontal, US-NCAP crash test, (NHTSA, 1999) of the BMW 3-series saloon (E46) with a HYBRID III 50th percentile as the 'driver' of the vehicle. A MADYMO model of this crash test is available, and is henceforth referred to as $\mathcal{M}$. The controlled variables are the chest deceleration c, and the head deceleration h, measured at the centers of gravity, and in the forward direction. The manipulated variables are the belt force F, and the mass flow ϕ into the airbag. It is chosen to solely manipulate the mass flow ϕ, and to keep the size of the vent in the airbag at a constant level, being twice the original value. The underlying reason is that the manipulation of only the mass flow is more realistic, considering the abundance of patented ideas and implementations, (Copperthite *et al.*, 1998; Solomon *et al.*, 2000; Hussey and Johnson, 1997; Jones and Webber, 2001; Damman *et al.*, 2001; Mascheck and Mattes, 2001; Brown *et al.*, 1998; Ryan, 1998).

For the above outlined objective, the general closed loop with $\mathcal{M}$ is shown in Figure 1.1. Here, r_h and r_c is the reference trajectory for the head respectively the chest deceleration, C is the to be designed control algorithm, A_{veh} the a priori known vehicle deceleration, Ψ and Ω is a vector that contains the constraints on the manipulated variables respectively on the controlled variables, for each time instant of the crash.

The constraints on the manipulated and controlled variables are:

- for the belt force $F(t)$, (Hesseling *et al.*, tion):
    - $\max F(t) \leq 6\,\text{kN}$,
    - $\min F(t) \geq 0\,\text{kN}$,
    - $\max |\dot{F}(t)| \leq 1.5\,\text{kN ms}^{-1}$, and

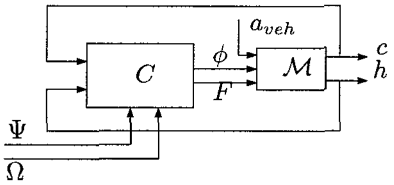

Figure 1.1 General closed loop with $\mathcal{M}$

  - $F(t) = 0$ for $t \leq 12\,\mathrm{ms}$,

- for the mass flow $\phi(t)$, (Peeters Weem, 2003):
  - $\max \phi(t) \leq 1.4\,\mathrm{kg\,s^{-1}}$,
  - $\min \phi(t) \geq 0\,\mathrm{kg\,s^{-1}}$,
  - $\max |\dot{\phi}(t)| \leq 90\,\mathrm{kg\,s^{-2}}$,
  - $\max \int_{t_0}^{t_e} \phi(t)dt \leq 40\,\mathrm{g}$, and
  - $\phi(t) = 0\,\mathrm{kg\,s^{-1}}$ for $t \leq 10\,\mathrm{ms}$,
- for the crash dummy motion, (Hesseling *et al.*, tion; Peeters Weem, 2003):
  - during the crash, the front of dummy torso may not be pushed through the back of the seat,
  - during the crash, the front of the dummy torso may not touch the steering wheel,
  - during the crash, the head of the dummy may not touch the steering wheel,

The control goal can now be exactly defined as a straightforward control design strategy to arrive at a control algorithm C, such that the maximum values of the head and the chest deceleration are as low as possible, accounting for constraints of F, ϕ, and the motion of the crash dummy.

The above control goal for the US-NCAP crash test is defined as nr. 8 of the ten crash test configurations as agreed upon in May 2003 with BMW. The focus in this report lays on the approach, rather than the interpretation of the obtained results, and the goal of this report is twofold:

- discuss the control design approach and the implementation in the closed loop with $\mathcal{M}$, and
- enable an evaluation of BMW about the proposed control design approach.

In Section 1.2, the control design approach will be elucidated. In Section 1.3, the resulting control algorithm C will be implemented in the closed loop with $\mathcal{M}$ and the results will be discussed. Finally, in Section 1.4, the results will be discussed.

