Design of a beltforce controller for the USNCAP57 crash

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Introduction

In the last decades, the focus in the automotive industry is set on the design of safer vehicles. By performing and analyzing crash tests every manufacturer developed safety systems. Today, new computational methods make it possible to build active safety restraint systems. The advance of an active system over a passive is that it acts different for various types of crashes. Differences are e.g. the direction of the crash (front, side, etc.) and the mass of the driver.
In this report a first step towards the development of an active safety belt in a vehicle is discussed.

The research that is performed by BMW and TUE, computer models are used. These models are based on the results of actual crash tests. In this research it is tried to control the pulling force of the safety belt in at the B-pillar in such way, that maximum safety of the driver is achieved. The results from the computer models can later be used in real life crash tests.

Formal research by Hesseling[1] defined that optimal safety is equivalent to minimizing the maximum amount of deceleration of the drivers chest during a crash. Hesseling showed that step response analysis and standard feedback control are sufficient to find an optimal solution for crash test USNCAP (57kmh) with one type of dummy (50% hybrid). Unfortunately this beltforce controller cannot be used for other types of dummies.
In this research, the algorithm of Hesseling is used for the same crash. Now a 5% dummy is used. The results are compared to the result of Hesseling. This comparison leads to a definition for the feasibility of one controller that gives optimal results in both situations.

The first chapter describes the algorithm and results of Hesseling. Some extra motivations are given. Chapter 2 and 3 describe how the algorithm is used for the crash USNCAP57 with 5% dummy. Chapter 4 compares the results with the results of Hesseling[1] and gives a validation of a mutual exclusive controller for both dummies in this crash. Chapter 5 describes conclusions and recommendations.

1 Solution algorithm

In formal research by Hesseling [1], a controller is built that controls the safety belt in crash USNCAP57 with 50% hybrid dummy (medium weight, 75[kg] man). This controller is unstable for the same crash with a 5% hybrid dummy (lightweight, 50[kg] woman). Based on the same algorithm, the goal is to find a controller for both cases.

The problem definition is:

> Develop a new beltforce controller for crash USNCAP57 with a 5% hybrid dummy by using the algorithm of Hesseling[1]. Compare the controller with the controller for a 50% hybrid dummy and define possibilities for development of one controller for both cases.

The algorithm that is used by Hesseling exists of the following steps:

1. Building a computer model of a the crash and the dummy, with the use of experimental data of crash tests.
2. Define improvements that the beltforce controller must accomplish.
3. Define an optimization algorithm for designing the new beltforce controller.
4. Identify the response of the complex computer model to beltforce with a low order transfer function.
5. Use the identified transfer function to built a regulator for the beltforce.
6. Testing of controller on the complex computer model and, based on the results, optimize the controller.

The rest of this chapter discusses each step and gives the results of Hesseling.

1.1 Computer model

The data of crash tests is introduced in a computer model to allow easy reproduction of the results. This is useful to reduce costs of development. It is also useful for predevelopment, because controllers can be tested in software and no exotic hardware is required.

The computer model is based on multi body dynamics and finite element methods. BMW and TNO together developed a model for the inner vehicle and the dummy. The computer model is assumed to be representative for the crash that is analyzed. This assumption is not argued here.
The model is designed in the computer program MADYMO. More information on multi body dynamics and FEM can be found in Madymo manuals[2] and Fenner[3].

Fig. 1.1 shows plots of the computer model (50% dummy). The model exists of 15 so called systems. Examples are: the dummy, the seat and the airbag. The airbag and the windshield are implemented as FEM models because of there complex shape.

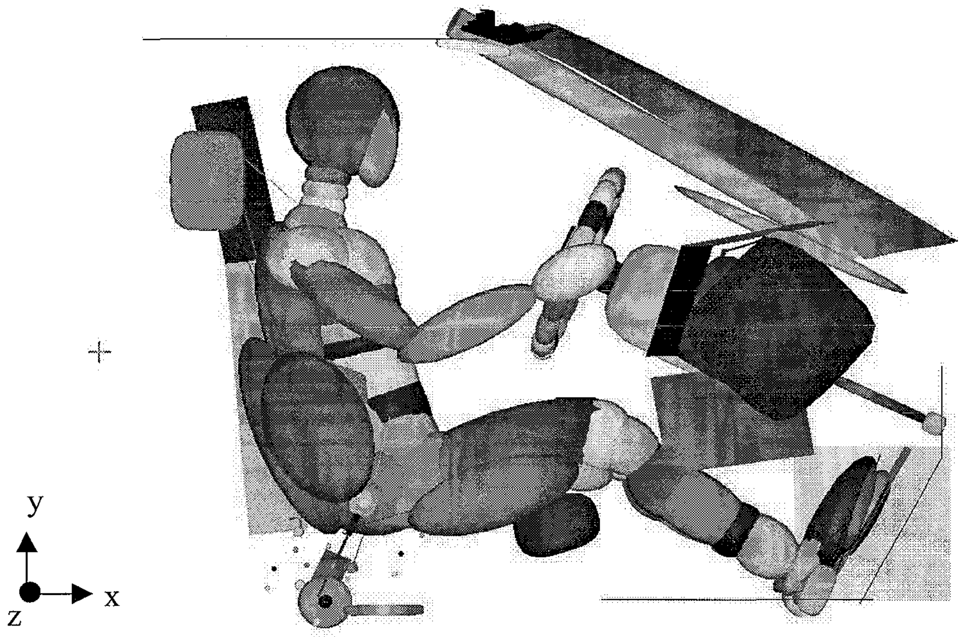


Fig 1.1 Side view of computer model with 50% dummy in a BMW.

The computer model has some simplifications towards reality. In this research it is assumed that this model gives a good representation of the real crash test. In order to use active controllers, MADYMO is coupled to the mathematical program MATLAB. The model with the 5% dummy is slightly different from the 50% dummy. This gives some differences in the output. The differences are discussed in chapter 2.

1.2 Improvements with new beltforce controller

In this step the current passive safety system is analyzed. Based on the results it is defined what improvements are required from the new active safety system. Fig. 2.1 shows the passive safety system as introduced in current vehicles.

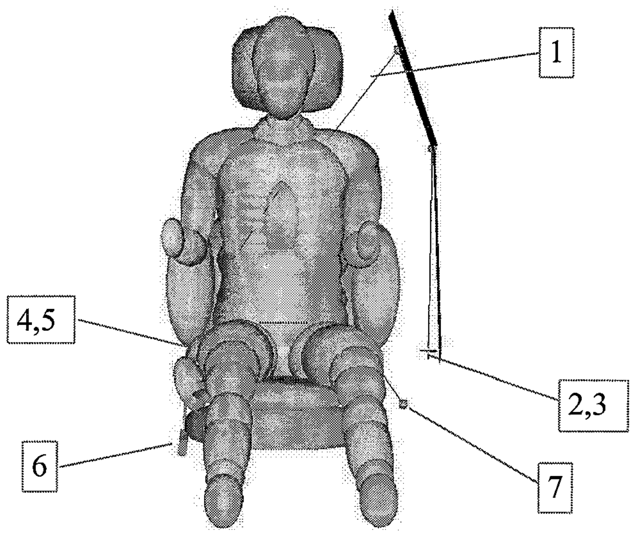
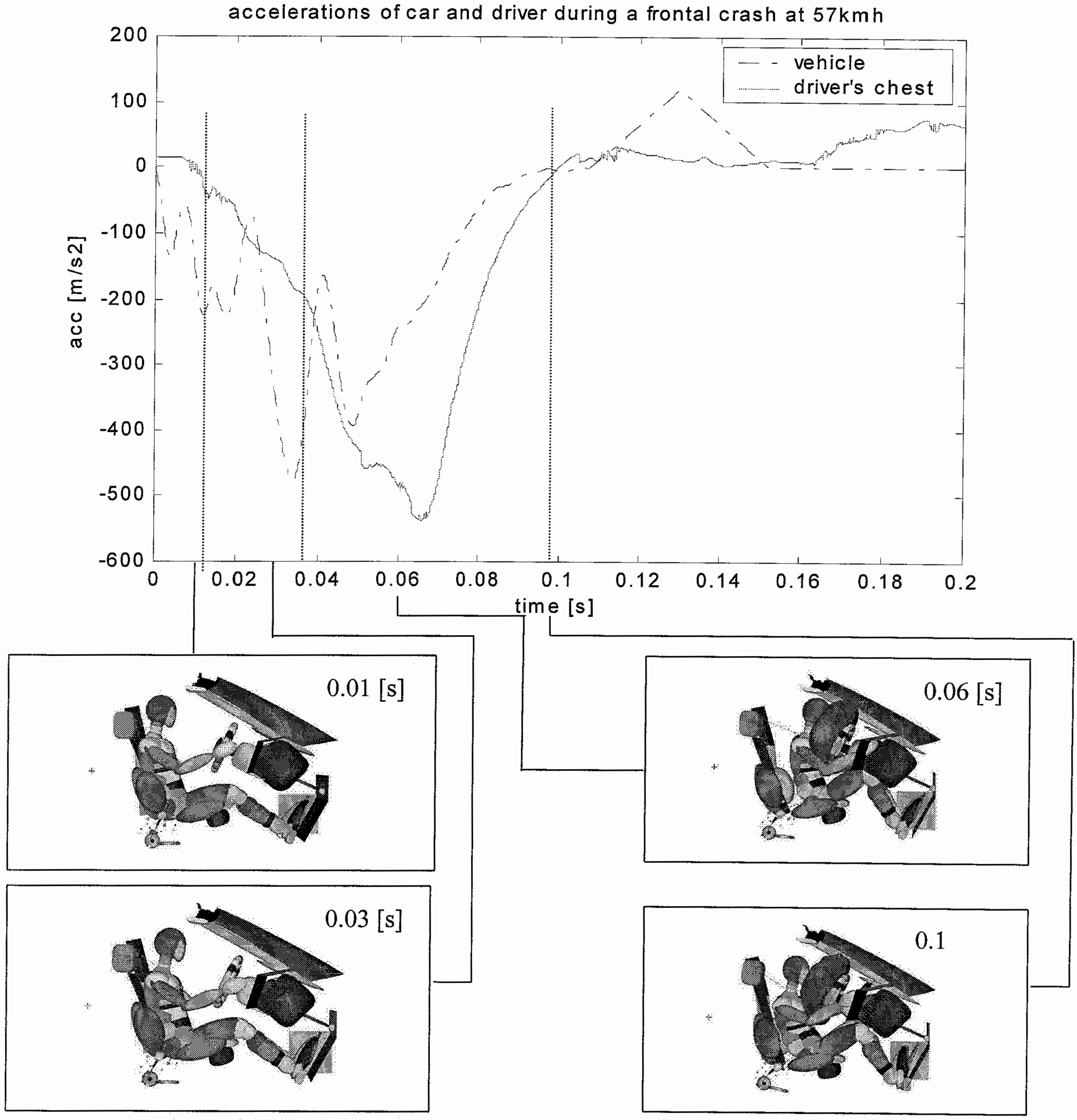


Fig.1.2 Front view of driver in his seat belt.

The passive safety belt mainly exists of 7 items:
1. The belt: a simple belt, with stiffness of approx. $5*10^5$[N/m]. the belt only has stiffness when pulled.
2. A belt guidance in the B-pillar of the car. By gently pulling the belt it will release from this cylinder. This cylinder has a low torsion stiffness.
3. A beltforce limiter that works as retractor and has settling time and allows slip of the belt out of the retractor, when the tension in the belt becomes to high (above 10[kN]).
4. The key on the belt that is used by the driver to attach the belt to the buckle.
5. The buckle: connects the belt to the pretensioner
6. The pretensioner. In a crash, this part abruptly pulls down the buckle. This movement tensions the belt.
7. The end-holder. Left of the driver, just below the seat, the other end of the seat belt is connected to the chassis.

If the USNCAP crash at 57kmh is analyzed for a car that has a passive safety belt and an airbag as restraint systems, the following 4 regions can be located. Fig. 1.3 shows the corresponding deceleration of the chest:
1. Low forces act on the driver due to initial conditions in the model. Since the initial position is defined by standard location of some dummy parts, the dummy is in total not perfectly fitted to his seat. This is not perfect and in this case, the initial indention cause low positive acceleration.
2. The retractor locks up and the pretensioner tensions. This results in a deceleration of the occupant.
3. The airbag inflates and prevents the driver from touching the steering wheel.
4. The car bounces back, but the driver's reaction is hardly noticeable.



The most obvious conclusion of figure 1.3 is that the driver starts to decelerate later and with higher maximum deceleration values than the vehicle. If Δt is the delay time at the start of the deceleration process of the driver's chest:

$$\Delta t(passive) = 0.01s \tag{1.1}$$

The next conclusion is the maximum value of driver's chest deceleration:

$$\max\left(\left|\ddot{x}_{chest,active}(t)\right|\right) = 550 \, {}^{m}\!/_{s^2} \tag{1.2}$$

Because of the time delay at the beginning of the crash, the occupant must decelerate faster at later points during the crash. This causes higher deceleration values. Hesseling[1] defined that injuries are caused by high values of deceleration or acceleration. The new beltforce controller should therefor prevent the dummy from these large accelerations and decelerations.

The improvement that is required from the new beltforce controller in comparison with the passive safety system is:

Lower the maximum value of decelerations during a crash.

In comparison to the old passive system, it is chosen to eliminate the pretensioner. The retractor is replaced by an actuator mass, to which a controlled force can be applied.

1.3 Optimization algorithm for new beltforce actuator.

In section 1.2 is mentioned that in the new beltforce actuator a single actuator at the B-pillar will replace the retractor. In the computer model this actuator is represented as an actuator mass, subjected to a controlled force.
Lowering down the maximum value of deceleration of the dummy is now realised by controlling the tension in the safety belt via this actuator.
There are however 3 boundary conditions:

- No inner vehicle parts (except the seat) are to be touched during the crash. This causes injuries.
- The occupant cannot start earlier with decelerating than the beginning of the crash (this is in reality not possible)
- During the crash it must always hold that:

$$\int_0^t \ddot{x}_{occupant}\, dt \leq \int_0^t \ddot{x}_{vehicle} \qquad (1.3)$$

  Because if not, than the occupant is forced through the back of the seat. At the end of the crash both sides of eq. 1.3 must be equal.

Analyzing the results of fig. 1.3, There are 2 ways to lower down the maximum value of deceleration:

1. Eliminate time delay at beginning of crash:
   This gives extra time to decelerate the occupant.
2. Use the space between the occupant and the steering wheel as buffer:
   The occupant has extra space to decelerate. This introduces a possible delay and gives extra deceleration time for the occupant. This lowers the necessary acceleration values.

Hesseling defined that the chest acceleration is representative for the rest of the occupant.. Standard feedback control (Franklin/Powell[4]) is introduced for beltforce control. This requires a setpoint for the chest acceleration (view fig. 3.1). Because the computer model uses a previously defined trajectory for the deceleration of the vehicle, Hesseling defined the setpoint trajectory by:

$$\begin{cases} r_{chest}(t) = \ddot{x}_{vehicle}(t) & 0 \le t \le t_a \\ r_{chest}(t) = a & t_a \le t \le t_e \\ r_{chest}(t) = 0 & t > t_e \end{cases} \tag{1.4}$$

The values for a and t_a are defined by measuring the distance between the occupant and the steering wheel at the beginning of the crash and comparing the relative distance between the occupant and the vehicle. Suppose a distance X between the driver and the steering wheel at t=0, then:

$$\iint_t (r_{chest} - \ddot{x}_{vehicle})dt < X \qquad 0 \le t \le t_e \tag{1.5}$$

This is implemented in an iterative process in Matlab. The solutions are the optimal values for t_a and a. Figure 1.4 shows the reference input (or trajectory) that was set by Hesseling for his research: a 50% dummy in car that crashes against a rigid wall at 57kmh.

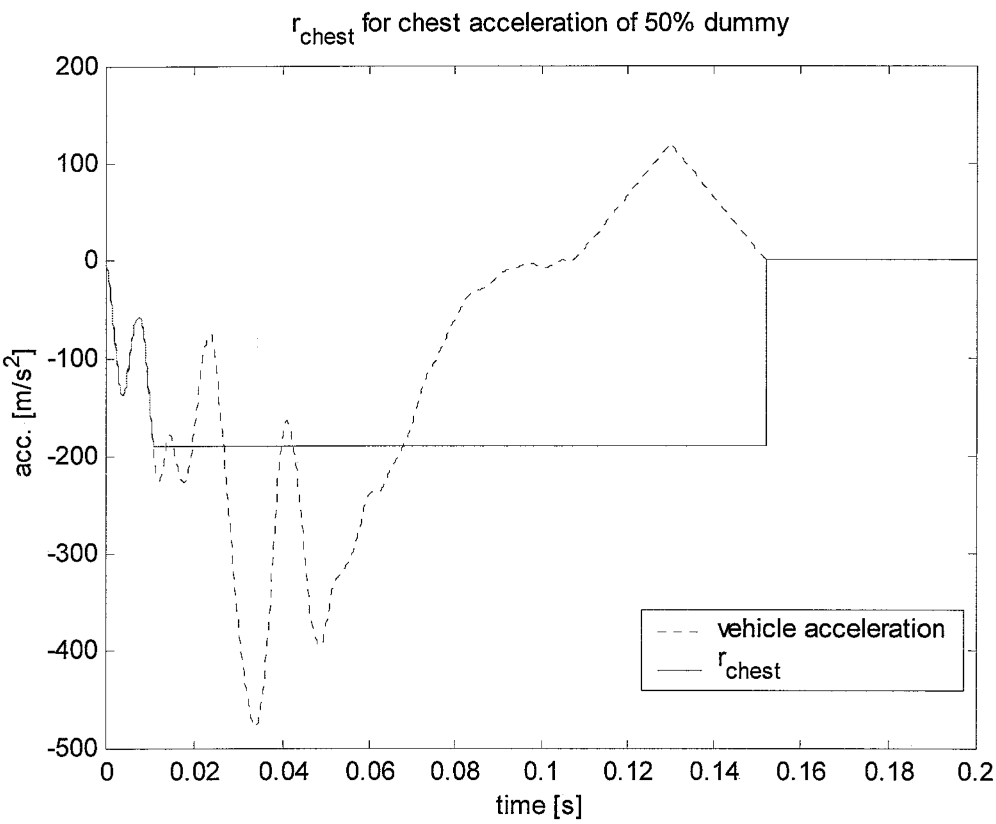


Fig.1.4 reference input for acceleration of chest of 50% dummy in car crash at 57kmh.

This setpoint is used in standard feedback, which implies that the acceleration of the driver's chest can be measured and used as feedback. In the computer model, this is always possible.

1.4 Identification of computer model with transfer function

The design of the beltforce controller is based on an identification of the computer model. In this model, there is one input: the force on the actuator mass. From this point on referred to as " beltforce" . Hesseling defined one output: the acceleration of the chest of the occupant (chest acceleration).

The design of the beltforce controller requires a mathematical identification of the plant transfer from beltforce to chest acceleration. For this SISO system the following three algorithms are available:
1. Impulse-response analyses
2. Non linear mathematics
3. Step-response analyses

The first method is to apply an impulse to the safety belt and then define the free response of the chest acceleration. With this information, the mechanics of the system can be identified. This algorithm is particularly useful when a system is unknown, but assumed to be an LTI-system. If the system is non-linear and time-dependent, then the eigenfrequencies will change during the free response. This makes it impossible to identify the system with this method.

The second method is non-linear mathematics in which is tried to identify the whole computer model with mathematical formula's. This method is only applicable for simple models. In complex models this solution method is too difficult. Here it cannot be used.

The last type is step-response analyses. This method introduces a step on the input of the model and then checks what the response of the output is. The response of the output is plotted and evaluated as if it is the response is from a simple model. For an LTI–model, one step-response test is enough to identify the whole system. In case of a non-linear, time-dependent model, for each point in time and each step size, a new response can be found.

Step response analysis is very useful in case of an unknown system. By applying steps on the input at several points in time and with several step sizes, conclusions can be drawn about the linearity and time-dependency of the system. Another advantage of this method is that the steps can also be introduced as perturbations to a nominal trajectory of a system. In this system, where the position of the dummy is alternated due to other factors than the beltforce, this is particularly useful.

Hesseling has chosen to use the method of step-response analyses to identify the system. Hesseling [1] well describes his used routine. The main information is also described underneath here:

Hesseling used the crash data of the original situation (see par. 1.2) as nominal situation to define a nominal trajectory for the pulling force on the belt (beltforce). At

several points in time during the crash and for several step sizes, Hesseling applied steps (perturbations) onto that nominal trajectory.
Formula 1.5 gives the mathematical interpretation:

$$F_{i,j}(t) = F_{orig}(t) + \Delta F_i \cdot \varepsilon(t - t_j^*) \quad (1.6)$$

where: $F_{i,j}(t)$ = new pulling force on belt [N]
F_{orig} = original (=nominal) pulling force on belt [N]
ΔF_i = step size [N]
$\varepsilon(t - t_j^*)$ = unit step at point t_j^* [-]

The values used by Hesseling for t_j^* are $[5\ 10\ 15\ 20\ 25\ 30\ 35\ 40]^T$ ms
The values used by Hesseling for ΔF_i are $[5\ 10\ 25\ 50\ 75\ 100\ 250]^T$ N.
Then Hesseling measured the output by looking at the response of the chest acceleration of the dummy:

$$\ddot{x}^{i,j}_{c,dist}(t) = \ddot{x}_{c,orig}(t) - x^{i,j}_{c,disturbed}(t) \text{ for } t > t_j^* \quad (1.7)$$

$\ddot{x}^{i,j}_{c,dist}(t)$ = Response acceleration of chest to step in beltforce $[m/s^2]$
$\ddot{x}_{c,orig}(t)$ = Original acceleration of chest to nominal beltforce $[m/s^2]$
$\ddot{x}^{i,j}_{c,disturbed}(t)$ = Acceleration of chest to nominal beltforce with step $[m/s^2]$

Afterwards, Hesseling analyzed whether the system could be identified as a LTI system. In order to do this, he had to compare all step responses with each other by normalizing them:

$$\ddot{x}^{i,j}_{c,norm}(t) = \frac{\ddot{x}^{i,j}_{c,dist}(t)}{\Delta F_i} \quad \text{for} \quad t > t_j^* \quad (1.8)$$

$\ddot{x}^{i,j}_{c,norm}(t)$ = Normalized $\ddot{x}^{i,j}_{c,dist}(t)$ $[m/Ns^2]$
$\ddot{x}^{i,j}_{c,dist}(t)$ = Response acceleration of chest to step in beltforce $[m/s^2]$
ΔF_i = step size [N]

As a result, it occurred that al these normalized step responses were almost the same for every ΔF_i at every t_j^*. This means that the complex multibody model can be identified by a simple LTI-model. Hesseling found the following second order LTI-model (representation in Laplace domain):

$$\frac{Kw_n^2}{s^2 + 2\varsigma w_n s + w_n^2} = \frac{-1.57 \cdot 10^4}{s^2 + 376.8s + 3.9 \cdot 10^5} \quad (1.9)$$

where:				
	K	=	-0.04	[1/kg]
	w_n	=	628	[rad/s]
	ς	=	0.3	[-]

In this research a slightly more difficult system is chosen: a third order LTI-model. More information about this is placed in par. 2.5 and 2.6.

1.5 Using the mathematical model to built a regulator

After identification of the computer model in mathematical terms, It is possible to design the beltforce controller.

While the computer model of the 50% hybrid dummy is identified as LTI, it should be possible to use classic controller methods (e.g. PID controllers) to built the beltforce controller. With the help of MATLAB and its userbox DIET, a controller is defined.. In Hesseling's model (50% dummy), the conclusion was the beltforce controller in figure 1.5:

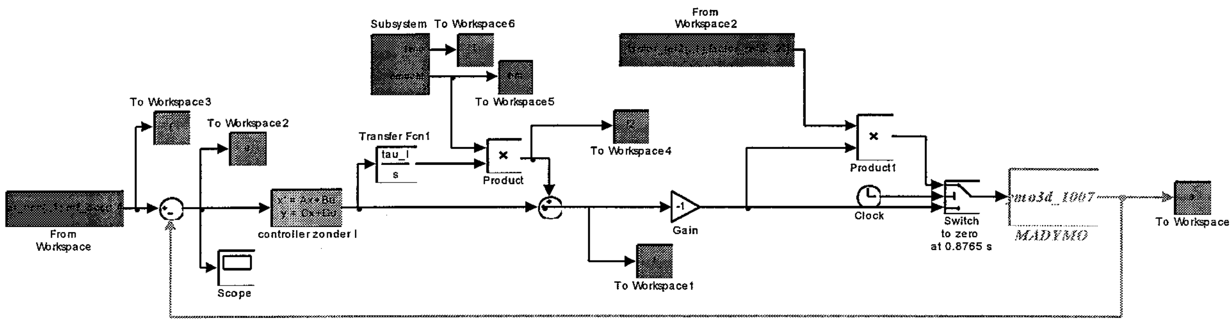


Fig 1.5 beltforce controller of Hesseling

In the system of fig. 1.5 the box 'MADYMO' is the representation of the computer model. The output of that system is the acceleration of the chest. At the left of the model the reference trajectory for the chest-acceleration is defined. The controller exists of a several items:

1. A state space control part which consists of:
   - Gain of 50
   - Lead/lag with zero at 500 [Hz] and pole at 1000 [Hz]. (2x)
   - Integrator with zero at 300 [Hz].
2. An extra 'initial integrator' that works from t=0 [s] to t=0.0025 [s] with a cut-off frequency at 300 [Hz]. This integrator is necessary to overcome several stick-slip problems and allow an early deceleration of the dummy's chest.
3. An extra unit that turns off the controller after t=0.865 seconds and sets the beltforce to zero. Because of this, the driver will be able to unlock himself from the safety belt after the crash.

1.6 Testing the regulator on the complex computer model

Finally, the beltforce controller is tested on the computer model. Hesseling In Hesseling's case he reached a satisfying result, which is plotted in figure 1.6.

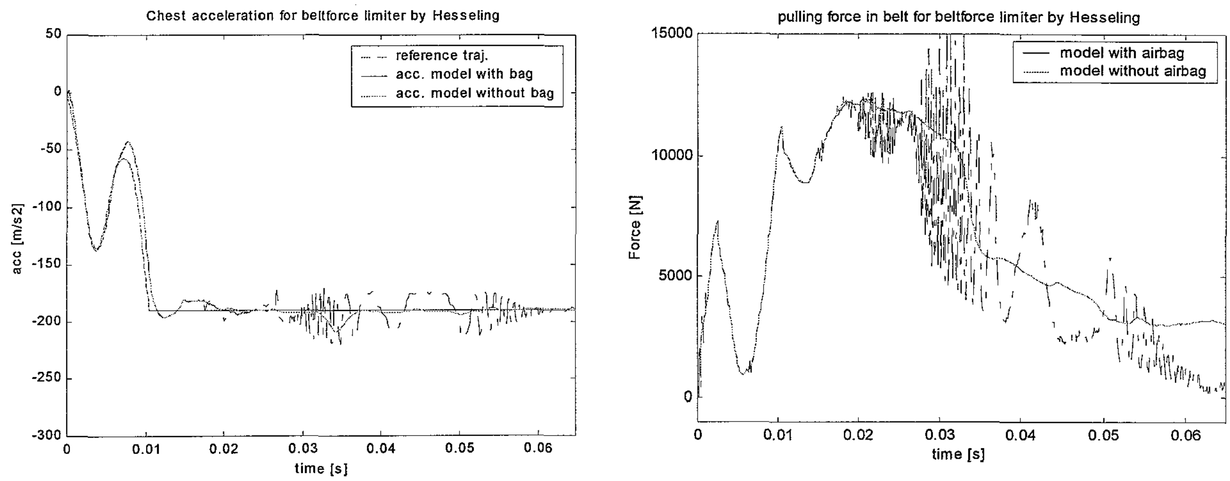


Fig. 1.6 accelerations and beltforces for beltforce actuator by Hesseling

In figure 1.6 is shownthat this controller works in both the situations with and without airbag. The model with airbag is however slightly unstable. The extra forces of the airbag on the dummy cause this. In the figure is also displayed that the deceleration never gets higher than approx. 210 $^{m}/_{s2}$, which is a big improvement towards the original maximum value of approximately 550 $^{m}/_{s2}$.
Looking at the beltforces of both cases, the airbag forces are less high than the forces without airbag. This is because the airbag helps in decelerating the dummy.

Finally the results of this beltforce controller, built by hesseling are:

The maximum amount of deceleration is minimised to:

$$\max\left(\left|\ddot{x}_{chest,active,d50\%}(t)\right|\right)=210\,{}^{m}/_{s^2} \quad (1.10)$$

2 System identification

In chapter 2 and 3 the algorithm, outlined in chapter one, is reused. Now the USNCAP crash at 57kmh with 5% hybrid dummy is analyzed.
In this chapter the identification of a transfer function from beltforce to chest acceleration is discussed.

2.1 The computer model

In this case a 5% hybrid dummy is used. This is a representation of a female driver with a weight of 49.21kg (in comparison, Hesseling's 50% dummy represents a 77 kg male driver).
The hybrid dummies are developed by TNO. For every dummy, the position in the vehicle is prescribed. This means that the 5% dummy sits closer to the steering wheel than the 50% dummy. In the model of the 50% dummy, the distance between the dummy's chest and steering wheel was 0.5m. In case of a 5% dummy this distance is reduced to 0.25m.

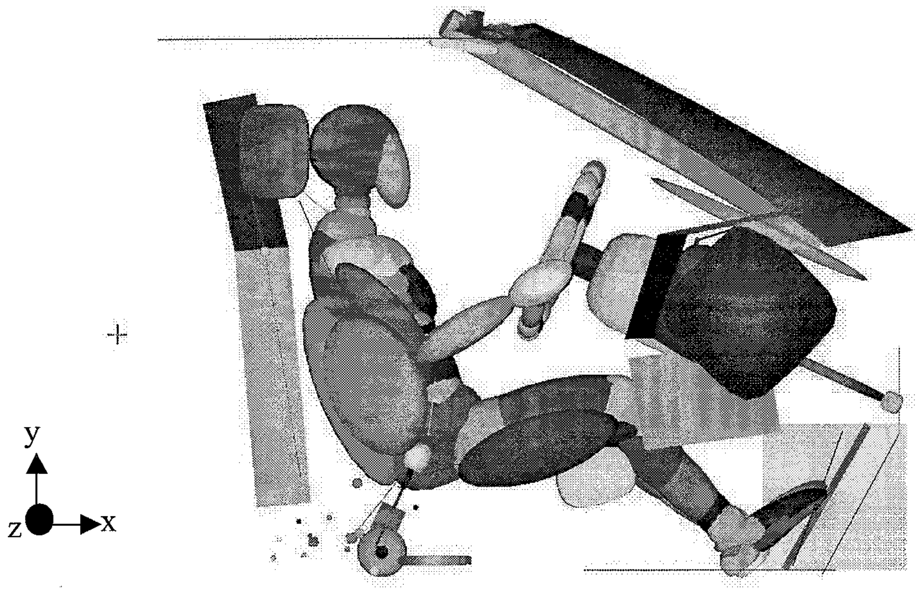


Fig. 2.1 multibody model for 5% dummy

One of the major problems with the model of the vehicle and the 5% dummy is that this dummy is an older model of a driver than the 50% dummy of Hesseling. Some problems now occur in the output chest-accelerations of the model. More details about this are given in par. 2.4 were the chest accelerations are analyzed.

2.2 Improvements with new beltforce controller

Review section 1, the goal is to minimize the amount of deceleration. The beltforce controller of Hesseling gives unsatisfying results in combination the 5% hybrid dummy (fig. 3.4).
To validate the differences between the two models, they are analyzed for their behaviour in case of the USNCAP57 crash with the original, passive safety belt (par.1.2).
Figure 2.2 shows the differences in accelerations on the dummy's chest and the beltforce.

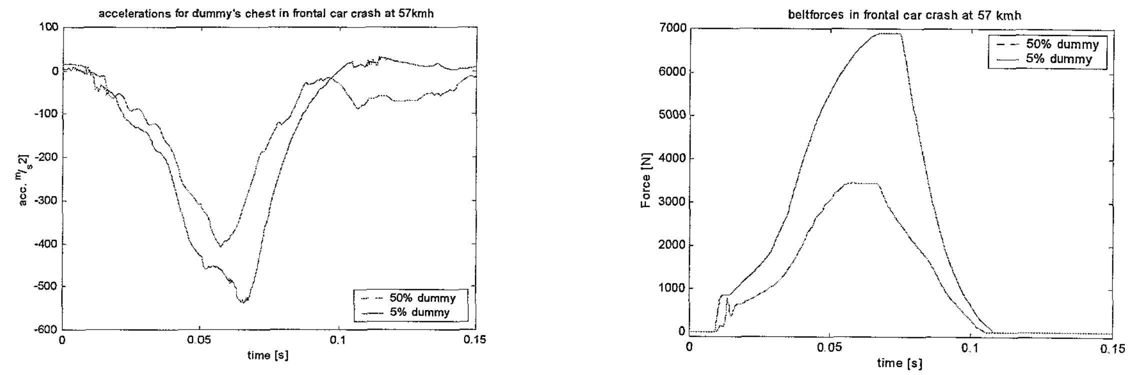


fig. 2.2 differences between crash-simulations with 5% or 50% dummy (both with airbag).

The following differences can be found in the plots of fig. 2.2:

1. The 5% dummy model has more time delay than the 50% dummy model:
   $$\Delta t(passive, d5\%) = 0.015s \qquad (2.1)$$
   This is caused by:
   - The initial position of the 5% dummy. This is slightly different, which means that the 5% dummy is not pushed out of its seat and needs more time to get out of the seat (see par. 1.2).
   - The 5% dummy has a lower mass.

   Both things result in a slower increase of the beltforce. Therefore, the lock up of the safety belt will occur later, which can be seen in the plot with beltforce in fig.2.2.
2. The maximum deceleration of the 5% dummy:
   $$\max\left(\left|\ddot{x}_{chest,passive,d5\%}(t)\right|\right) = 400 \, {}^{m}/_{s^2} \qquad (2.2)$$
   The 50% dummy's maximum is 550 $^{m}/_{s2}$.
3. The beltforces of the 5% dummy are only half the values of the model with the 50% dummy.
4. The 50% dummy is decelerated faster than the 5% dummy. Likewise, the deceleration of the 50% dummy goes back to zero earlier.

The differences have the following influences on the design of a controller for the 5% dummy in comparison to Hesseling[1]:

1. In figure 1.6 can be seen that Hesseling built a controller with an extra integrator at the beginning of the crash (break off at t=0.0025ms). This integrator was necessary to overcome several initial conditions. Difference 1 shows that the initial

conditions are different in case of the 5% dummy, therefore it is necessary to revalidate this integrator.

2. The maximum deceleration of the 5% dummy is about 30% lower than the 50% dummy. The beltforces of the 5% dummy are about 50% lower than those in the model with the 50% dummy. This means that the plant transfer from beltforce to chest acceleration is not proportional. Therefor a system identification of the USNCAP crash at 57kmh with 5% hybrid dummy is necessary.

2.3 Optimization algorithm for new beltforce controller.

Section 1.3 describes the optimization algorithm as set by Hesseling. In this case the same algorithm is used. Since the position of the dummy is slightly different, also the setpoint (refernce trajectory) is reset.

Since in this case the position of the dummy is slightly different. The algorithm is the following must be redefined. In combination with the previous sections, the following steps are defined:

2.4 Redesign of reference input

The same constrains as defined in section 1.4 are defined are used here. In combination with the fact that the distance between the dummy and the steering wheel is 0.25m in stead of 0.5[m] (section 2.1) the trajectory of fig. 2.3 is found:

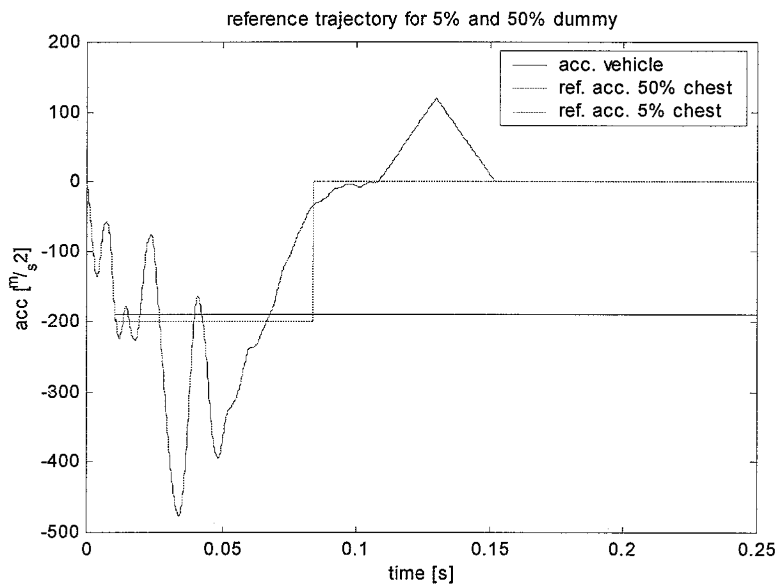


Fig. 2.3 reference trajectory for 5% and 50% dummy

Fig. 2.3 shows a plot of the deceleration of the car, the reference trajectory for the 50% dummy and for the 5% dummy. The maximum deceleration in case of a 50% dummy is 190 $^m/_s2$. In case of the 5% dummy it is 200 $^m/_s2$.

Remark: The setpoint of Hesseling is not set to zero here, while his controller is set to zero at t=0.0865s. The sharp edge at approx. 0.0865s gives problems in the controller that is later designed. Arbitrarily is decided that this can later be alternated. Here this is not done. Therefor most results in the rest of this report will not show results after t=0.08s.

2.5 Step response analyses

T the identification of the SISO system with step response analysis is described in section 1.4.

In order to reduce simulation time, the following changes are made towards the algorithm that Hesseling used:

- Only the situation without airbag is tested, to see how the system behaves. Later also the model with airbag is identified to describe differences.
- The beltforce is are prescribed directly in MADYMO.
- Unit steps are introduced at time points $t_j^*=[15\ 20\ 25\ 30\ 35\ 40\ 45\ 50\ 55]^T$ ms. The first 10 ms suffer from initial conditions and therefor give no useful information. After 60ms the dummy contacts the steering wheel, which gives a state that must be avoided at all time.
- The used stepsizes are $\Delta F_i = [5\ 10\ 25\ 50\ 100]$. Smaller sizes give strange results, and higher values provide no extra information.

Fig. 2.4 shows a plot of several chest accelerations that are a response to a unit step at time point t = 45ms. The rest of the chapter uses these steps as an example. All other step-response analyses are placed in supplement A.

Linearity of the plant transfer is checked by normalizing the step responses. For the results of fig. 2.4 normalisation leads to fig. 2.5
Figure 2.5 shows two phenomena, which both also occur in all other step-responses (supplement A and B).
The first phenomenon is a dominant response frequency with $f \approx 150Hz$. This is one of the eigenfrequencies of the computer model in $t \in [45,55]$ ms.

The second phenomenon is the large disturbance in the chest accelerations for $t \in [49.5;53.3]$ ms. These peaks are different from the model with the 50% dummy and perhaps caused by a bug in the 5% dummy. This is supported by the fact that the model of the 5% dummy is older than the model of the 50% dummy.
In figure 2.5 can be seen that the dominant response frequency is followed again at t = 0.51ms, after a short time of this strange disturbance. For identification purposes the data is filtered to eliminate the peaks.

With the use of MATLAB the chest acceleration is filtered with a second order causal-anti-causal low-pass Butterworth filter with a cut-off frequency of 200Hz. This cutt-off value is chosen, because the base frequency of the strange peaks is 300 Hz.

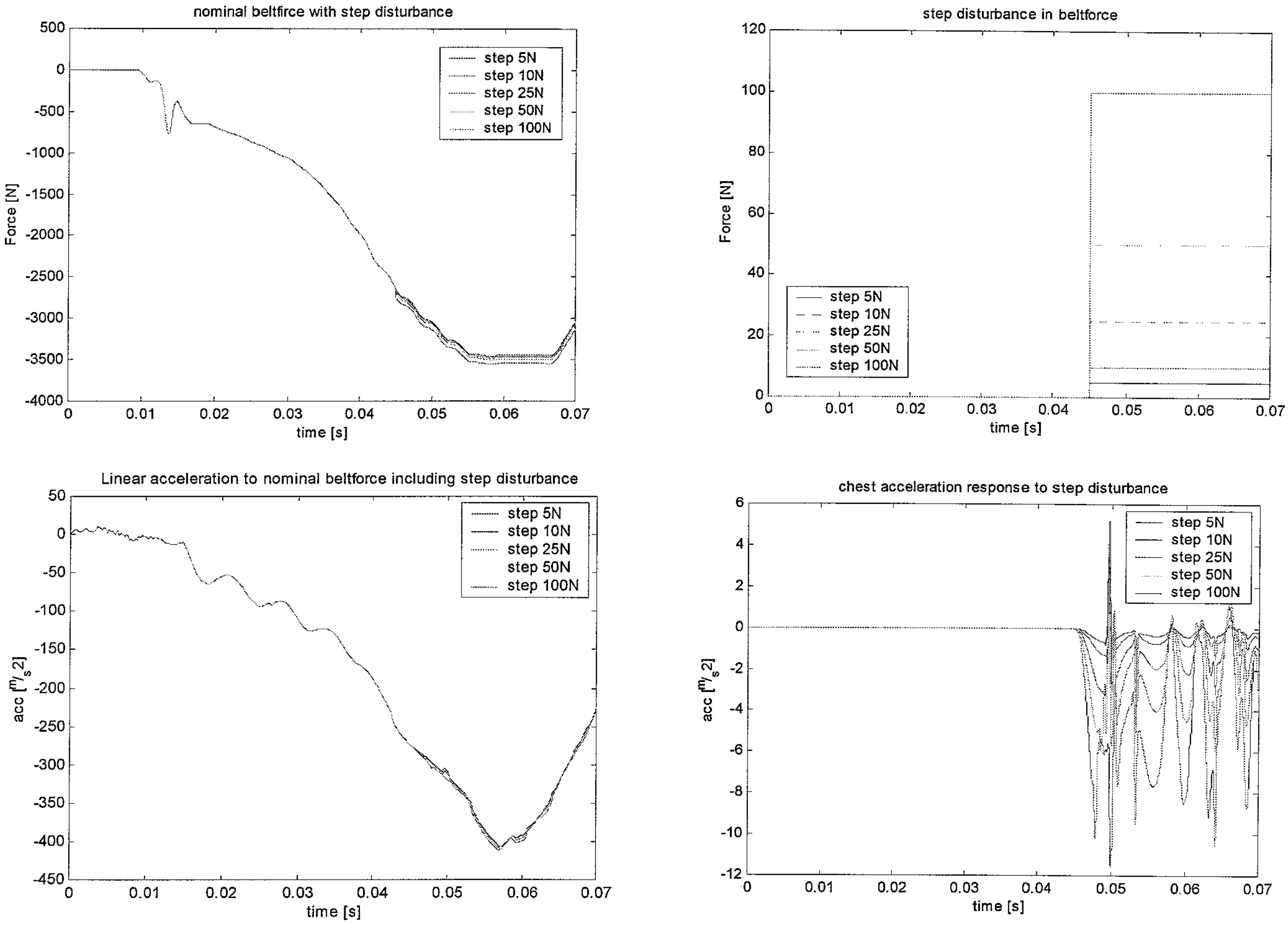


Fig. 2.4: Step on input (beltforce) and response on output (chest acceleration) for model of 5% dummy without airbag. Nominal refers to values for beltforce and chest acceleration in figure 2.1
Upper left: beltforces as prescribed in MADYMO.
Upper right: beltforces as prescribed in MADYMO minus the nominal beltforce
Down left: chest accelerations, measured in MADYMO
Down right: chest accelerations, minus their nominal values

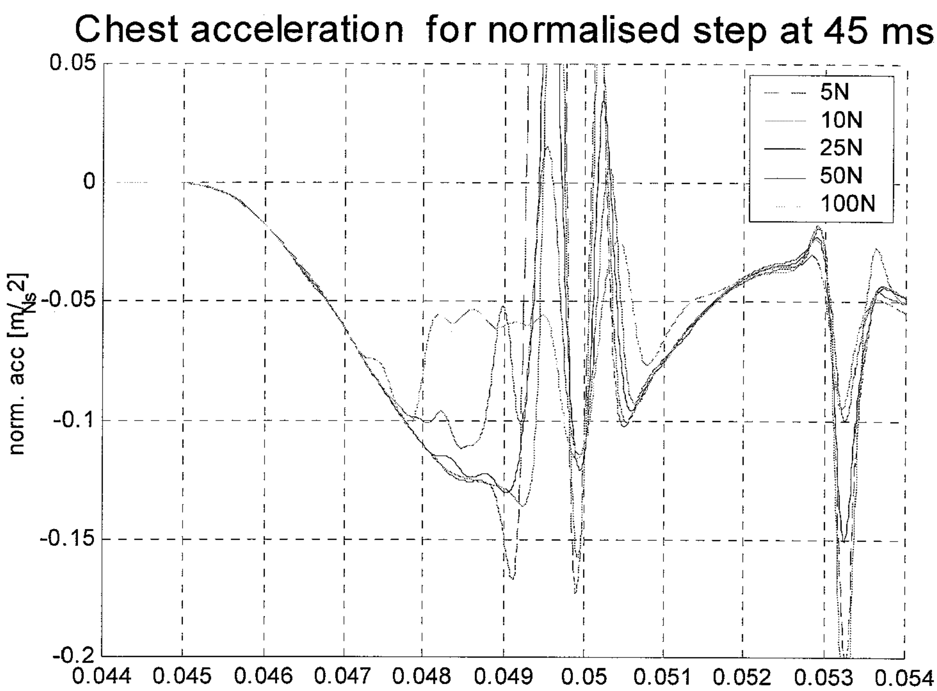


Fig. 2.5 Normalised acceleration for model with 5% dummy without airbag

Intermezzo:

One remark to filtering: it would be best to filter only the data that is generated for time $t_j^* < t < t_e$. This is best, because this causal-anti-causal filter looks back and forwards in the unfiltered signal and then gives a general solution. This means that, if all data for $0 < t < t_e$ is filtered, then, in the output of the filter the response to a perturbation initiates earlier than in real time.