1.2 Approach

First, the state of the art of control design approaches is discussed, then the necessary extensions will be discussed. The state of the art control design approach is based on 'loop shaping for performance', which inherently requires the definition of a to be tracked reference trajectory r_c and r_h.

1.2.1 State of the art

The state of the art of the control design approach consists of four steps, Figure 1.2.

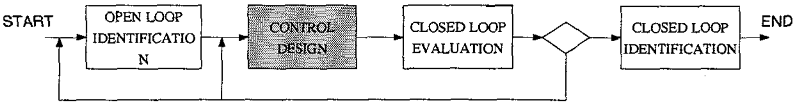

Figure 1.2 flowchart of the full control design approach

The last step, being the closed loop identification, is not relevant for this report and hence, will not be discussed, but can be found in (Hesseling *et al.*, tion).

The three remaining steps are:

- The first step is to identify the transfer from F to c, referred to by $H^{belt}(s)$, respectively from ϕ to h, referred to by $H^{airbag}(s)$. Here, s refers to the continuous-time domain, and hence both transfers are linear and constant in time. The identification has already been done for both transfers, (Hesseling *et al.*, tion; Peeters Weem, 2003). It boils down on the estimation of the investigated transfer using measurements of the controlled variable in the open loop system with $\mathcal{M}$, and with small stepwise perturbation added to a known trajectory of the manipulated variable. To estimate the transfer, the concept of partial realization for noisy measurements over a length shorter than needed to attain a steady state, (de Schutter, 2000; van Helmont *et al.*, 1990; Ho and Kalman, 1965), is used. The identification approach is outlined in detail in (Hesseling *et al.*, tion). It is noted that for the identification of $H^{belt}(s)$ and $H^{airbag}(s)$, the open loop system with $\mathcal{M}$ is used, where the airbag respectively the belt are omitted. To prevent confusion, the MADYMO model where the airbag or where the belt is omitted is referred to as $\mathcal{M}^{no\,airbag}$ respectively $\mathcal{M}^{no\,belt}$.
- The second step is to design a control algorithm C. For the control of c in $\mathcal{M}^{no\,airbag}$, and for the control of h in $\mathcal{M}^{no\,belt}$, and accounting for constraints on the dummy motion only, this step has already been done, (Hesseling *et al.*, tion; Peeters Weem, 2003). It boils down on 'loop shaping for performance' using a priori defined performance and stability criteria, being the 5 % settling time, the maximum allowable error $e_{\max}$, and the phase and gain margin, PM respectively GM. A controller $C^{belt}(s)$ respectively $C^{airbag}(s)$ is designed using the closed loop systems with $H^{belt}(s)$ respectively $H^{airbag}(s)$, aiming for the least achievable bandwidth frequency that satisfies the control design criteria. For the control of h, a P controller has resulted, and to control c, a PI controller has resulted. The control design approach is outlined in detail in (Hesseling *et al.*, tion).
- The third step is the implementation of controllers $C^{belt}(s)$ and $C^{airbag}(s)$ in the closed

loop system with $\mathcal{M}^{no\,airbag}$ respectively $\mathcal{M}^{no\,belt}$, and, after that, the evaluation of the controllers. These implementation and evaluation has are already been done, (Hesseling *et al.*, tion; Peeters Weem, 2003). The results showed a stable closed loop in both cases, for which (at least for the belt), the control design criteria are satisfied. For the control of c in the closed loop with $\mathcal{M}^{no\,airbag}$, and for the control of h in the closed loop with $\mathcal{M}^{no\,belt}$, the results are shown in Figure 1.3 respectively Figure 1.4.