In mathematical terms the best algorithm would be:

$$\ddot{x}^{i,j}_{c,norm,filt}(t) = \begin{cases} \ddot{x}^{i,j}_{c,norm}(t), 0 \le t \le t_j^* \\ filter(\ddot{x}^{i,j}_{c,norm}(t)), t_j^* \le t \le t_e \end{cases}, \tag{2.3}$$

As represented in fig. 2.5, this is not done. The data is filtered from t_0 to t_e. The reason that this is done, is that the filter has such a low cut-off frequency (200 Hz), that the initial response at $t=t_j^*$ is too high-frequent for this filter. Using eq. 2.3 will then result in an unwanted jump in $\ddot{x}^{i,j}_{c,norm,filt}(t)$ at $t=t_j^*$. This ruins the signal for LTI-system identification.

Therefore the whole signal is filtered according to equation 2.4:

$$\ddot{x}^{i,j}_{c,norm,filt}(t) = filter(\ddot{x}^{i,j}_{c,norm}(t)), 0 \le t \le t_e \tag{2.4}$$

In figure 2.6 the filtered results are represented:

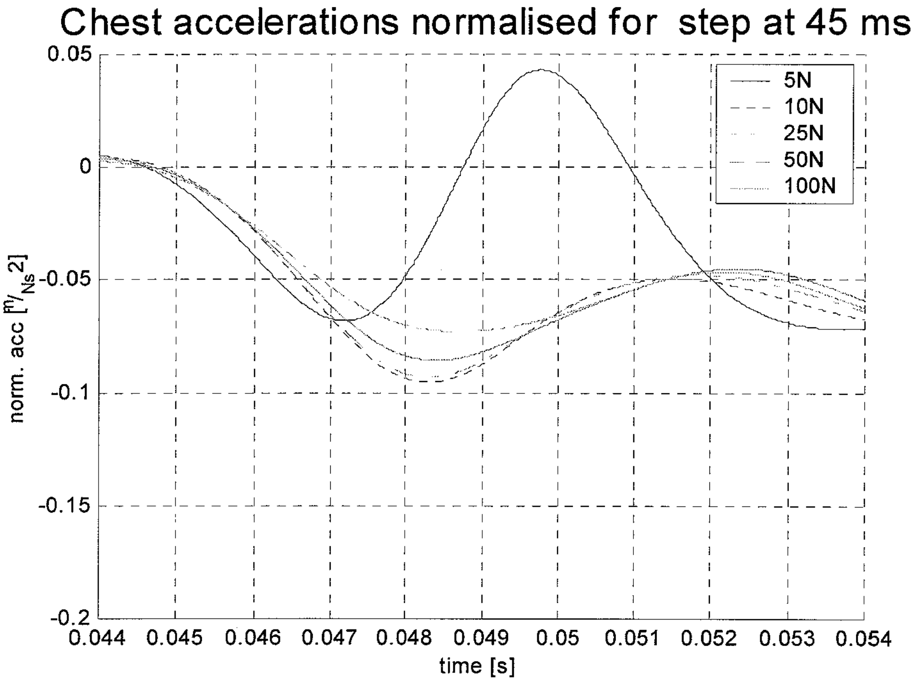


Fig. 2.6 Data of step disturbance at t=45ms, normalised and filtered at 200 Hz for model with 5% dummy without airbag

Figure 2.6 shows that the filter is not able to eliminate the strange peak for the response completely at a stepsize of 5 Newton. In all other signals the strange peak is gone. Since the strange results are supposed to be caused by bugs in the dummy, they are not further discussed here. Because all other responses behave linear,.the results of the beltforces with stepsize 5N are neglected in the rest of this analysis.

The mean step response of all stepsizes at t = 45ms(excluding 5N of course), is calculated by:

$$\bar{\ddot{x}}^{i,j}_{c,norm}(t) = \frac{1}{k}\sum^{k} \ddot{x}^{i,j}_{c,norm}(t) \tag{2.5}$$

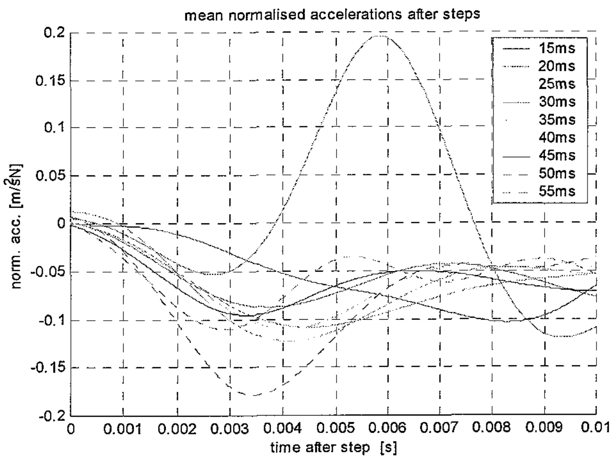
where k= 4 = number of responses that are used (10N,25N, 50N, 100N)

This is also done for other all other t_j^* .
All step-responses for al F_i and t_j^* can be compared to each other by introducing time delay:

$$\bar{\ddot{x}}^{i,j}_{c,norm}(\tau) = \bar{\ddot{x}}^{i,j}_{c,norm}(t - t_j^*) \text{ for } t > t_j^*, \tag{2.6}$$

where τ = step-response after introducing step onto nominal beltforce [s]

fig. 2.7 shows the results of all mean normalised chest accelerations for all t_j^*:



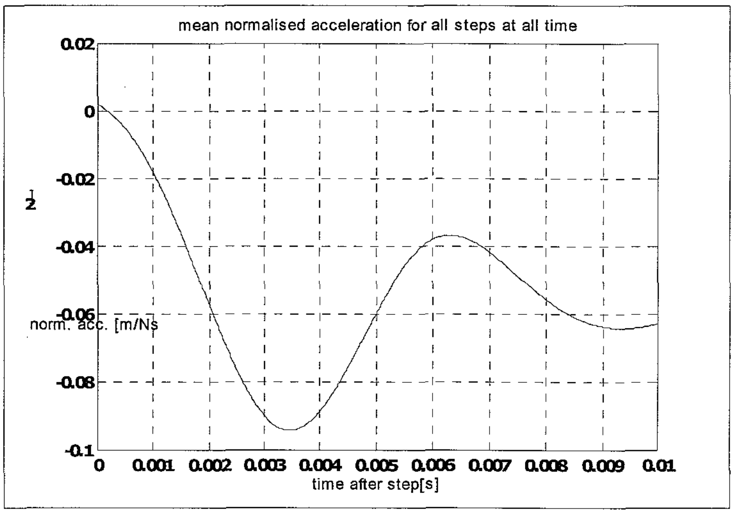


Fig.2.7: Mean normalised responses for the model with the 5% dummy without airbag, per step time (left) and totally for all steps at all time (right)

For the model of the 5% dummy with airbag, the same steps are taken. Here only the mean results are represented. All individual step–responses for the model of the 5% dummy with airbag are displayed in supplement B.

Fig. 2.8 shows the mean results of these step-responses:

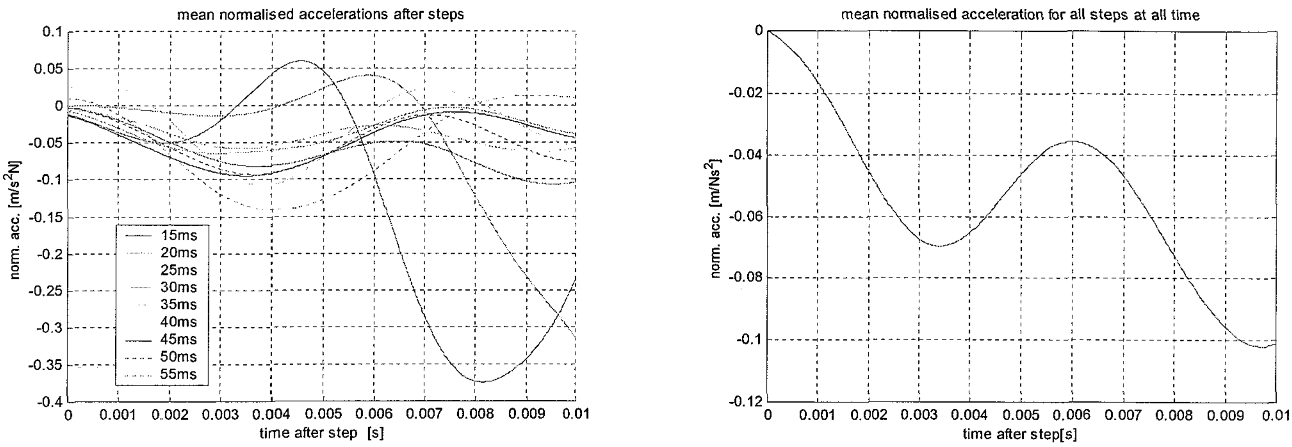


Fig.2.8: Mean normalised responses for the model with the 5% dummy with airbag, per step time (left) and totally for all steps at all time (right).

From the figures 2.7 and 2.8 a few conclusions will follow:

1. Normalized step responses for different time points t_j^* do have approximately the same dominant response frequency. The responses for steps at 15ms and 20ms are extremely different.
2. The differences between all the step responses are however still quite large, This results in a total mean curve in the right plots in figures 2.7 and 2.8, that does not seem to match with the majority of the curves in the left plots.
3. Due to the airbag, the response has less damping.

The mean response, shown in fig. 2.7, is very much influenced by the response at 15ms and 20ms. This gives basis to the conclusion that the system cannot be identified as being LTI. However, at first an LTI system is assumed and a trail-and-error method is introduced for system identification. The following choices are made:

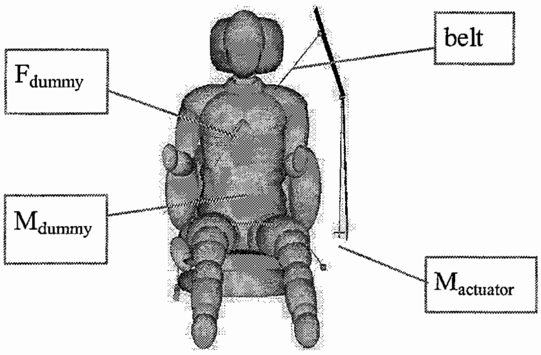
1. One mean curve $\ddot{x}^{mean\_i,j}_{c,norm}(\tau)$ at one time point t_j^* is chosen as basis for a the LTI-transfer function that represents the transfer from beltforce to chest acceleration.
2. The beltforce controller is designed, based upon this curve. This controller is tried on the complex multibody model and based on these results, the controller will be optimized.
3. Based on the results in the computer model, it will be validated whether or not the fitted LTI-system was a good one.

As basis for the system identification, the curve that is chosen is the mean chest accelerations with a step in the beltforce at $t_j^* = 45$ ms. For both situations with and without airbag, an LTI-system will be fitted in par. 2.6 (fig. 2.9).

2.6 System identification based on standard LTI-system

Hesseling used a standard second order LTI-system to fit the step-responses of the complex multibody model. This was done while the step-responses seemed to fit to a second order system.

In this research it is tried to build system identification around simplification of the computer model.
In the easiest way the model can be represented by: an actuator mass, a safety belt that is represented by a spring and a damper (Kelvin-Voigt element, see MADYMO manuals) and a dummy, represented by a single mass. Fig. 2.8 gives a plot of all system parts and the schematic representation.



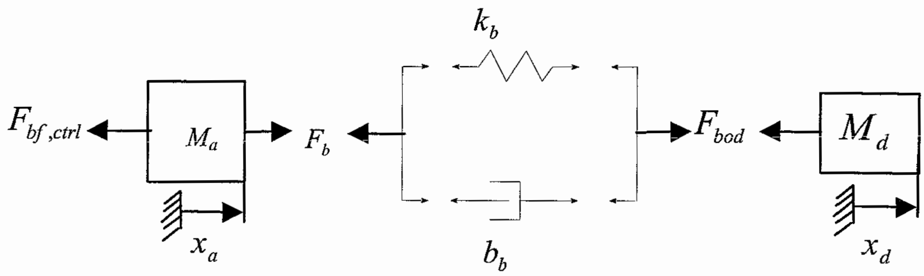


Fig. 2.9 schematic representation of simplified multi-body system

In figure 2.9:

$F_{bf,ctrl}$	=	applied beltforce on actuator [N]
M_a	=	actuator mass [kg] (=0.1 kg)
M_d	=	dummy mass [kg] (=49,21 kg)
x_a	=	position of the actuator mass in one dimension (see fig. 2.1) [m]
x_d	=	position of the dummy's chest in one dimension [m]
F_b	=	force from actuator on belt [N]
F_{bod}	=	force from belt on dummy [N]
k_b	=	stiffness belt [N/m]
b_b	=	damping belt [Ns/m]

Newton's second law of motion describes the model of fig. 2.9:

$$\begin{aligned} m_a\ddot{x}_a &= -F_{bf,ctrl} + F_b \\ m_d\ddot{x}_d &= -F_{bod} \\ F_b &= k_b(x_d - x_a) + b_b(\dot{x}_d - \dot{x}_a) \\ F_{bod} &= k_b(x_a - x_d) + b_b(\dot{x}_a - \dot{x}_d) \end{aligned} \qquad (2.3)$$

Combining all equations in 2.3 leads to:

$$\begin{aligned} m_a\ddot{x}_a &= k_b(x_d - x_a) + b_b(\dot{x}_d - \dot{x}_a) - F_{bf,ctrl} \\ m_d\ddot{x}_d &= -k_b(x_d - x_a) - b_b(\dot{x}_d - \dot{x}_a) \end{aligned} \qquad (2.4)$$

Writing equation 2.4 into state space notation:

$$\underline{x}^T = \left[(x_d - x_a) \quad \dot{x}_d \quad \dot{x}_a\right]^T$$

$$\dot{\underline{x}} = \begin{bmatrix} x_3 - x_2 \\ -{}^{k_b}\!/_{m_d}(x_d - x_a) - {}^{b_b}\!/_{m_d}(\dot{x}_d - \dot{x}_a) \\ {}^{k_b}\!/_{m_a}(x_d - x_a) + {}^{b_b}\!/_{m_a}(\dot{x}_d - \dot{x}_a) - {}^{(F_{bf,ctrl})}\!/_{m_a} \end{bmatrix} = \begin{bmatrix} 0 & -1 & 1 \\ -{}^{k_b}\!/_{m_d} & -{}^{b_b}\!/_{m_d} & {}^{b_b}\!/_{m_d} \\ {}^{k_b}\!/_{m_a} & {}^{b_b}\!/_{m_a} & -{}^{b_b}\!/_{m_a} \end{bmatrix}\underline{x} + \begin{bmatrix} 0 \\ 0 \\ -{}^{1}\!/_{m_a} \end{bmatrix} F_{bf,ctrl} \qquad (2.5)$$

The state space notation of 2.5 shows that the simplified transfer from beltforce to chest acceleration is identified by a third order LTI-system.

To estimate the plant transfer a standard third order LTI-SISO-system is chosen (Franklin & Powell,1995):

$$\frac{K\,{}^{w_n^2}\!/_{\tau}}{\left(s + {}^{1}\!/_{\tau}\right)\left(s^2 + 2\varsigma w_n s + w_n{}^2\right)} \qquad (2.6)$$

With MATLAB the standard third order LTI-system is fitted to the original step-response data. Introducing MATLAB, a least square method is introduced to find the optimal paramaters:

$$J = \min\left(\int_0^{0.01}\left(\ddot{\bar{x}}^{\,i,45ms}_{c,norm}(\tau) - \ddot{x}_{LTI}(\tau)\right)^2 dt\right) \qquad (2.7)$$

This gives the following results:

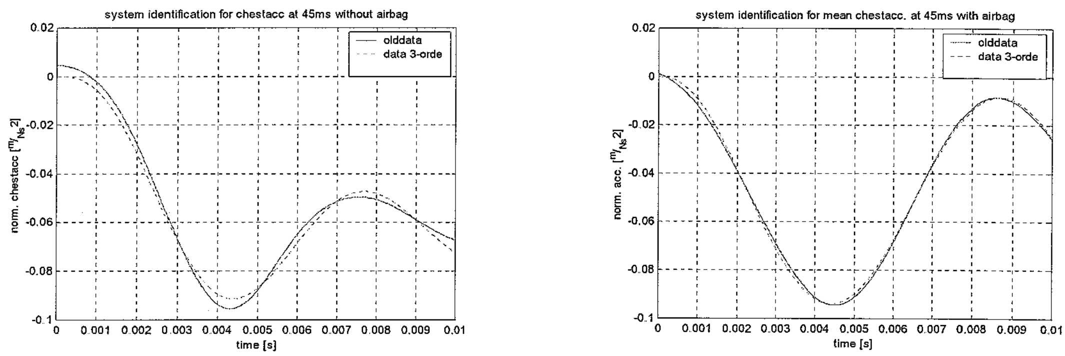


Fig. 2.10 left: system identification for model with 5% dummy without airbag
Right: system identification for model with 5% dummy with airbag.

The corresponding LTI-systems to figure 2.10 are:
The plant transfer representing the computer model without airbag:

K= -0.06 [1/kg]
w_n= 951 [rad/s]
τ= 0.0001 [s/rad]
ζ= 0.14 [-]

$$K\frac{{}^{w_n^2}\!/_{\tau}}{\left(s + {}^{1}\!/_{\tau}\right)\cdot\left(s^2 + 2\varsigma w_n s + w_n^2\right)} = \frac{-5.279\cdot 10^7}{s^3 + 1112s^2 + 1.132\cdot 10^6 s + 7.614\cdot 10^8} \qquad (2.5)$$

The plant transfer representing the computer model with airbag:

K=	-0.0492	[1/kg]
w_n=	736	[rad/s]
τ=	0.0001	[s/rad]
ζ =	0.0293	[-]

$$K\frac{w_n^2/\tau}{\left(s+1/\tau\right)\cdot\left(s^2+2\varsigma w_n s+w_n^2\right)}=\frac{-1.812\cdot10^8}{s^3+6838s^2+8.344\cdot10^5 s+3.68\cdot10^9} \qquad (2.6)$$

3 Design of beltforce controller

Chapter 2 described the system identification of the computer model, which resulted in an LTI-model. This model is used to design the beltforce conroller.

3.1 Methods for building a controller

The first decision that has to be made is which type of controller will be used to control the system. There are several methods available, such as Sliding Mode Control, Model Predictive Control, Adaptive Control, etc. One of the most common methods is PID-controllers with feedback control in closed loop. Hesseling used this method to design his controller.
In this research, The same choice is made, This is done while this type of controllers is very robust to system uncertainties and disturbances or noise. In closed loop, this type of controller yields a tracking error that is zero:

$$\ddot{x}_{setpoint}(t) - \ddot{x}_{chest}(t) = e(t) = 0 \qquad (3.1)$$

Figure 3.1 shows the standard layout for a feedback system with a PID- controller for an LTI system.

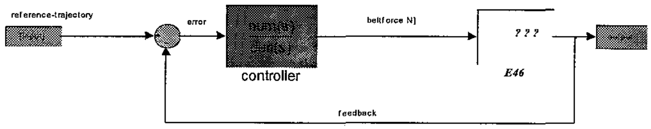


Fig. 3.1 Standard feedback LTI-system for this model, the PID controller is represented as a transfer function.

For building this controller, several routines are available. In this research stability analysis is used. MATLAB in combination with toolbox DIET, in which it is possible to design PID-like controllers in frequency domain.

3.2 Beltforce controller for third order LTI

In chapter two, the complex multibody model of the 5% dummy without airbag is identified by a third order LTI system. The bode plot of this third order system is drawn is figure 3.2.
In figure 3.2 is shown that the phase of the LTI-model for the 5% dummy is 0° until approx. 100 $^{rad}/_{s}$ (or 15 Hz) after that it starts to lower to 270 degrees at 10000 $^{rad}/_{s}$ (=1500 Hz). The Magnitude is always lower than 0 dB. Therefore this system is stable. Figure 3.2 also shows the differences between the identified transfer functions with the 50% dummy and the model with the 5% dummy: a higher eigenfrequency, higher magnitude and less damping for the model with the 5% dummy.

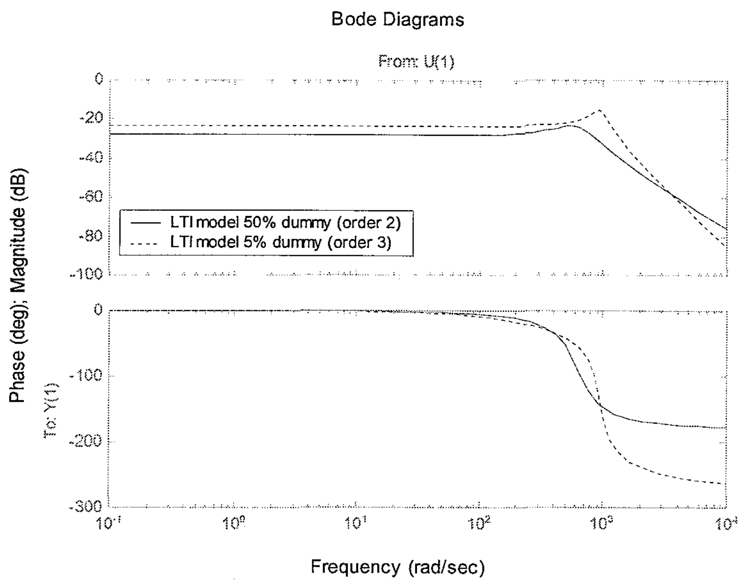


Fig. 3.2 bode diagram for second order fit for model with 50% dummy and third order fit for the model with the 5% dummy and no airbag.

The first step is a controller based on the controller of Hesseling. The plant transfer is force to acceleration. Normally force and acceleration are related by Newton's second law of motion:

$$F = m \cdot \ddot{x} \tag{3.2}$$

Although fig. 2.2 showed that this relation is not proportional for the different dummy types, it is tested here for the beltforce controller. Figure 3.3 shows this test model. In comparison to Hesseling's model, an extra gain is introduced for mass compensation.

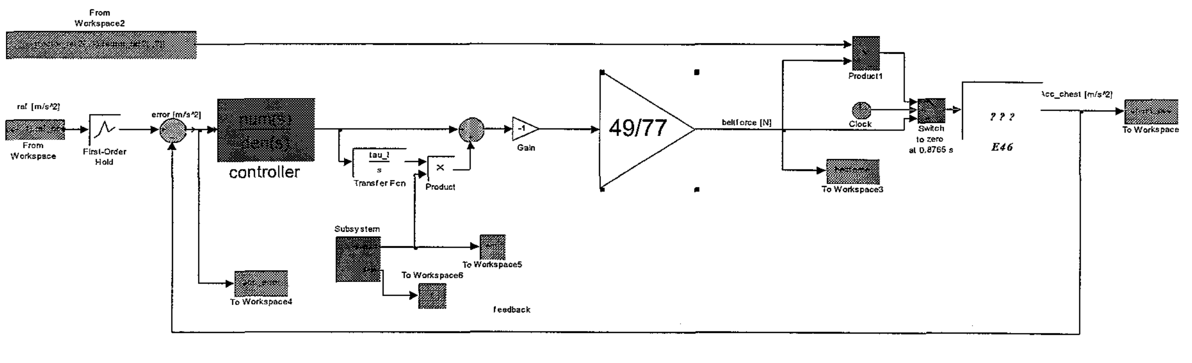


Fig. 3.3 modified beltforce actuator of Hesseling to compensate mass differences with 5% dummy

The 50% dummy is 77kg while the 5% dummy is 49kg. Therefor the total beltforce is multiplied with a gain of 49/77. Testing the controller in the multibody model gives the following result for the chest acceleration in comparison to the preferred setpoint:

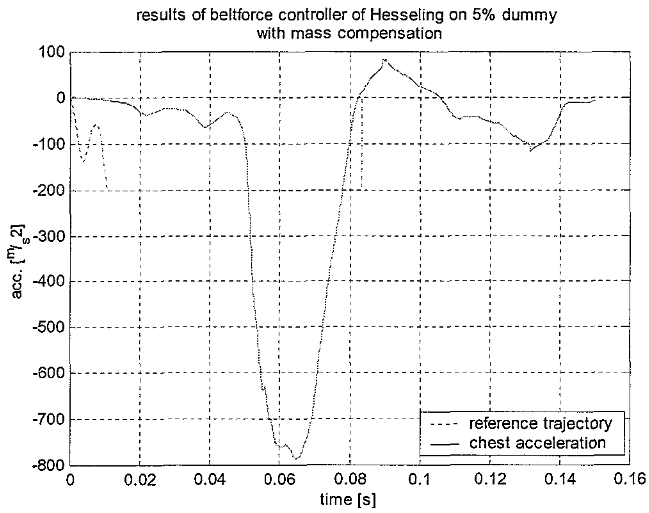


Fig. 3.4: Results of beltforce actuator of Hesseling on 5% dummy model without airbag,

Fig. 3.4 shows high accelerations at t=0.06s. Contact between the dummy and the steering wheel cause them. Apparently, the controller is not powerful enough to decelerate the dummy in the first 0.06 seconds of the crash.

A simple modification of the controller of Hesseling does not work. Therefore the controller is fully redesigned for the 5% dummy.

3.3 Design of a controller and beltforce limiter

The object of the controller is to minimize tracking errors. Two central design constraints are:

1. The magnitude in the open loop of controller and LTI-model must have a slope of –2 in the Bode diagram (phase of –180 degrees). This reduces tracking error for frequencies below bandwidth frequency.
2. The bandwidth is about 300 Hz (1800 rad/s). Review chapter 2 to see that large disturbances of 300 Hz and higher are filtered. Based opn this system identification the maximum bandwidth is 300Hz.

3.3.1 Gain

The goal of the controller is to lower the tracking error (eq. 3.1). Looking at the characteristics of the fitted LTI-model in fig. 3.2, the magnitude must be increased to at least 0db for low frequencies. Setting the gain to 15.4 does this. The results for the open loop are plotted in the plot of figure 3.5. It is easy to see that the open loop is unstable, because at phase -180°, the Magnitude is above 1dB (at ~1000 $^{rad}/_{s}$).

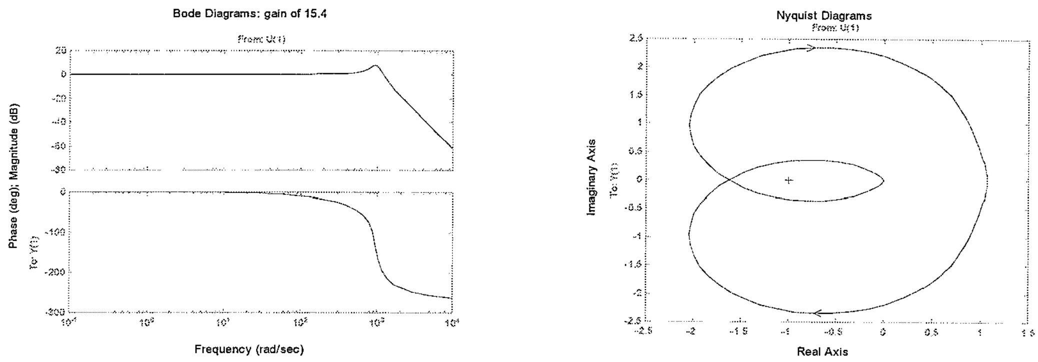


Fig. 3.5 Bode diagram (left) and Nyquist plot (right) of open loop for controller with gain 15.4 on LTI-system for 5% dummy, without airbag.

3.3.2 Phase margin

The next step is to accomplish the slope of –2 in magnitude and to stabilize the system. For low frequencies, phase margin is decreased and more magnitude is introduced by adding two integrators. At 1000 rad/s and higher, phase must be increased with at least 90 degrees and if possible more, this is done with a double lead/lag filter. Standard values for zeros and pole are 1/3 and 3 times bandwidth respectively. The two integrators are introduced with a zero at 100 Hz, just below the eigenfrequency of the LTI-model. If this controller is implemented this results in figure 3.6. This Controller 2 has the following parameter settings:

- Gain of 15.
- Lead/lag with zero at 100 Hz and pole at 900 Hz
- Lead/lag with zero at 100 Hz and pole at 900 Hz
- Integrator with zero at 100 Hz.
- Integrator with zero at 100 Hz.

Bandwidth 300 Hz (phase margin 10°, gain margin 7 dB)

The Bode and Nyquist diagrams for controller 2 are plotted in fig. 3.7:

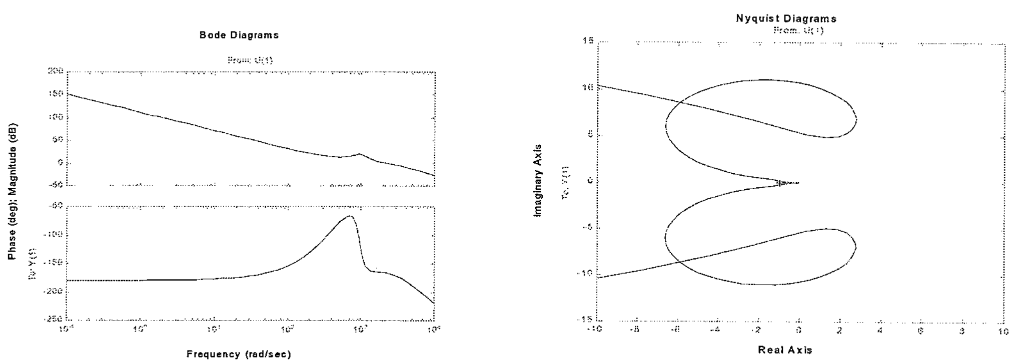


Fig. 3.7: bode and nyquist diagrams of open loop of LTI-model and controller 2

The corresponding results of controller 2 and the computer model are plotted in figure 3.8.

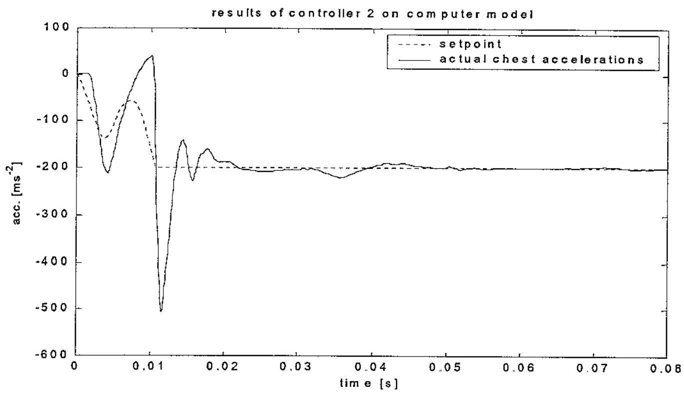


Fig. 3.8: results on actual model without airbag.

The results show very much overshoot at t=0.01s. In order to reduce this, bandwidth is increased with the lead/lags and alternating the cut off frequencies of the integrators.

Controller 3:

- Gain of 15.
- Lead/lag with zero at 100 Hz and pole at 900 Hz
- Lead/lag with zero at 50 Hz and pole at 900 Hz
- Integrator with zero at 100 Hz.
- Integrator with zero at 100 Hz.

Bandwidth 575 Hz (phase margin 17°, gain margin 7 dB)

The open loop results are as shown in fig. 3.9:

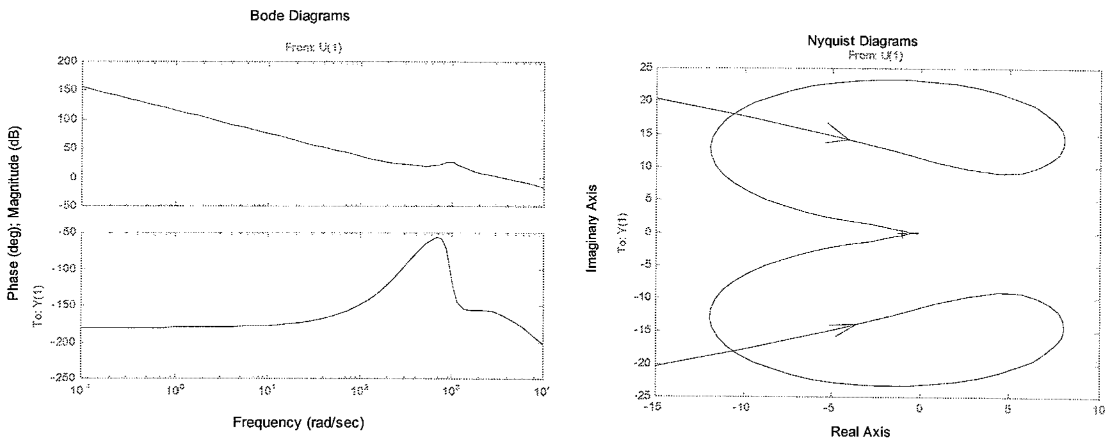


Fig 3.9: Bode diagram (left) and Nyquist plot of open loop of controller on 3rd order LTI model of USNCAP57 crash. with 5% dummy, without airbag

The results with the computer model are plotted in the next section

Two things are in contradiction with the choices of section 3.1. The first is the bandwidth of 575 Hz. This is higher than the 300 Hz. Obviously, disturbances with f = 300 Hz do not influence the controller performance if bandwidth >300 Hz.
The second is the phase margin around 700 rad/s. This is a result of the low damped LTI-model, which has a sharp cut off at this frequency. The controller must have sufficient phase margin to prevent the open loop from a negative phase margin at 1000 rad/s.

3.4 Results of beltforce controller with computer model

The implementation is shown in fig. 3.10. The blok E46 represents the computer model of MADYMO.

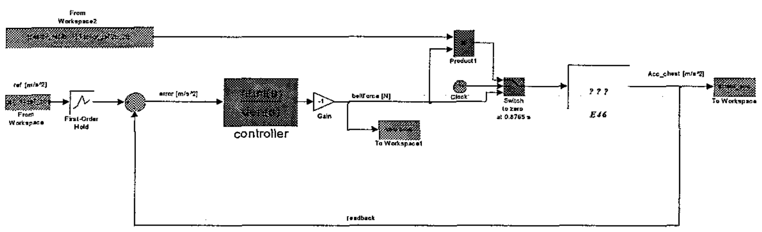


Fig. 3.9: Layout of the beltforce limiter that is used for controller 1, 2 and 3

Fig 3.10 shows the results when controller 3 is used on the LTI-system and on the computer model without airbag:
Figure 3.10 shows a satisfying result for the control of the computer model:
- The overshoot at t=0.005s and 0.01s is gone.
- The chest acceleration has overshoot of approx. 20 $^{m}/_{s2}$ in the first 0.01s of the crash. This is satisfying, because the maximum amount of deceleration is not reached here, but later at t=0.035s.
- The maximum deceleration is less than 210 $^{m}/_{s2}$ at t=0.035s. The reason for this is oscillatory behavior of vehicle acceleration (fig. 1.3)

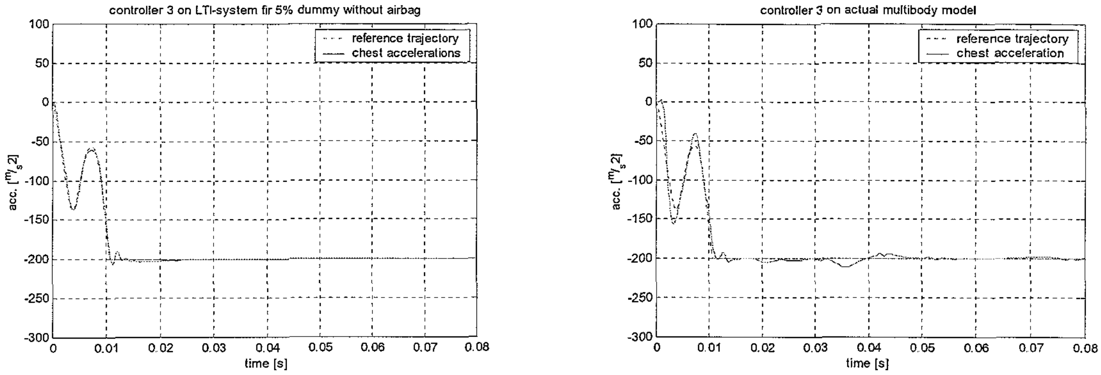


Fig 3.8 results of controller 3 on LTI-system (left) and actual multi body model of 5% dummy without airbag

Fig 3.11 shows the results when controller 3 is used on the LTI-system and on the actual multibody model:

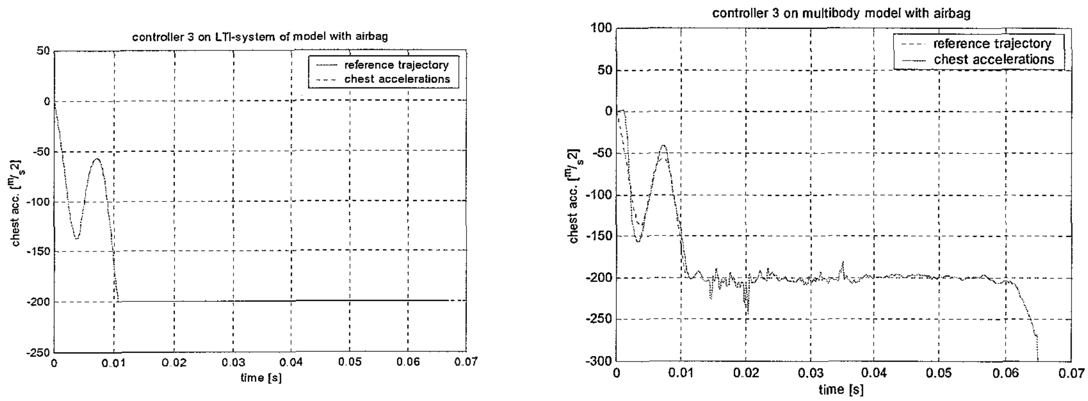


Fig 3.11 Results of controller 3 on LTI-system (left) and actual multi body model of 5% dummy with airbag

The following conclusions follow from fig. 3.10 and 3.11:

1. The system of beltforce controller and computer model seems to be stable for both situations with and without airbag, though it is based on the LTI-model without airbag.
2. The airbag model shows more noise in the phase where the dummy is also in contact with the airbag.
3. After filtering the results of the system with airbag, the maximum deceleration in both models is approx. 210 $^{m}/_{s2}$. The peak at 0.035s are not shown in the airbag case, because the airbag damps the transfer from vehicle acceleration to dummy acceleration.

This controller 3 gives a satisfying result, because it minimizes the maximum amount of deceleration with an overshoot of 5% for the model without airbag.

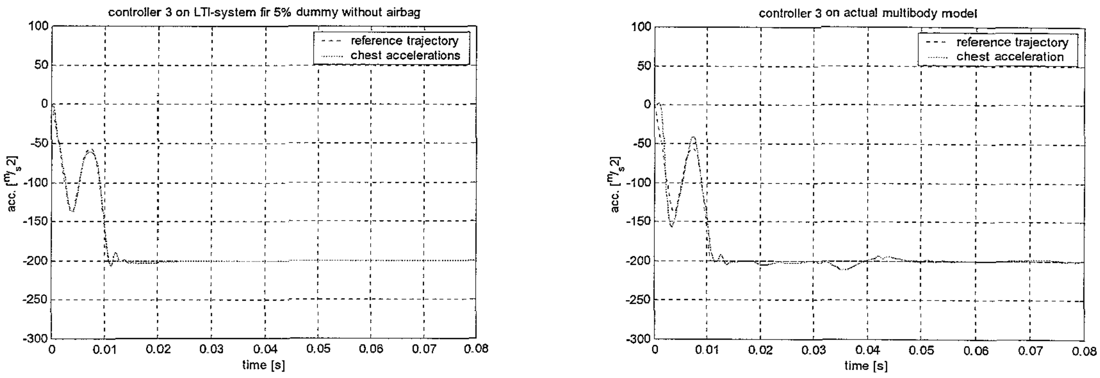


Fig 3.10 results of controller 3 on LTI-system (left) and actual multi body model of 5% dummy without airbag

In figure 3.11 the differences in chest accelerations and beltforces between the original passive safety systems and the new beltforce actuator (= beltforce controller and actuator mass) are plotted:

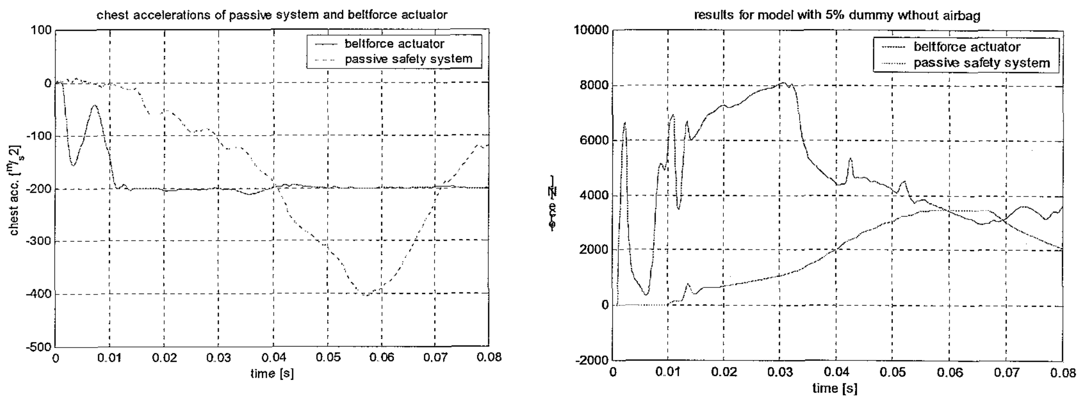


Fig. 3.11 Chest accelerations (left) and beltforces (right) for the model without airbag.

The beltforces in the model with the beltforce controller are much higher at the start of the crash.

The concluding results of the of the smart beltforce actuator with controller are:

$$\max\left(\left|\ddot{x}_{chest,active,d5\%}(t)\right|\right) = 210\, {}^{m}\!/_{s^2} \qquad (3.3)$$

This result is satisfying

4 Comparison of Controllers

The controller that is designed in this research has other characteristics than the controller of Hesseling. The last chapter showed that slight modifications to the controller of Hesseling do not give satisfying results for the 5% dummy.

This chapter it is tried to find one controller for both models of 5% dummy and 50% dummy, by using the controller of chapter 3 as basis. This beltforce controller is applied to the model of the 50% dummy. Hesseling's 2nd order LTI-model gives a stable open loop (fig. 4.1):

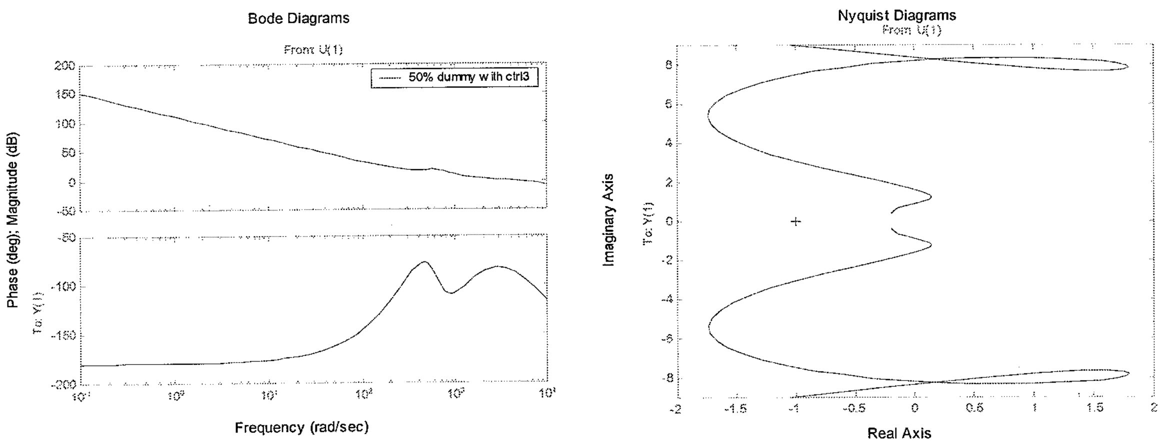


Fig. 4.1 Bodediagram and Nyquist plot of open loop of beltforce controller (chapter 3) and the 2^{nd} order LTI-system of the multibody model with the 50% dummy.

The controller is implemented in the feedback system of fig. 3.7, where E46 represents the multibody model with the 50% dummy. The results are shown in fig.4.2.

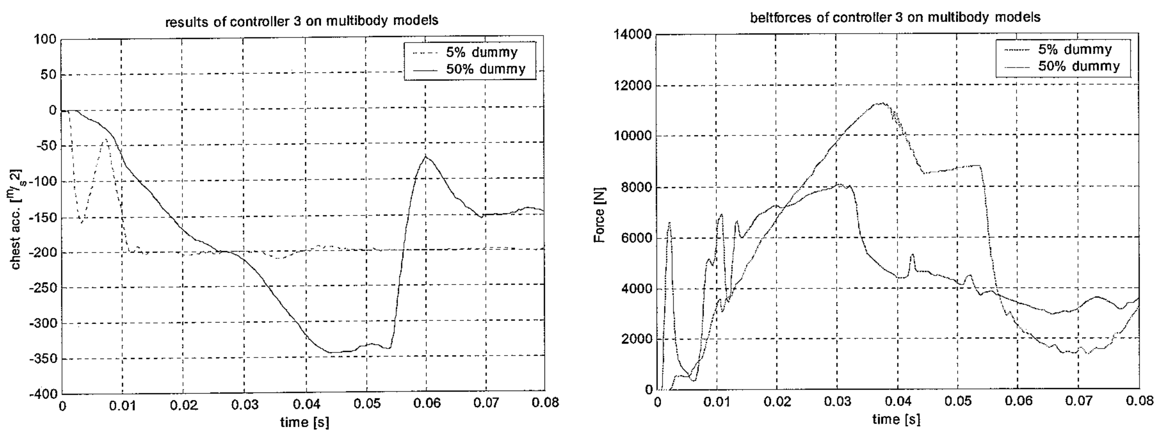


Fig. 4.2 results of the same beltforce actuator for the model with the 5% dummy and the model with the 50% dummy

The model with the 50% dummy must follow the setpoint of figure 1.4. Fig. 4.2 shows that this setpoint is not followed. The beltforce is increased too slowly and setpoint is not followed. Later major overshoot occurs because of integrator windup.