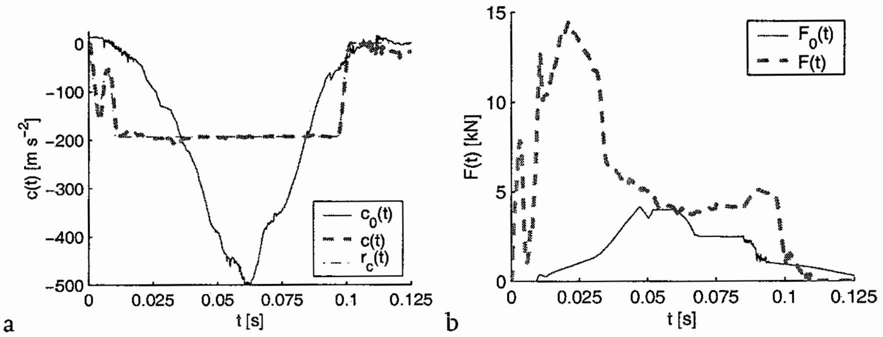

Figure 1.3 Results of the evaluation of $C^{belt}(s)$ in $\mathcal{M}^{no\,airbag}$. The original chest deceleration $c_0(t)$ and the controlled chest deceleration $c(t)$ in (a), and the original belt force $F_0(t)$ and the manipulated belt force $F(t)$ in (b).

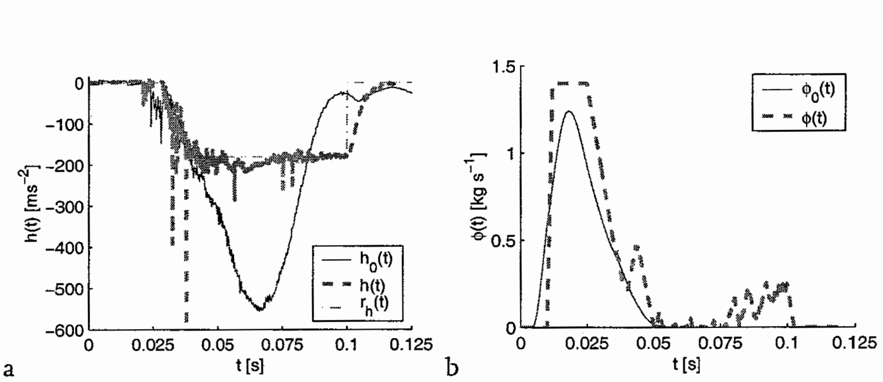

Figure 1.4 Results of the evaluation of $C^{airbag}(s)$ in $\mathcal{M}^{no\,belt}$. The original head deceleration $h_0(t)$ and the controlled head deceleration $h(t)$ in (a), and the original mass flow $\phi_0(t)$ and the manipulated mass flow $\phi(t)$ in (b).

1.2.2 Necessary extensions

The state of the art control design approach considers the control of c and h separately. For the simultaneous control of c and h, necessary extensions to the control design approach are:

- modifying $\mathcal{M}$, such that both F and ϕ can be manipulated, and such that c and h can be measured,
- reconsider the design of $C^{belt}(s)$ and $C^{airbag}(s)$, and

- reconsider the reference trajectories $r_c(t)$ and $r_h(t)$

Modification to $\mathcal{M}$

The modifications to $\mathcal{M}$, necessary to enable simultaneous control, are straightforward and simple. First, a so-called `EXTERNAL OUTPUT` for h and for c has to be defined in the MADYMO DATA-file, and correspondingly, two signals from MADYMO to MATLAB have to be defined in the MATLAB/SIMULINK model. Secondly, a so-called `EXTERNAL INPUT` signal for F and ϕ has to be defined in the MADYMO DATA-file, and correspondingly, two signals from MATLAB to MADYMO have to be defined in the MATLAB/SIMULINK model. The details of these modifications can be found in (TNO Automotive, 1999, MADYMO User's Manual 3D, pp. 335 – 358).