4.1 Optimizing beltforce controller for 50% dummy

The beltforce controller of chapter 3 is slightly modified by introducing mass compensation. See section 3.1 for more information: a gain of 77/49 is implemented. This results in:

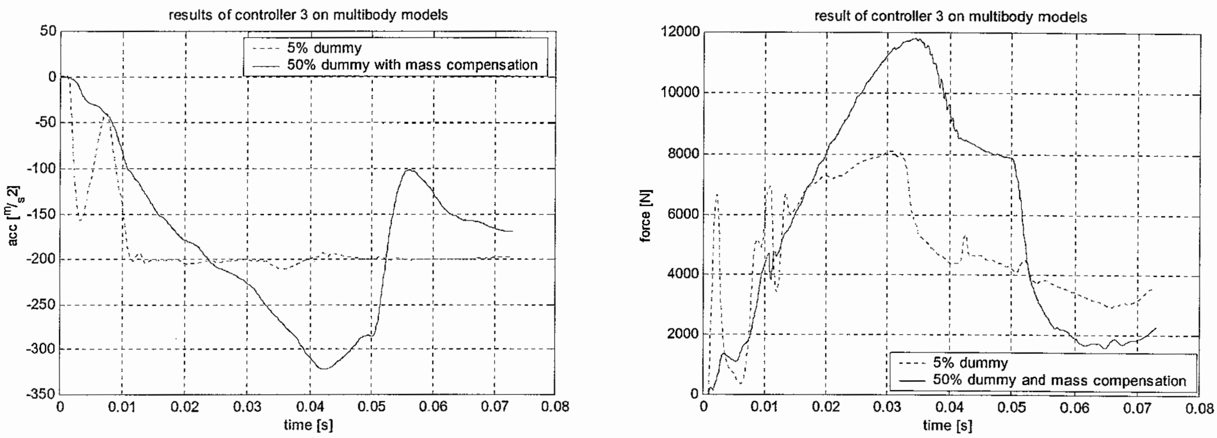
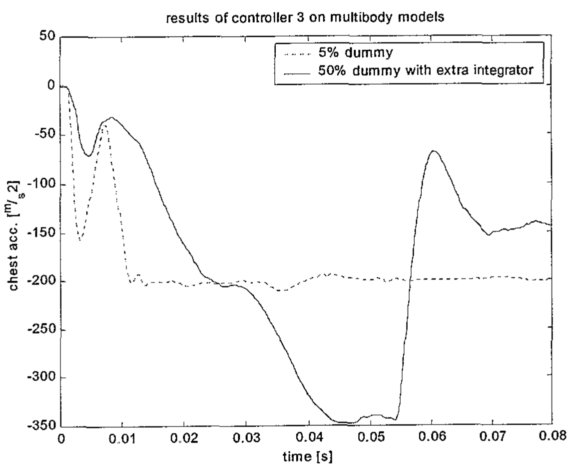


Fig 4.3 results of the beltforce actuator for the model with the 5% dummy and the model with the 50% dummy. Mass compensation is applied via an extra gain in the controller of (77/49), See fig. 3.3 for details on this.

Figure 4.3 shows that an extra gain to compensate the mass-differences between the two dummies increases the tracking performance marginally for the model with the 50% dummy. Just like in figure 4.2 , the beltforce at the start of the simulation is too low

In order to get higher beltforces at the start of the simulation, The integrator that Hesseling originally used in the first 0.0025 seconds of the crash is introduced (section 1.6). Fig 4.4 shows the results:



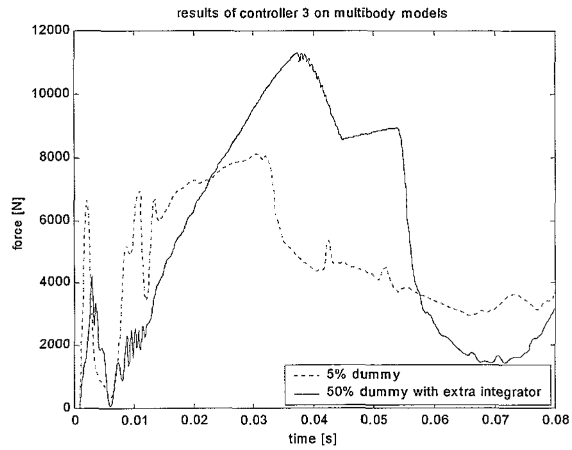


Fig 4.4 results of the beltforce controller of chapter 3 and the model with the 50% dummy. Mass compensation and an extra integrator that works between $0<t<0.0025$ s is applied in the same way as displayed in par.1.5

Fig. 4.4 shows that the extra integrator in the controller of the beltforce actuator, allows a higher beltforce at the start of the simulation. It is clearly not enough and as soon as the integrator is set to zero, the beltforce is decreases. Thus, until t=0.03s the 50% dummy decelerates too little. Later in the process, the integrators cause overshoot.

4.2 Exclusive controllers

The previous sections show that it is not possible to define one controller that gives satisfying results for both models of the USNCAP crash with 5% hybrid dummy and 50% hybrid dummy. It is also not possible to find a mutual exclusive controller by slight modification of each controller.

Another remark must be made in this context: the static controller that is used in this research is based on system identification of only a small time span ($0.01<t<0.06$ s) of the simulated crash. If for example initial conditions are to be implemented, then this static controller is not sufficient.

In order to build one controller that gives optimal results for both models, there are only two options available:

1. A controller that is based on other controller techniques
   This means e.g. a non-static controller for implementation of initial conditions.
2. A model based control method that first fully identifies what dummy is used and then defines what controller and which parameter values are used.

Explicit model predictive control is able to incorporate both options. However, since this is a computer simulation that can be redone, a method like e.g. learning control is also applicable.

5 Summary and conclusions

The goal in this research was to build a smart restraint system for the safety belt: a beltforce actuator. In this case, it is a big advantage to make use of computer simulation methods. In this research a multibody model of a BMW and a 5% hybrid dummy model in a USNCAP57 crash is used.
The next step is to apply a control design strategy for manipulation of a beltforce actuator for the multibody model. To do this, first the model has to be analysed and identified. Control is introduced by feedback control of the beltforce. For this feedback loop, an input reference is defined for the dummy's chest, based on the deceleration of the car and the position of the driver in the car.
The controller is based on an identification of the actual computer model. With the use of step response analyses a 3rd order LTI-model is found. This LTI-model is the basis for the controller. With classic control methods, a PID-like controller is realised and tested on the actual computer model. Optimisation takes place by redesigning the controller, based on results from the computer model. The results are satisfying if the beltforce actuator ensures that the reference-trajectory is followed and that the deceleration of the dummy's chest is minimised. This situation is reached.
A comparison with a beltforce controller, designed by Hesseling for the same crash, but with a 50% hybrid dummy does not result in one controller that is optimal for both dummies.

The following conclusions are found:
It is possible to design a beltforce controller based on a 3rd order LTI-tranfer function of the computer model of the USNCAP crash at 57kmh with a 5% hybrid dummy.
To accomplish satisfying results, a controller with one gain, two lead/lag filters and two integrators is necessary.
It is not possible to use this, static controller that is designed for the 5% dummy in the same model with the 50% dummy. Alternating a controller, based on the 50% dummy and use it on the 5% dummy is also not possible.

Recommendations for further research are a better identification of the model to define the behaviour in the first 0.01s of the crash. With the use of different control methods such as model predictive control or learning control it should be possible to design one controller that gives optimal results. Off course this recommendation is only applicable to analysed crash tests: the USNCAP crash at 57kmh with the 5% dummy and the 50% dummy.

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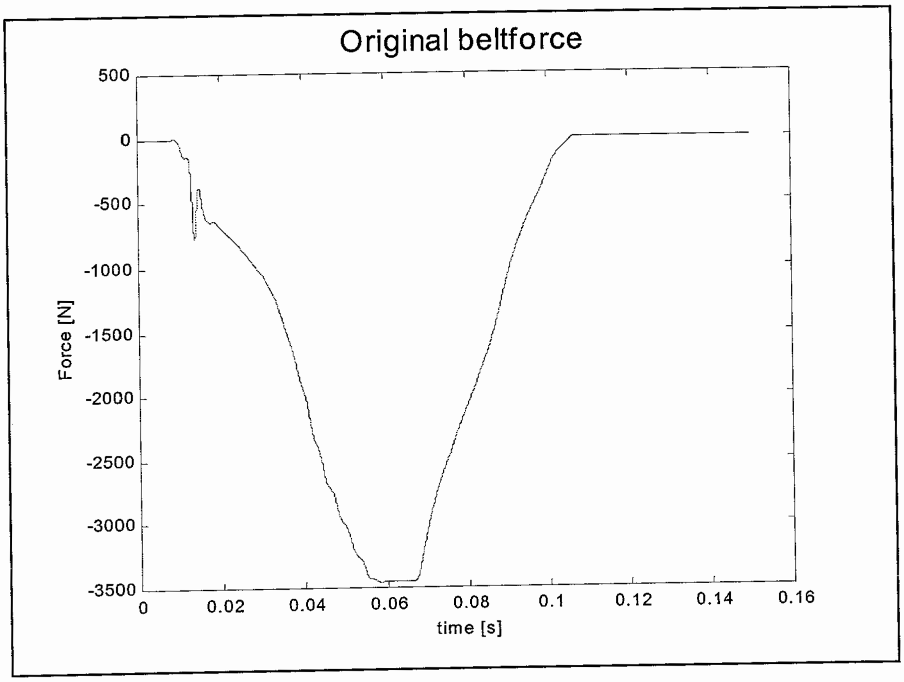
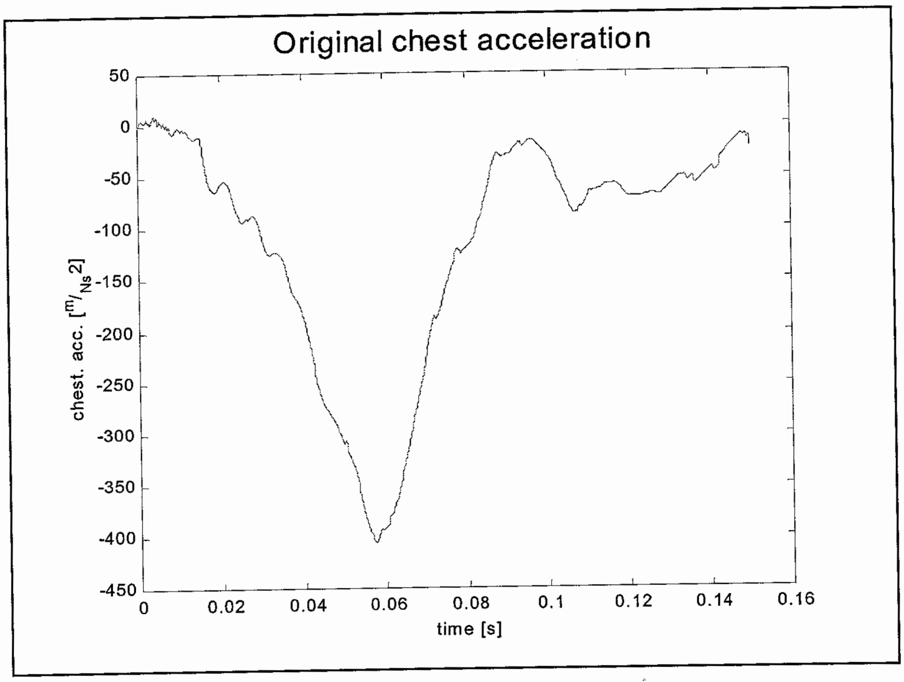
Appendix A: Step response without airbag

chest responses for multibody model 5% dummy without airbag





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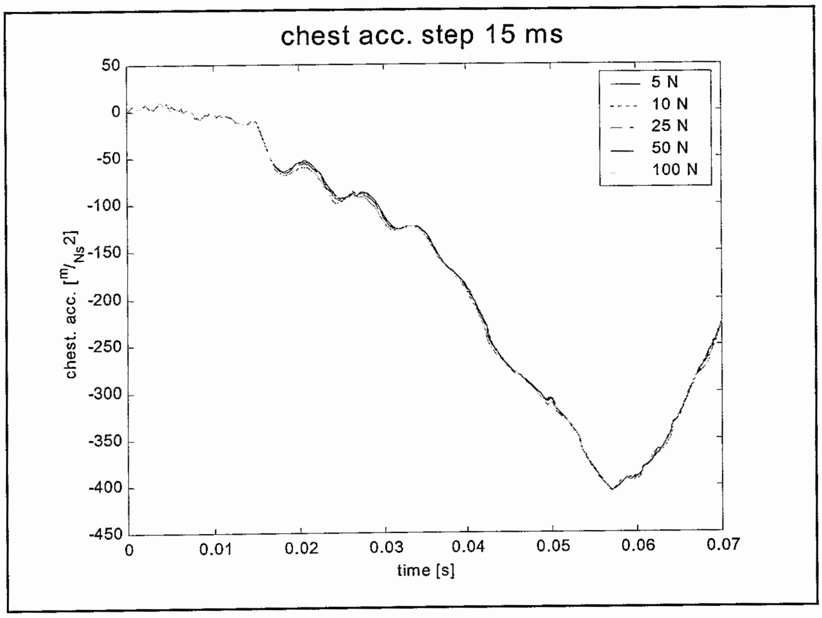

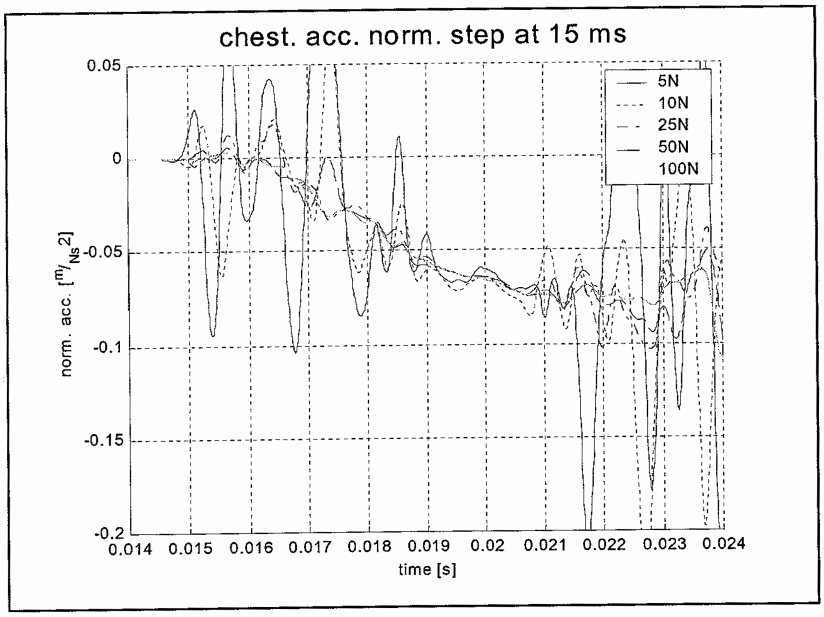

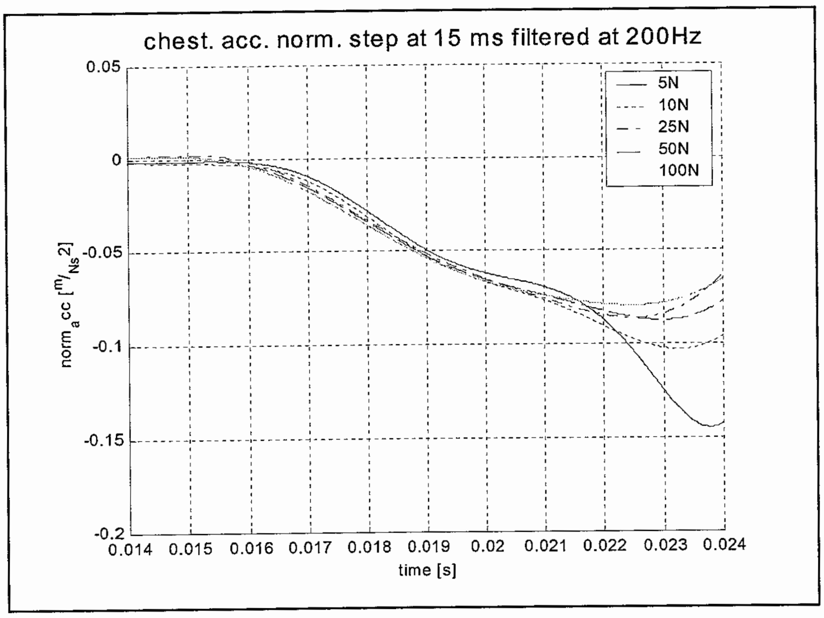

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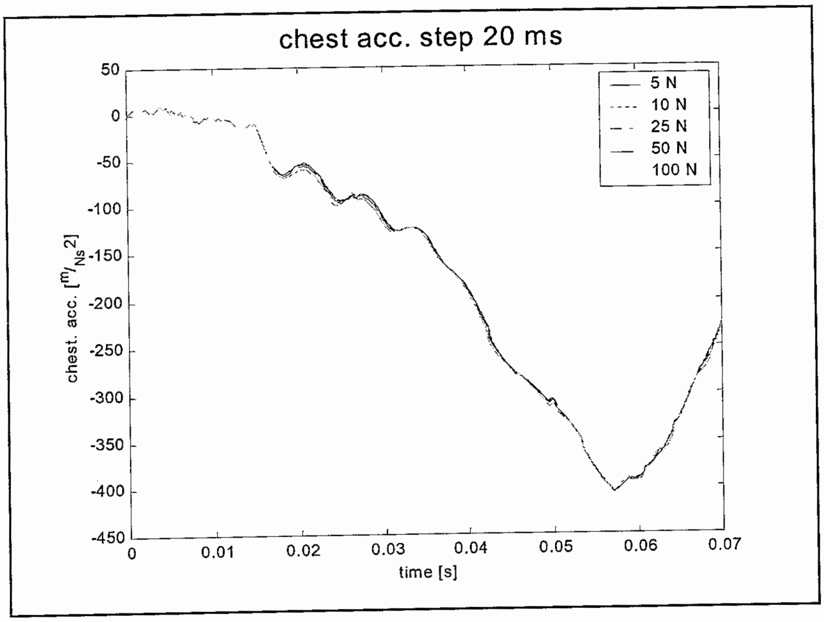

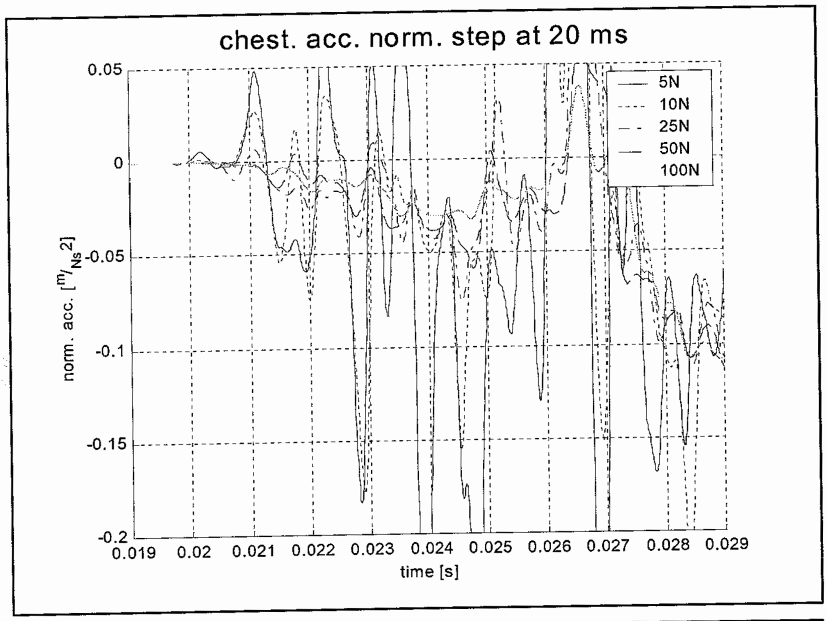

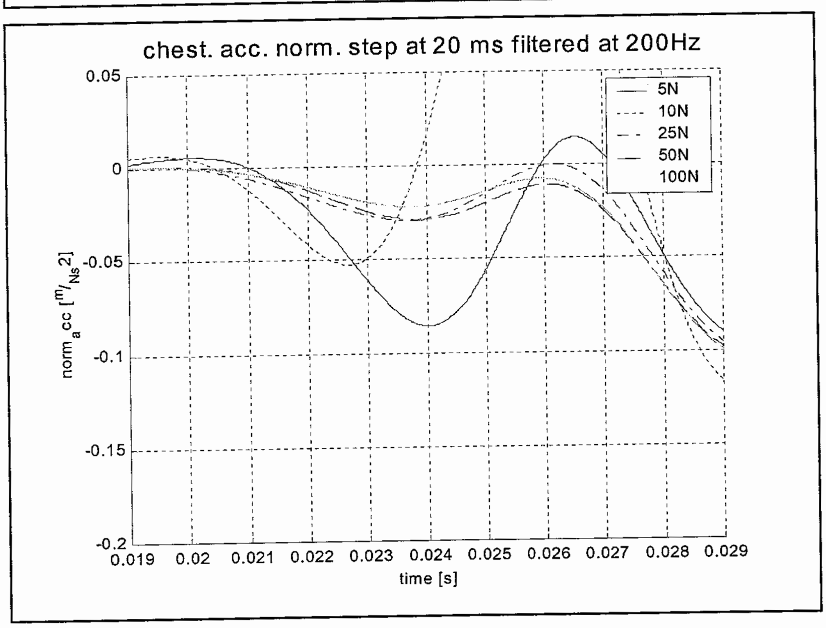

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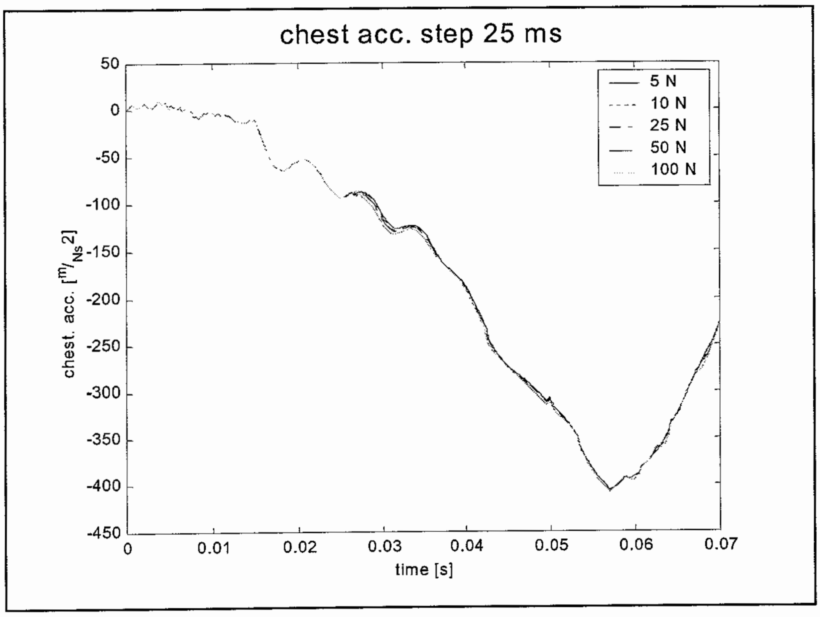

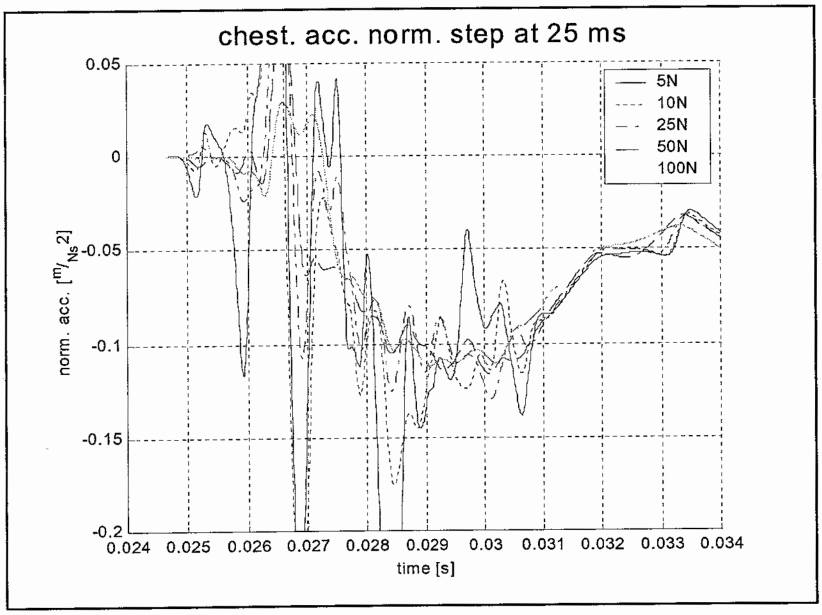

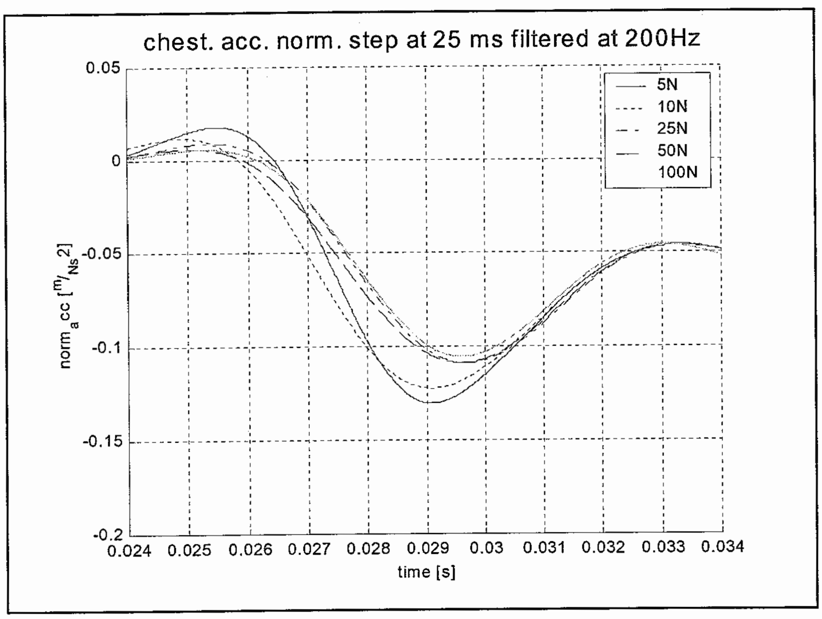

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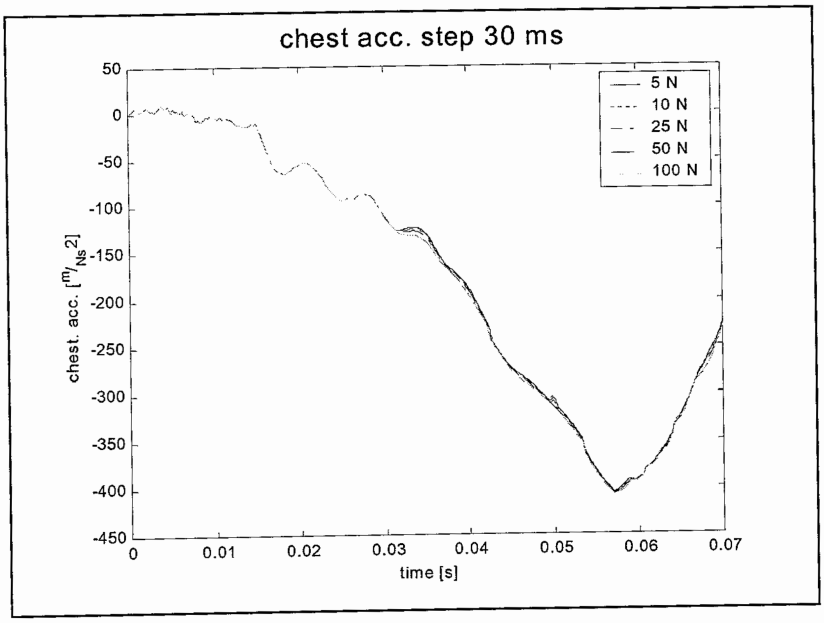

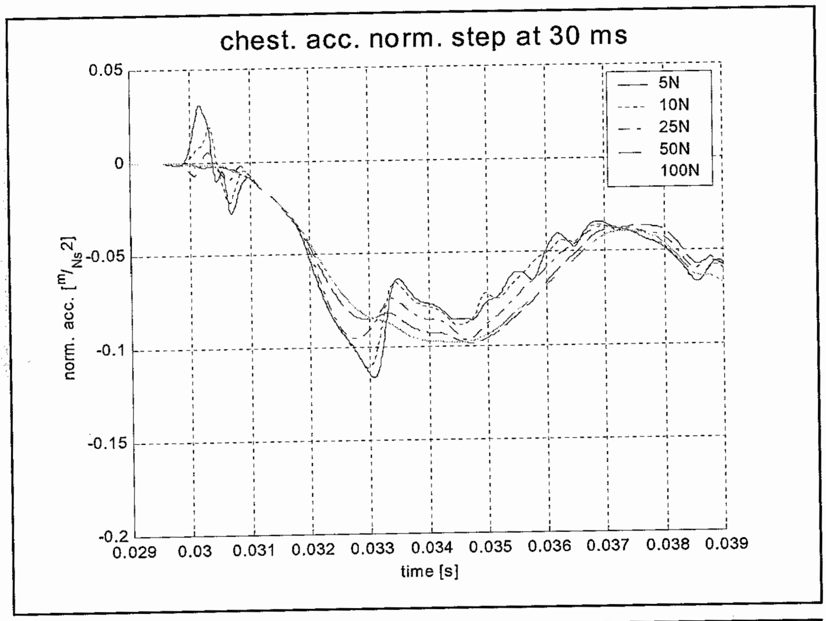

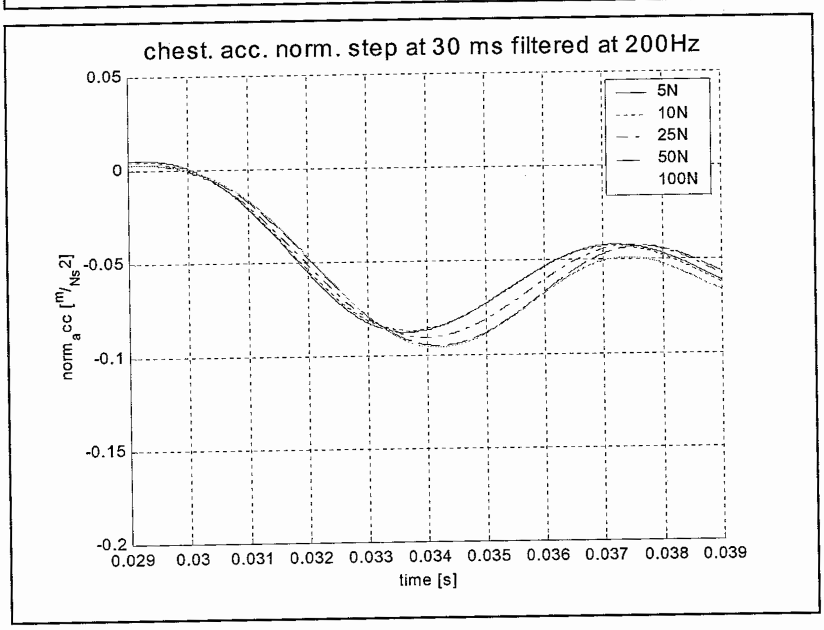

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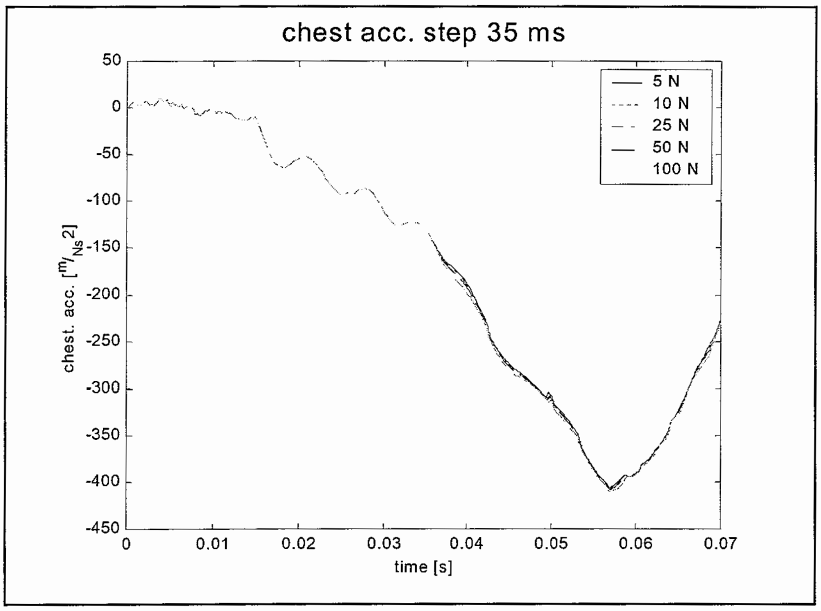

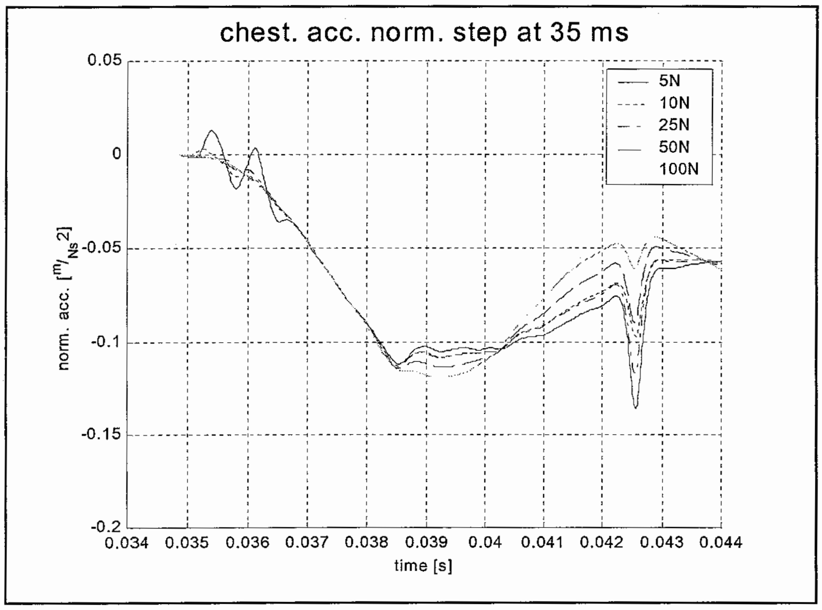

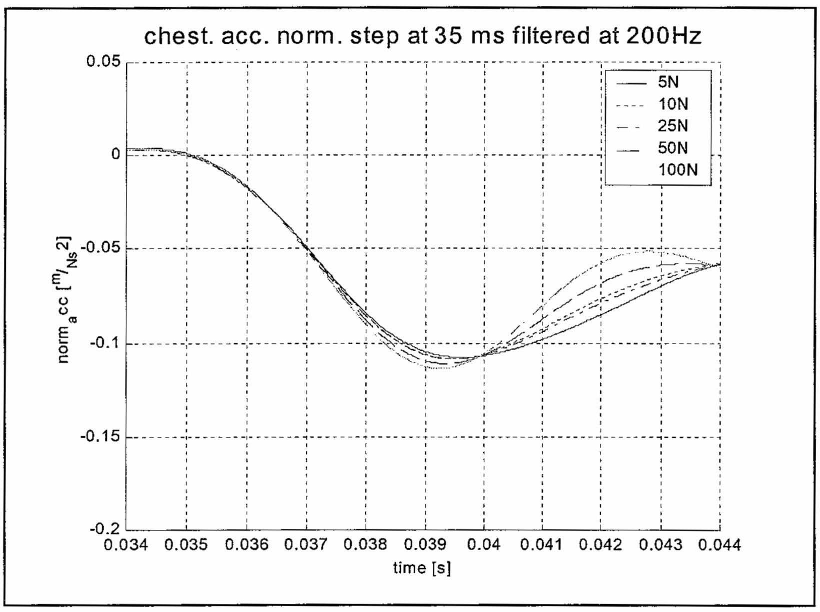

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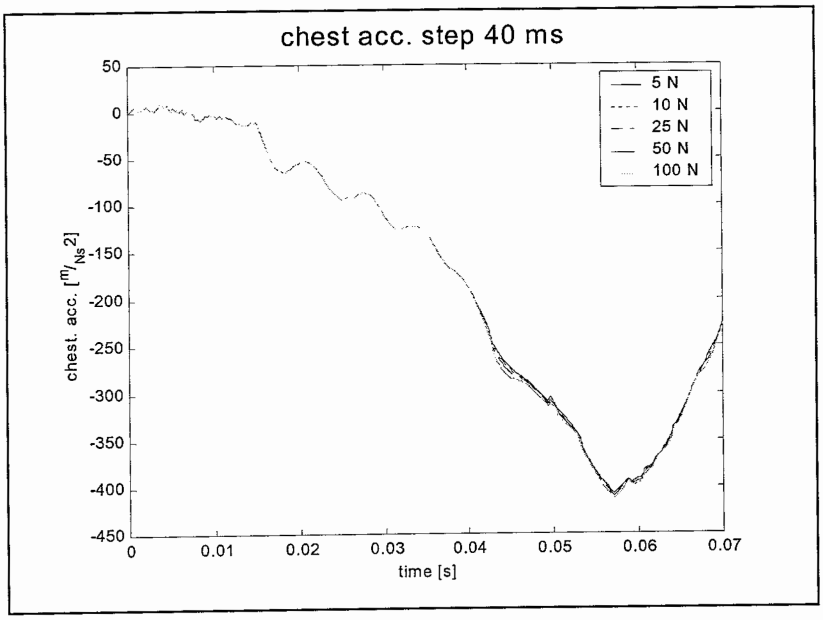

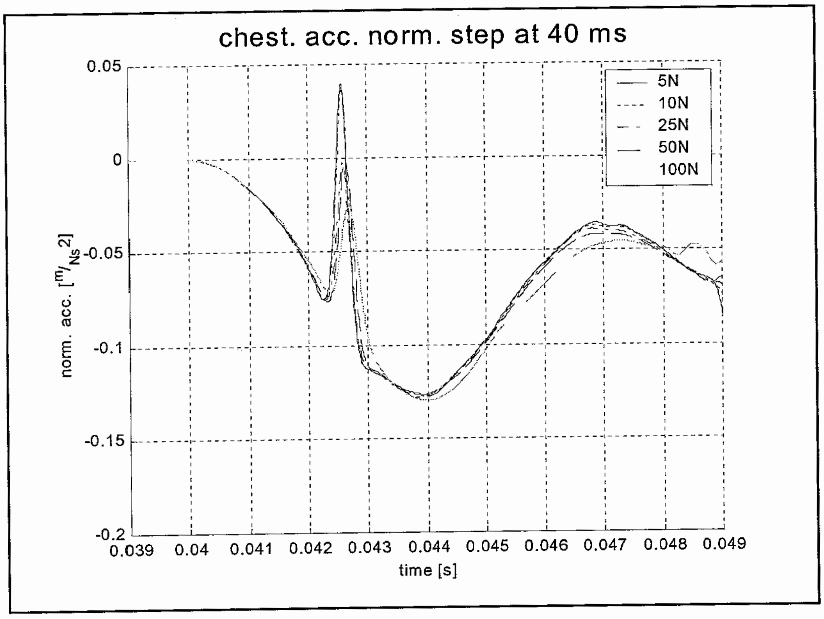

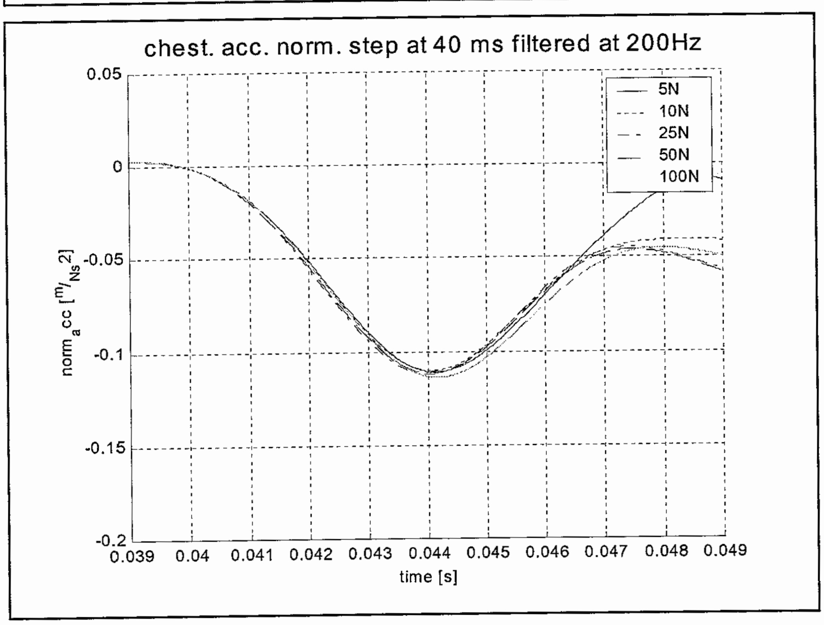

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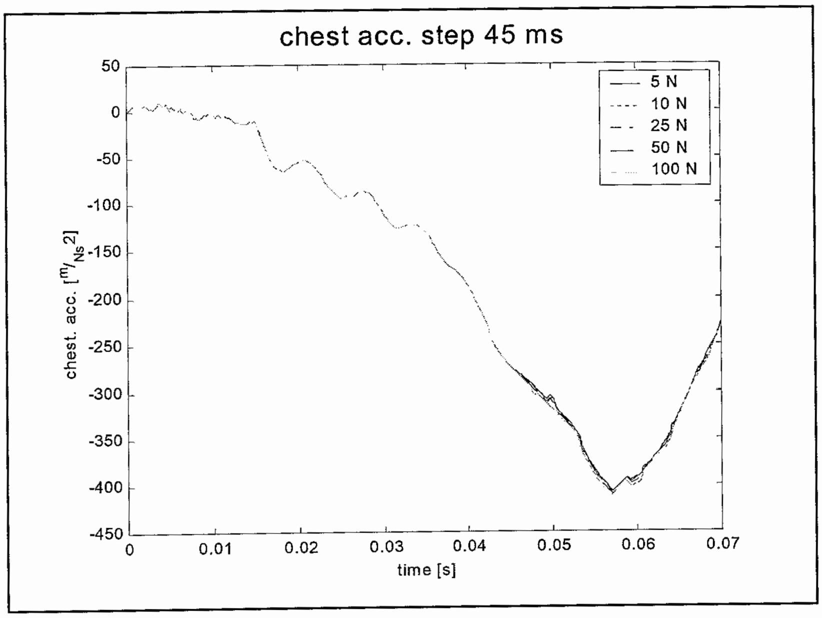