Control design for $C^{belt}(s)$ and $C^{airbag}(s)$

Obviously, both manipulated variables have an influence on all occupant injury measures, being not only the chest and head deceleration, but also, for instance, the chest deflection, VC-criterion. Since we only focus on the control of the chest and head deceleration, two important assumption are made, making the control design straightforward:

- it is assumed that the belt force significantly influences only the chest deceleration, and that the mass flow significantly influences only the head deceleration. This assumption is based on suggestions made in several publications with (Kallieris *et al.*, 1998; Mackay *et al.*, 1994; Johannessen and Mackay, 1995) being only some of them.
- it is assumed that the influence of the belt force on the head deceleration and of the mass flow on the chest deceleration, can be interpreted as a disturbance on the head deceleration respectively the chest deceleration. This assumption is based on the physical insight in the crash dummy, which shows that the connection between the chest body and the head body is (relatively) weak.

If these assumptions are correct, it may be justified to define two decoupled feedback loops. Then, it is possible to straightforwardly account for the constraints on the manipulated variables by clipping them into the closed loop, just after the controller, and to account for the dummy motion constraints by providing an appropriate reference trajectory. The 'new' closed loop with $\mathcal{M}$ is shown in Figure 1.5, compare Figure 1.1 and Figure 1.5.

Note that in the 'new' closed loop with $\mathcal{M}$, no additional models for the disturbance of F on h and for the disturbance of ϕ on c is taken into account. It is assumed that, with an appropriate control design of $C^{airbag}(s)$ and $C^{belt}(s)$, including robustness and stability design criteria, these disturbances are already accounted for. This means that the controllers $C^{belt}(s)$ and $C^{airbag}(s)$ design for $\mathcal{M}^{no\,airbag}$ respectively $\mathcal{M}^{no\,belt}$ may be used.

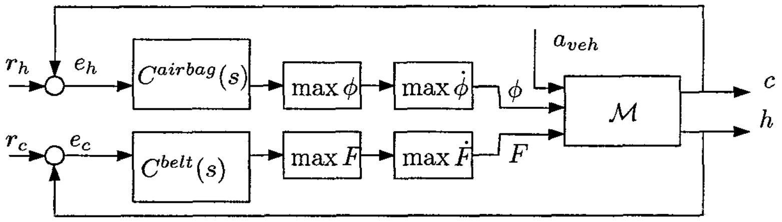

Figure 1.5 General closed loop with $\mathcal{M}$

Design of r_h and r_c

Since for the simultaneous control with two separate feedback loops, two reference trajectories r_c and r_h are to be obtained, that, if stably tracked with a small error $e_c = r_c - c$ respectively $e_h = r_h - h$, do not result in violations of the constraints on the manipulated variables, and do not result in violation of the constraints on the dummy motion.

It can be concluded from (Hesseling *et al.*, tion; Peeters Weem, 2003), that violation of the manipulated variables, in general, occurs for $t \leq 40$ ms. As a result of that, a part of the kinetic energy of the chest and the head is not absorbed by the belt respectively the airbag, and the chest and the head touch the steering wheel at the end of the crash. So, the amount of the to be absorbed kinetic energy for the chest and head deceleration for $t \geq 40$ ms increases, if contact with the steering wheel at the end of the crash is to be avoided.

Clearly, numerous approaches exist to arrive at an appropriate reference trajectory. Here, the approach proposed in Ikels *et al.* (2001), will be used, because of its simplicity, effectiveness and straightforwardness. The value of the reference trajectories $r_h(t)$ and $r_c(t)$ for $t \geq 40$ ms will be subsequently altered, until a closed loop simulation with $\mathcal{M}$ shows that the chest respectively the head does not touch the steering wheel, LOOP 1a respectively LOOP 1b in Figure 1.6. The choice to firstly determine a reference trajectory for the chest and then for the head is arbitrary. After an appropriate trajectory $r_h(t)$ and $r_c(t)$ is found, the procedure is repeated to check whether the value of $r_h(t)$ and $r_c(t)$ for $t \geq 50$ ms can be lowered even more, LOOP 2 in Figure 1.6. The abbreviations in Figure 1.6 mean:

- LOOP 1a
    - S1: Simulation of the closed loop with $\mathcal{M}$ and the constraints on the manipulated variables implemented conform Figure 1.5, with the objective to obtain appropriate trajectory of r_c. The resulting reference trajectory is referred to as r_c^k, where k refers to the k-th iteration in LOOP 2.
    - Q1: Question: Does the chest deceleration show an impact the steering wheel?
    - O1: Operation: change reference trajectory $r_c(t)$ for $t \geq 40$ ms.
- LOOP 1b
    - S2: Simulation of the closed loop with $\mathcal{M}$ and the constraints on the manipulated vari-

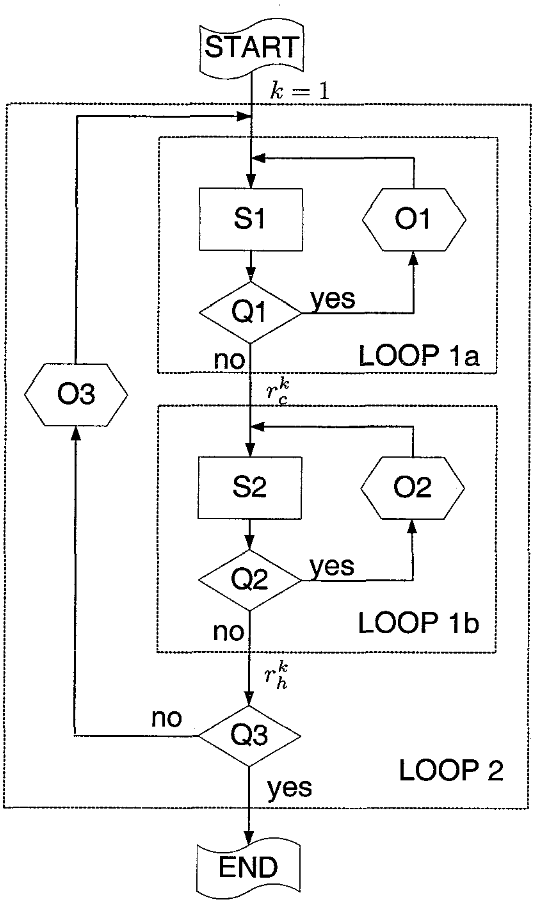

Figure 1.6 Schematic flow diagram to obtain the appropriate reference trajectories $r_c(t)$ and $r_h(t)$

ables implemented conform Figure 1.5, with the objective to obtain appropriate trajectory of r_h. The resulting reference trajectory is referred to as r_h^k, where k refers to the k-th iteration in LOOP 2.

- Q2: Question: Does the head deceleration show an impact on the steering wheel?
- O2: Operation: change reference trajectory $r_h(t)$ for $t \geq 40\,\text{ms}$.

- LOOP 2
  - Q3: Question: Are the reference trajectories $r_c^k(t)$ and $r_h^k(t)$ equal to $r_c^{k-1}(t)$ respectively $r_c^{k-1}(t)$?
  - O3: Operation: $k = k + 1$; Decrease the value of the reference trajectory $r_c^k(t)$ and $r_h^k(t)$ for $t \geq 40\,\text{ms}$.

To actually change the reference trajectory $r_c(t)$ or $r_h(t)$ for $t \geq 40\,\text{ms}$, if the dummy motion constraints are violated (O1 and O2), various procedures can be followed. Some examples are the bi-section method, as applied by (den Hamer, 2003), a constant or linear adaptation law for $r_c(t)$ or $r_h(t)$ for $t \geq 40\,\text{ms}$, (Ikels *et al.*, 2001). Here, it is chosen for a constant change of the to be tracked deceleration r_h or r_c of $5\,\text{ms}^{-2}$.

1.3 Results

Recall that the focus in this report lays on the approach, rather than on the obtained results.