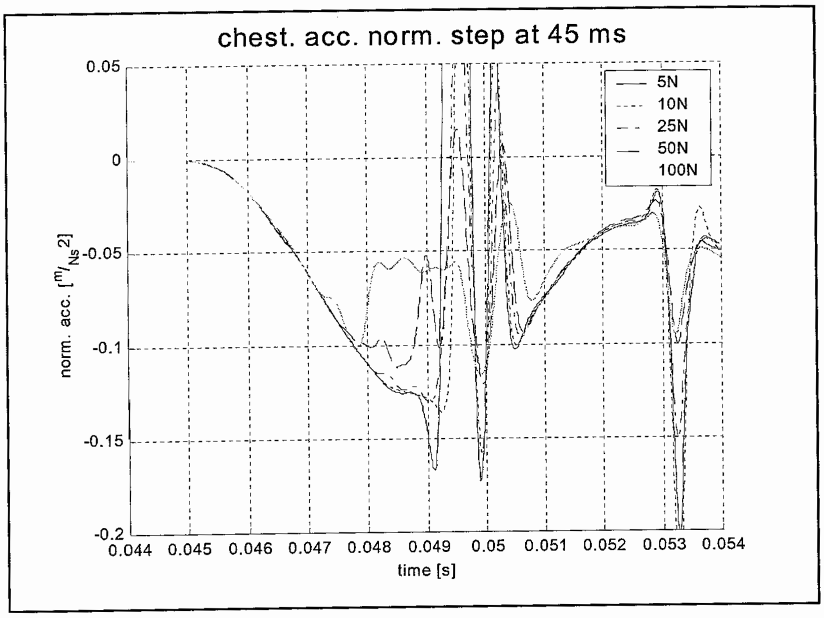

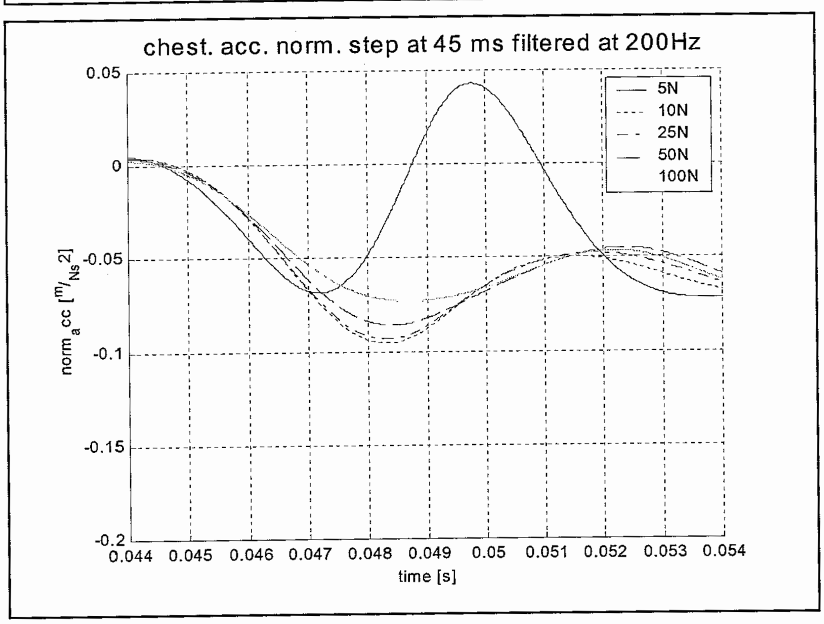

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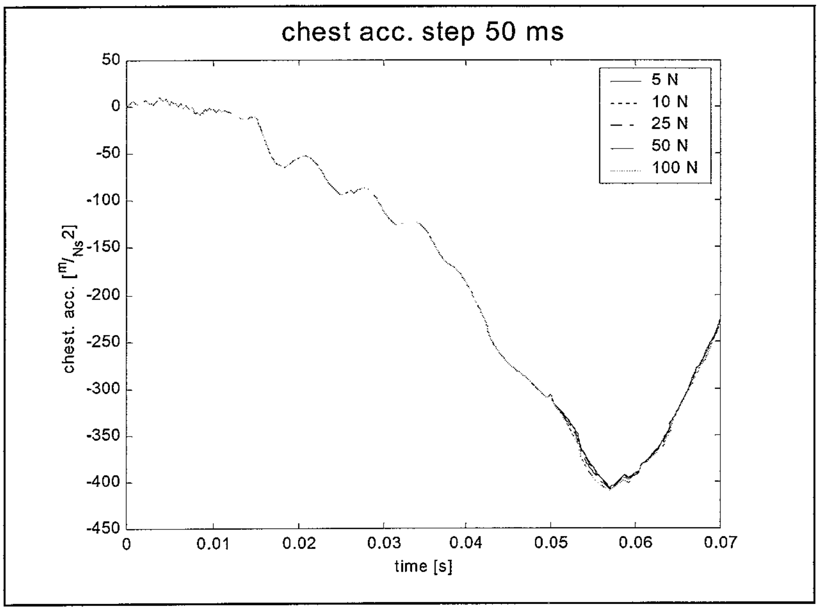

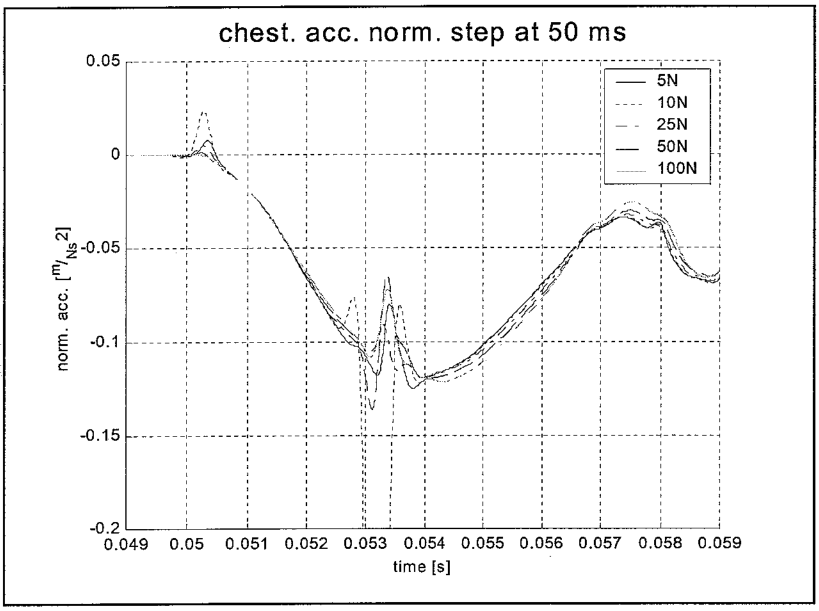

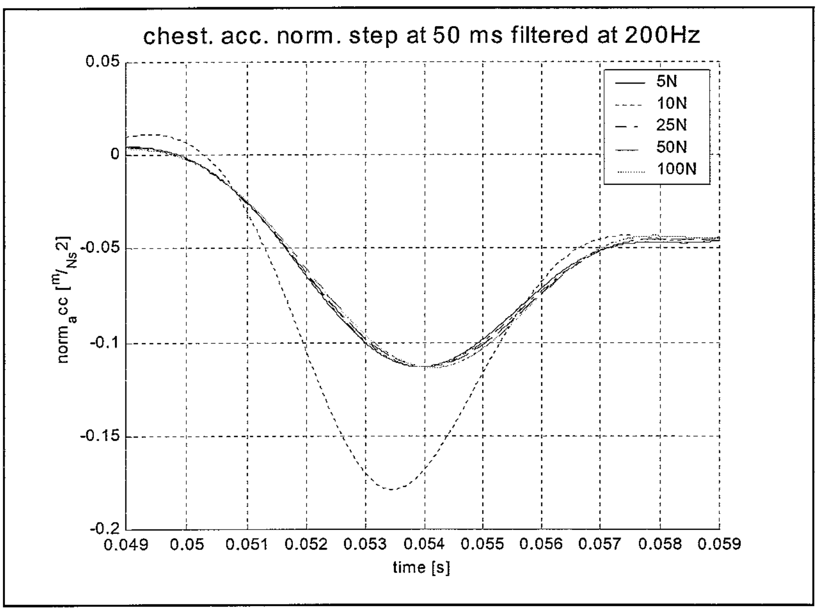

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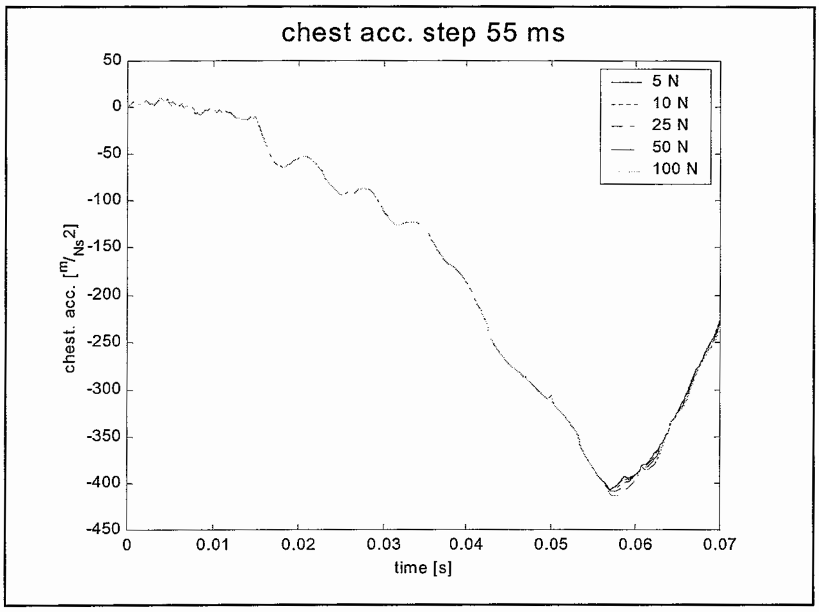

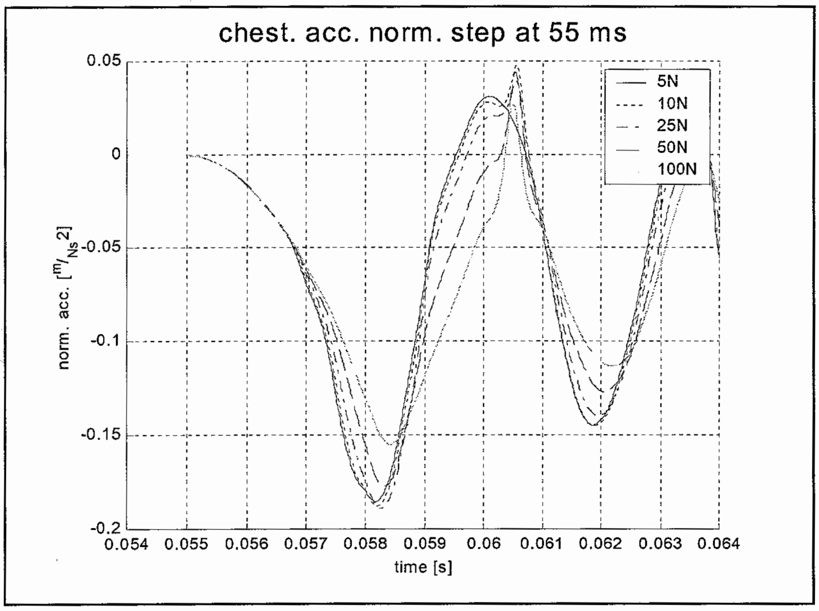

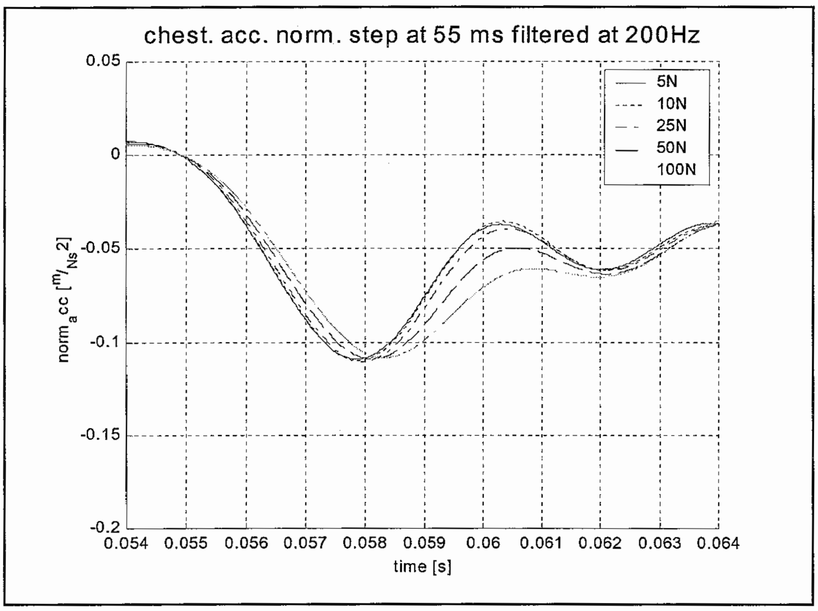

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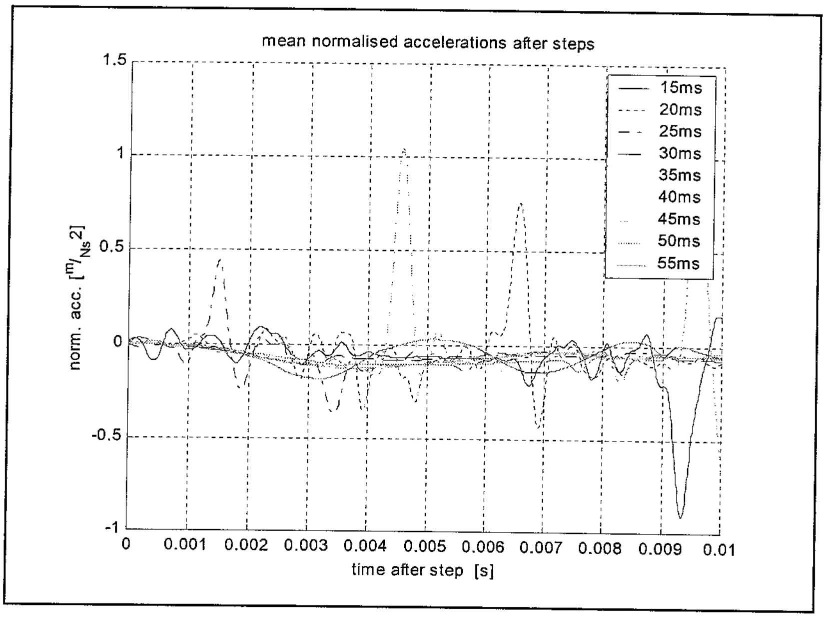
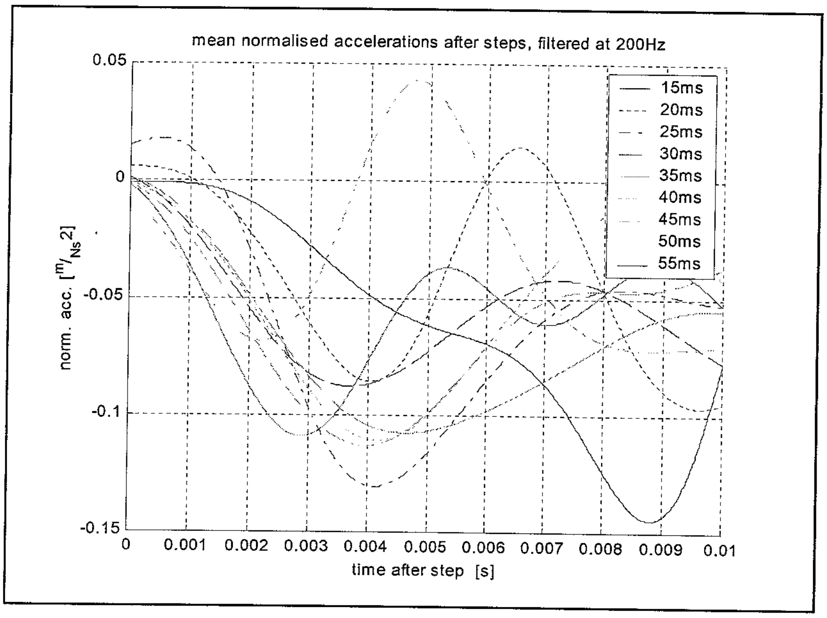
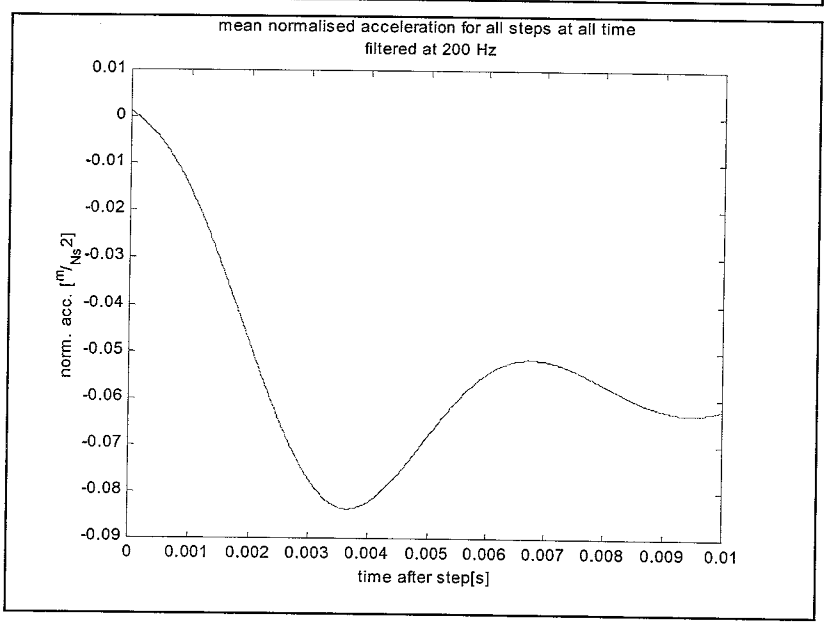
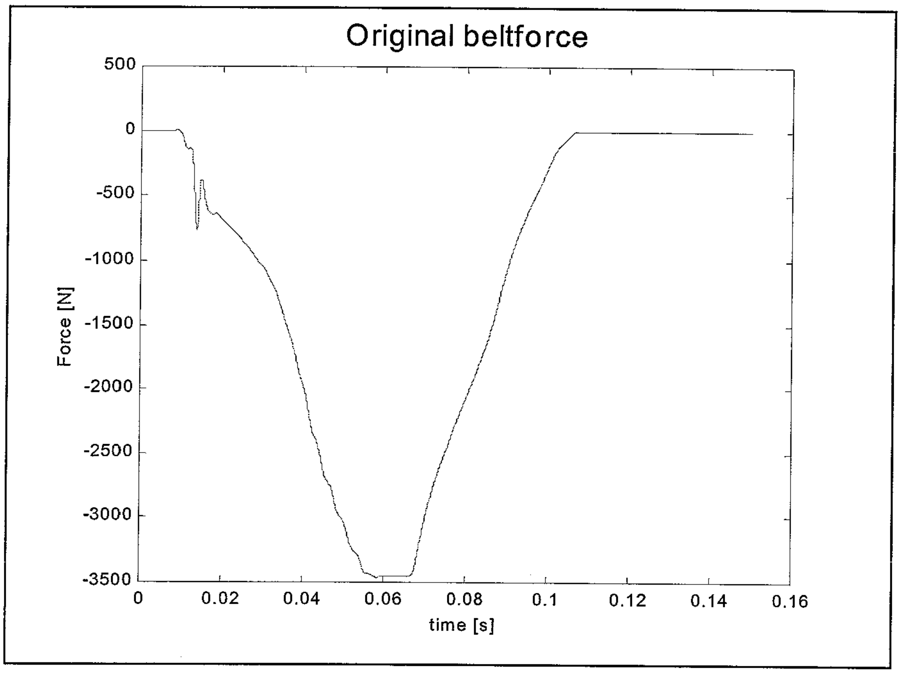


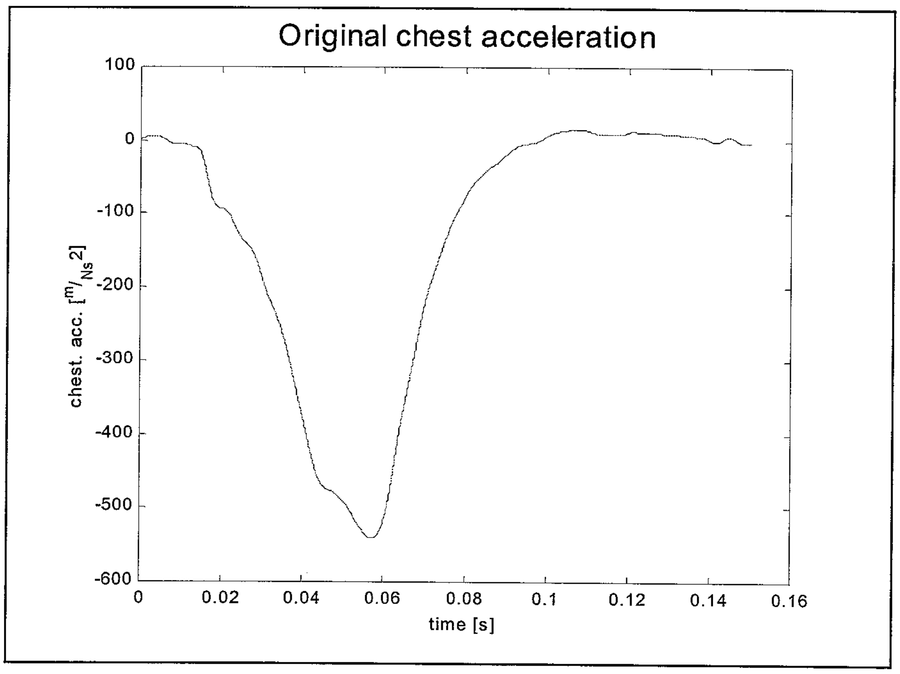




Appendix B: step responses with airbag

chest responses for multibody model 5% dummy with airbag





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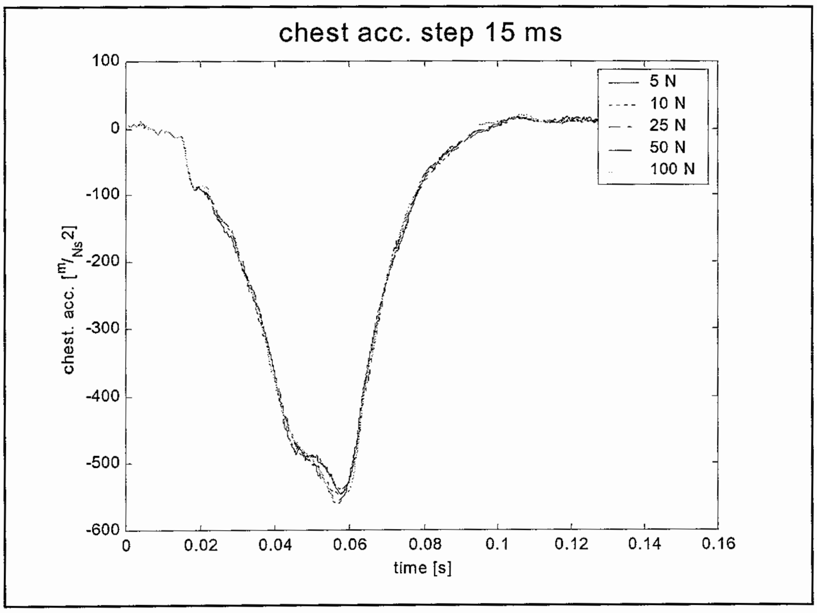