The outlined approach is used to simultaneously control the chest and head deceleration, during a crash with a HYBRID III 50th percentile dummy as the 'driver' of a mid-size passenger vehicle (E46), subjected to a frontal US-NCAP crash. The results are shown in Figure 1.7 and Figure 1.8, where they are compared with the original trajectories. The total amount of simulation is 15, and only one iteration using LOOP 2 has been necessary.

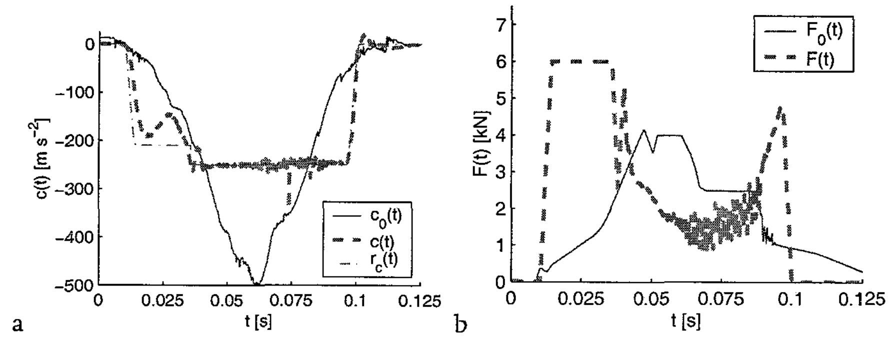

Figure 1.7 Results of the evaluation of $C^{belt}(s)$ in $\mathcal{M}^{no\ airbag}$. The original chest deceleration $c_0(t)$ and the controlled chest deceleration $c(t)$ in (a), and the original belt force $F_0(t)$ and the manipulated belt force $F(t)$ in (b).

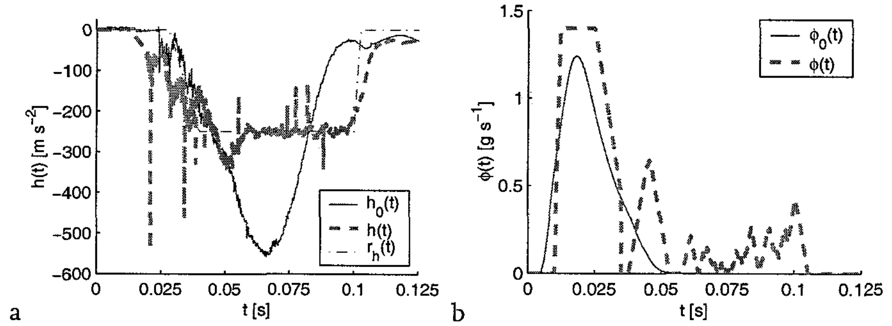

Figure 1.8 Results of the evaluation of $C^{airbag}(s)$ in $\mathcal{M}^{no\ belt}$. The original chest deceleration $h_0(t)$ and the controlled chest deceleration $h(t)$ in (a), and the original mass flow $\phi_0(t)$ and the manipulated mass flow $\phi(t)$ in (b).

The high frequent oscillations in the head and chest deceleration are due to the finite element model of the airbag. They may be further suppressed by further tuning the low-pass filter in $C^{belt}(s)$ and implementation of a low-pass filter in $C^{airbag}(s)$. The desired performance for the closed loop behavior are achieved, but will not be discussed in this report. The closed loop results indicate that the closed loop with $\mathcal{M}$ is stable.

In Figure 1.9 and Figure 1.10, the results are compared with the controlled trajectories from the evaluation of $C^{belt}(s)$ in $\mathcal{M}^{no\,airbag}$ and $C^{airbag}(s)$ in $\mathcal{M}^{no\,belt}$, where the constraints on the manipulated variables were not accounted for.

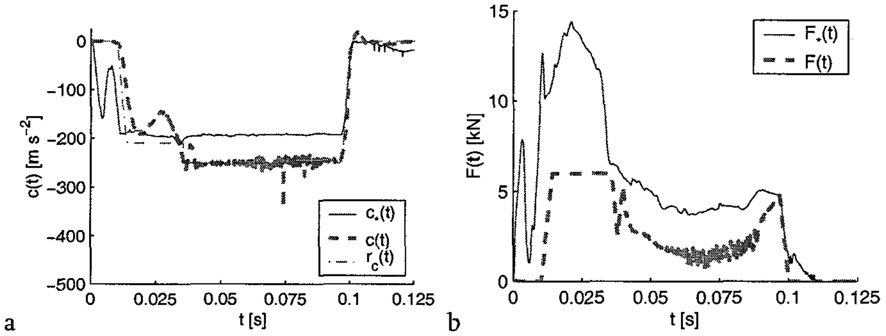

Figure 1.9 Results of the evaluation of $C^{belt}(s)$ in $\mathcal{M}$. The chest deceleration $c_*(t)$ from Figure 1.3a, and the controlled chest deceleration $c(t)$ in (a), and the belt force $F_*(t)$ from Figure 1.3b and the manipulated belt force $F(t)$ in (b).

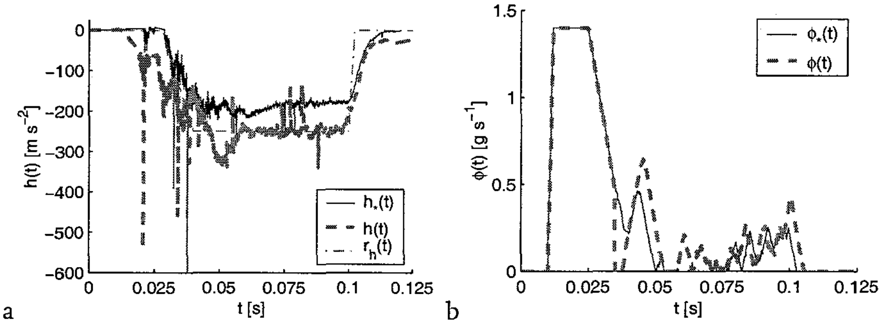

Figure 1.10 Results of the evaluation of $C^{airbag}(s)$ in $\mathcal{M}$. The head deceleration $h_*(t)$ from Figure 1.4a and the controlled chest deceleration $h(t)$ in (a), and the mass flow $\phi_*(t)$ from Figure 1.4b and the manipulated mass flow $\phi(t)$ in (b).

1.4 Discussion

The outlined approach shows to be a very straightforward way to achieve the trajectories of the belt force and of the mass flow, resulting in least achievable values of the tracked chest deceleration respectively head deceleration. Especially the fact that the controllers $C^{airbag}(s)$ and $C^{belt}(s)$, do not have to be tuned or redesigned makes the approach very attractive. It may be carefully concluded that the influence of the belt force on the head deceleration and the influence of the mass flow on the chest deceleration can indeed be considered marginal, and do not require redesign of the controllers $C^{airbag}(s)$ or $C^{belt}(s)$.

The approach, as it is discussed here, is very basic. Especially, a more sophisticated procedure to change the reference trajectory, if the constraints on the dummy motion are not satisfied, can make the approach significantly more effective. In addition, experience of the user will significantly increase the effectiveness of the approach.

Some critical notes are:

- To find appropriate reference trajectories for the chest deceleration and the chest deflection are controlled by manipulation of the belt force respectively the mass flow, the outlined approach is unsuited. In addition, also if the belt force and the mass flow are manipulated to control the chest deceleration, the chest deflection or the head deceleration only, the approach cannot be used.
- The approach cannot be effectively used for analysis of the sensitivity of the occupant injuries to the constraints, since the full iterative loops have to be repeated for each new situation.
- The approach cannot be used if one occupant injury is to be minimized (*e.g.*, the chest deceleration c), whereas another occupant injury may not be higher than an a priori defined value.
- The approach is unsuited to account for constraints that cannot be clipped into the closed loop with $\mathcal{M}$ and that cannot be translated into requirements for the reference trajectory.

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