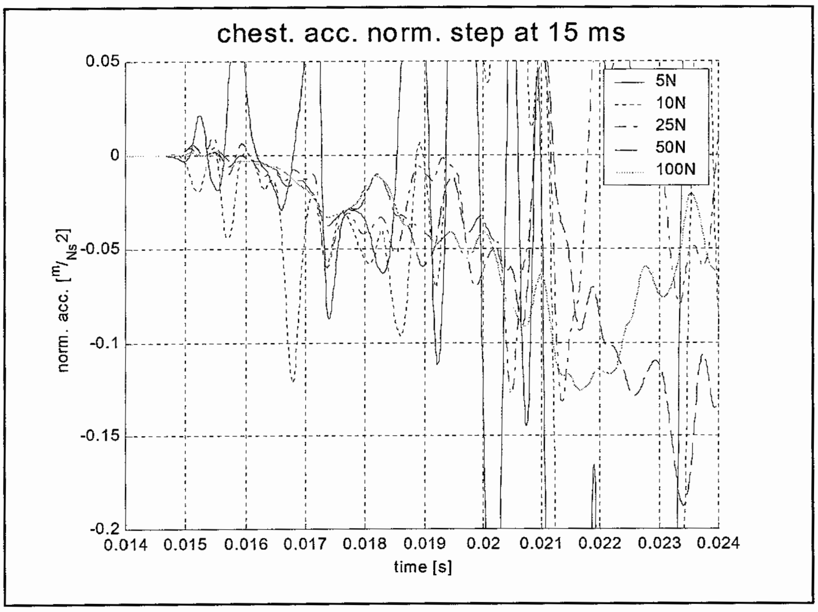

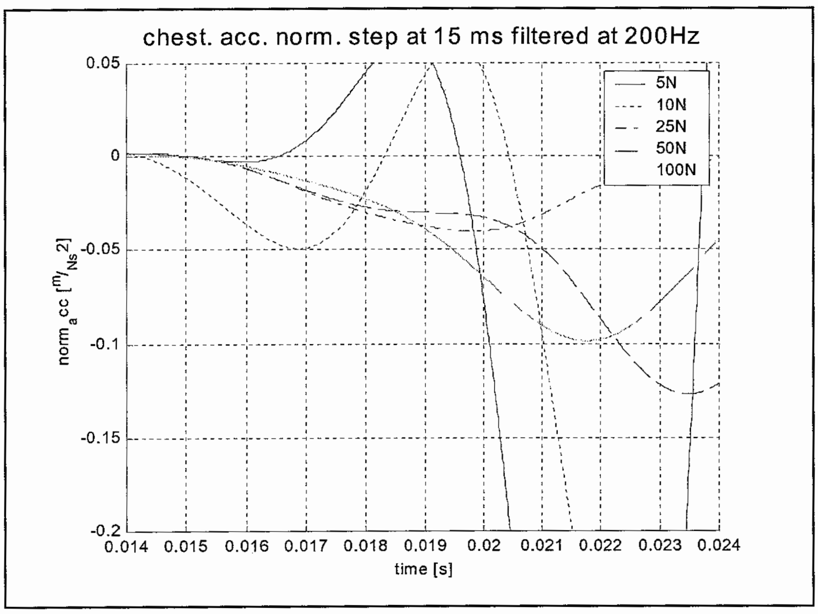

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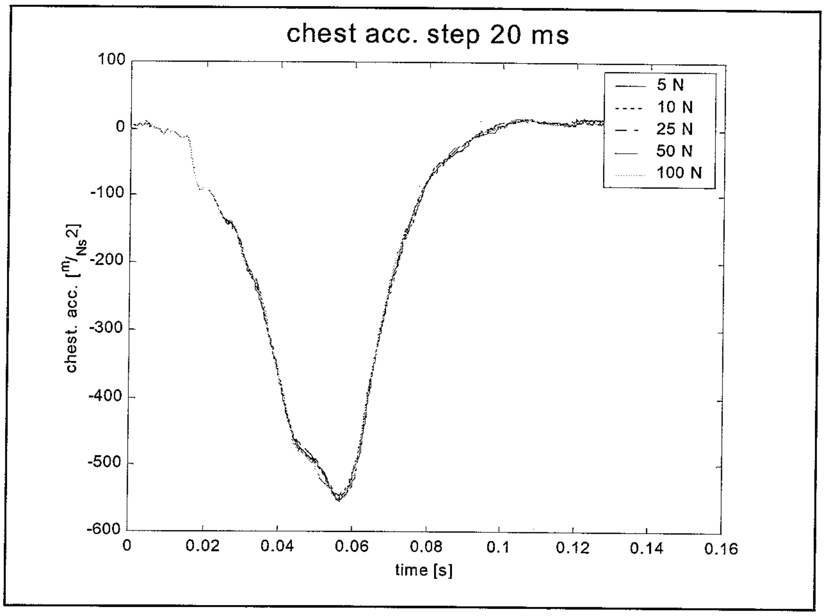

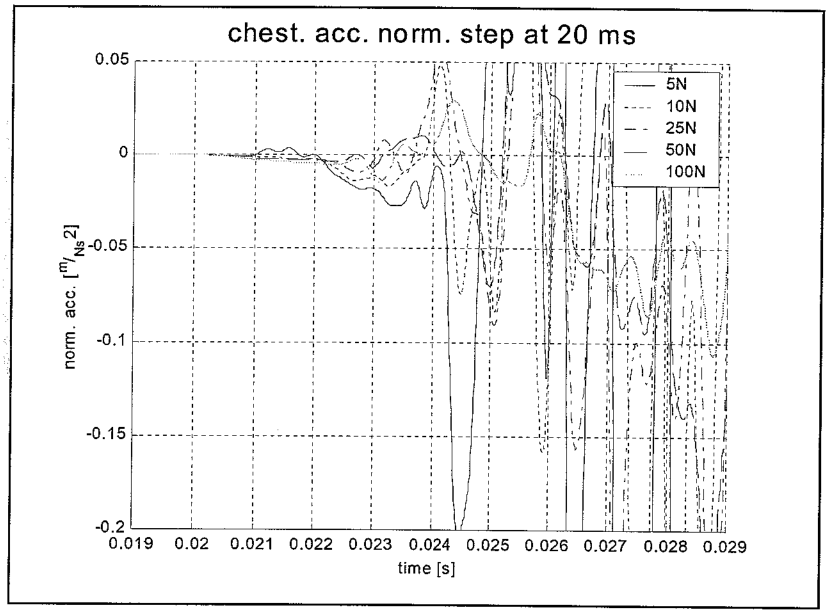

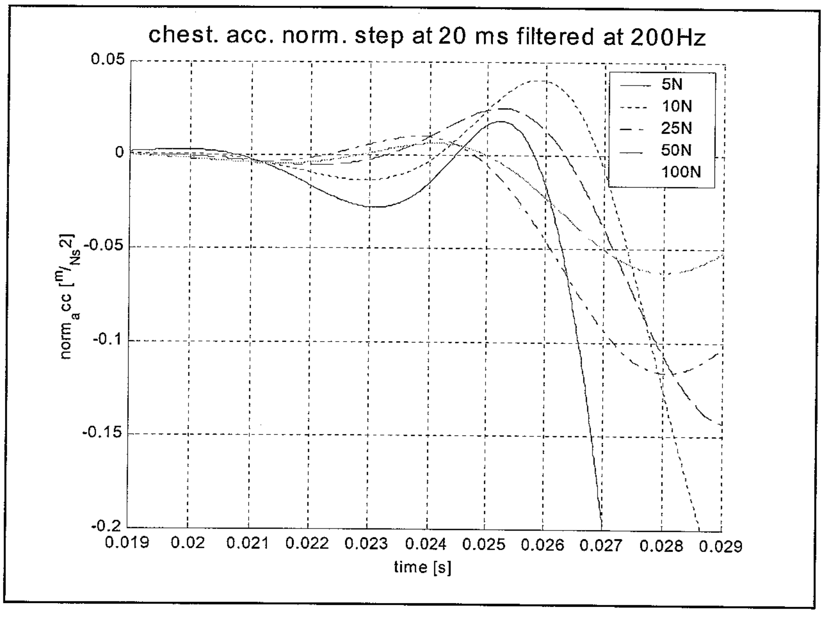

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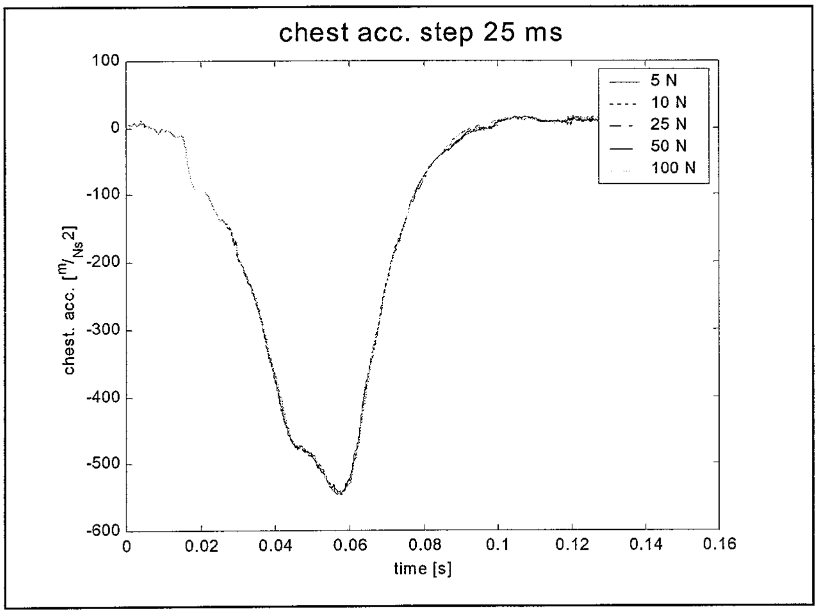

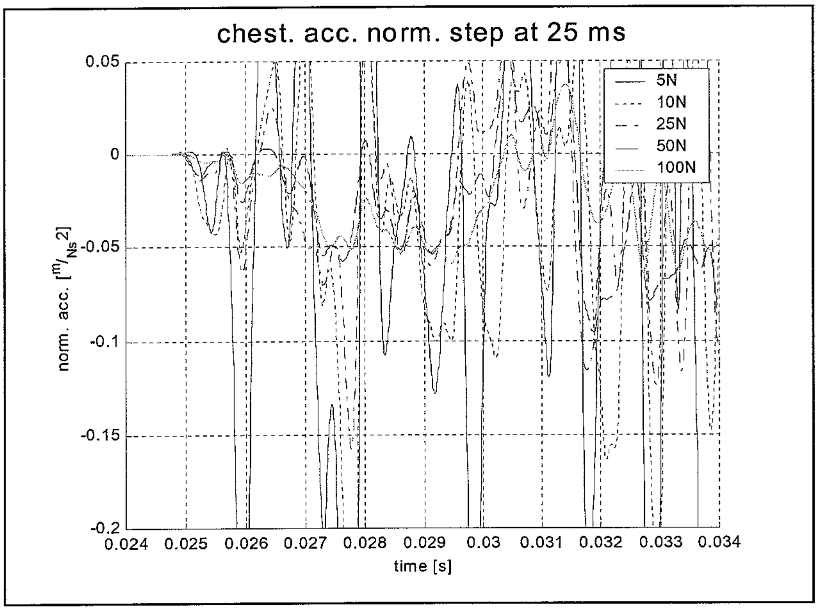

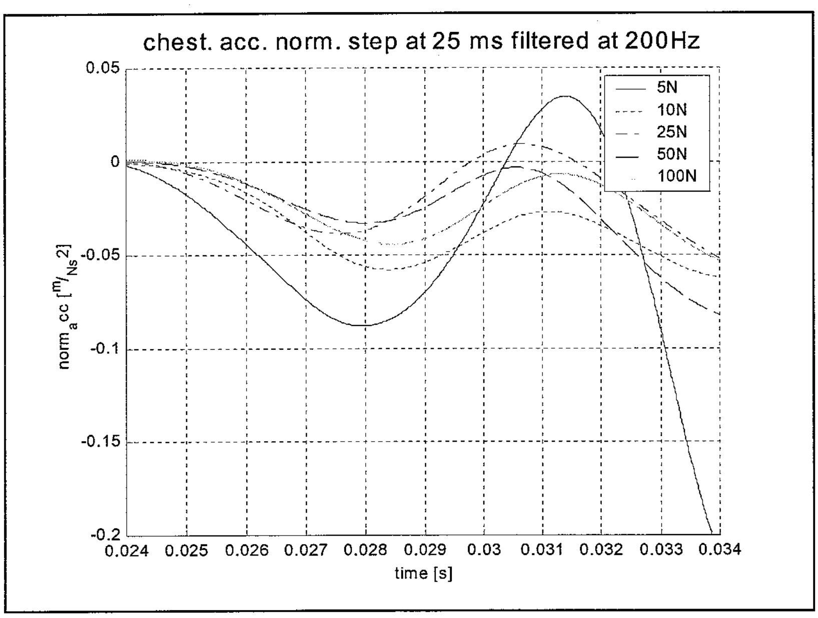

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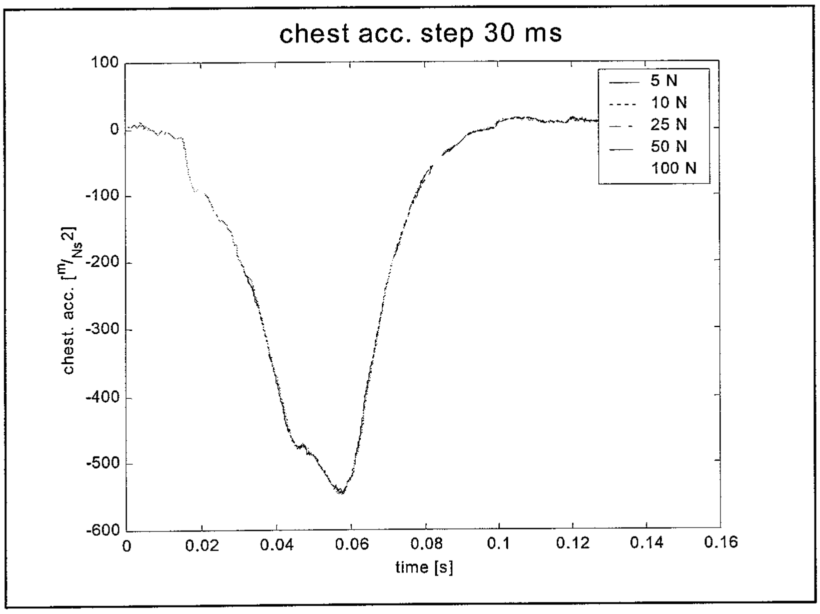

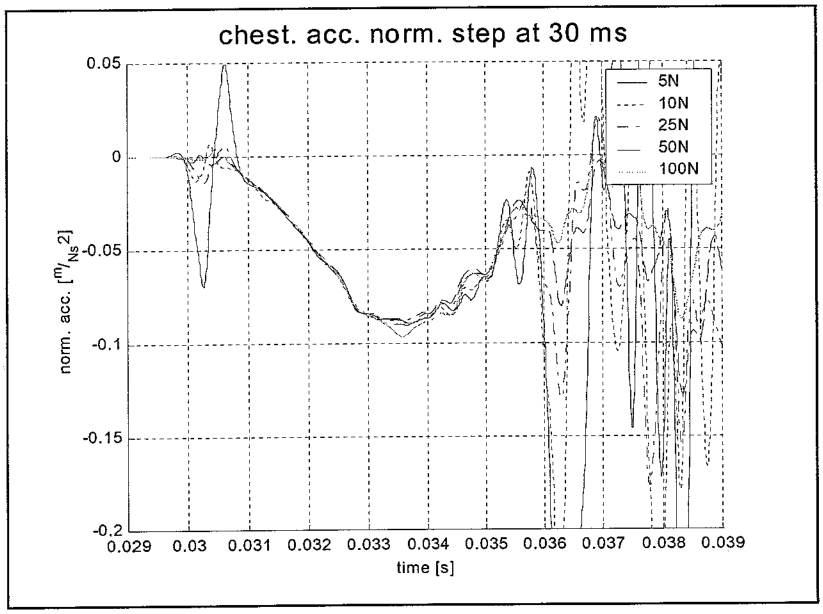

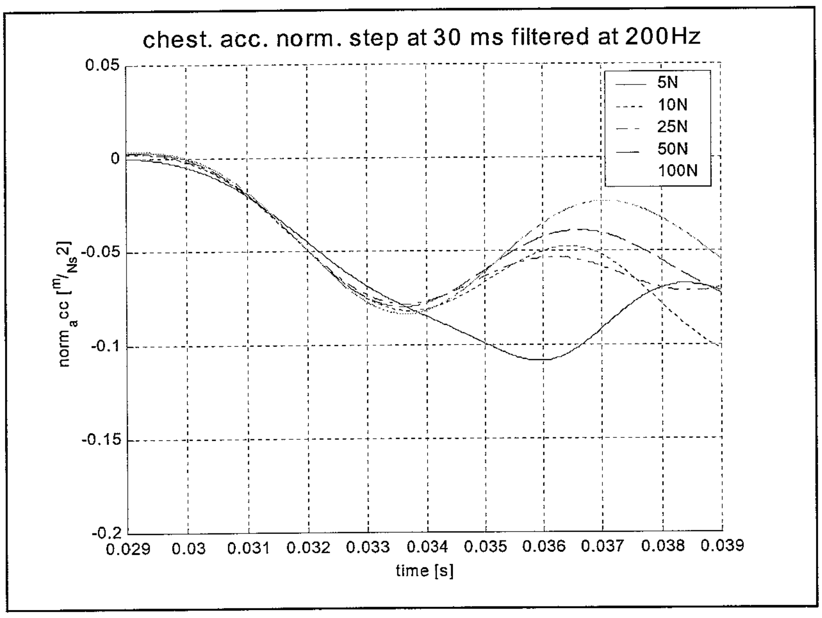

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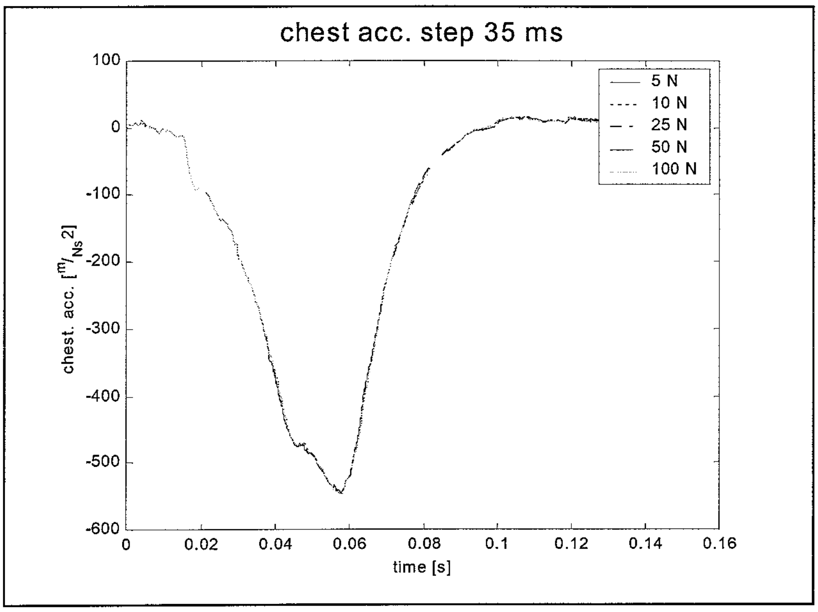

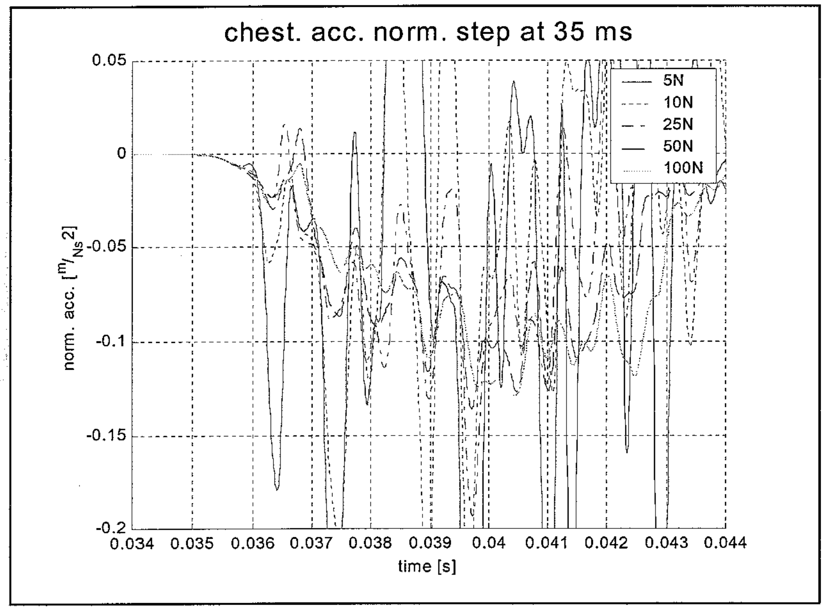

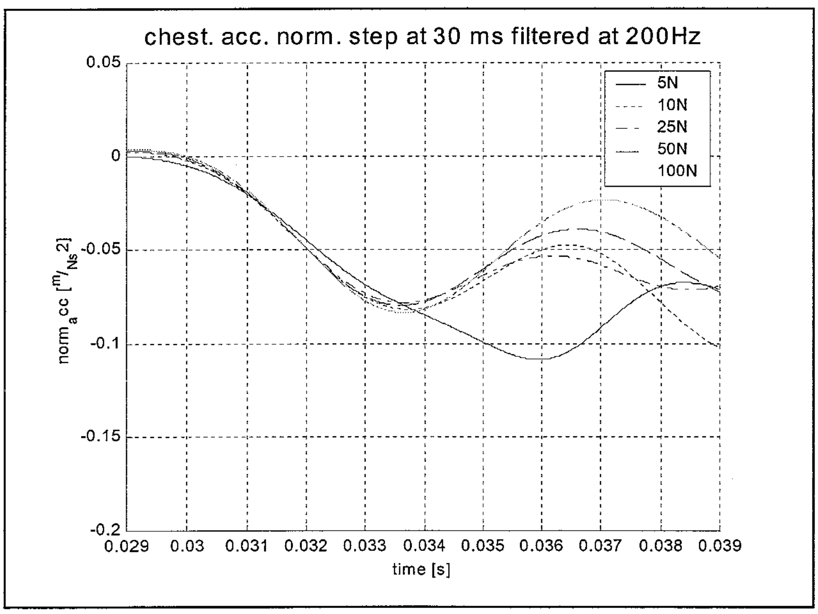

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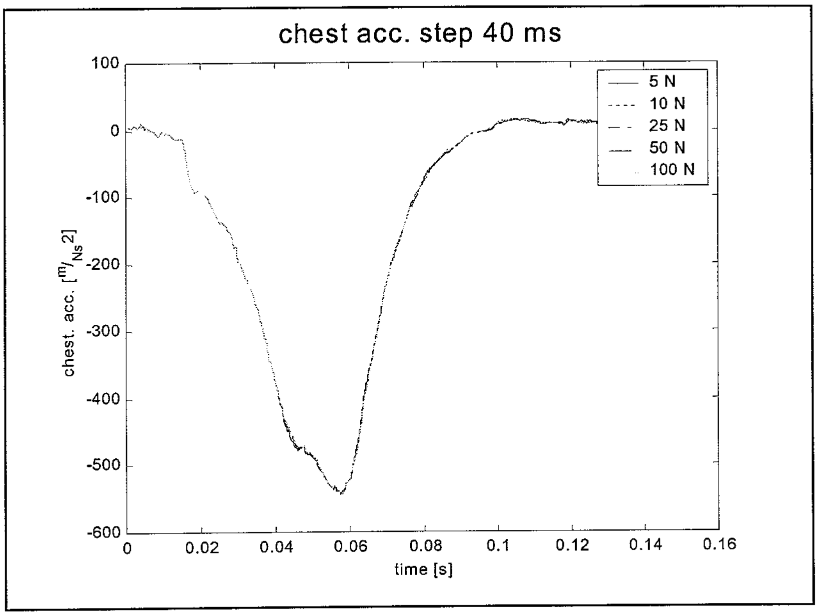

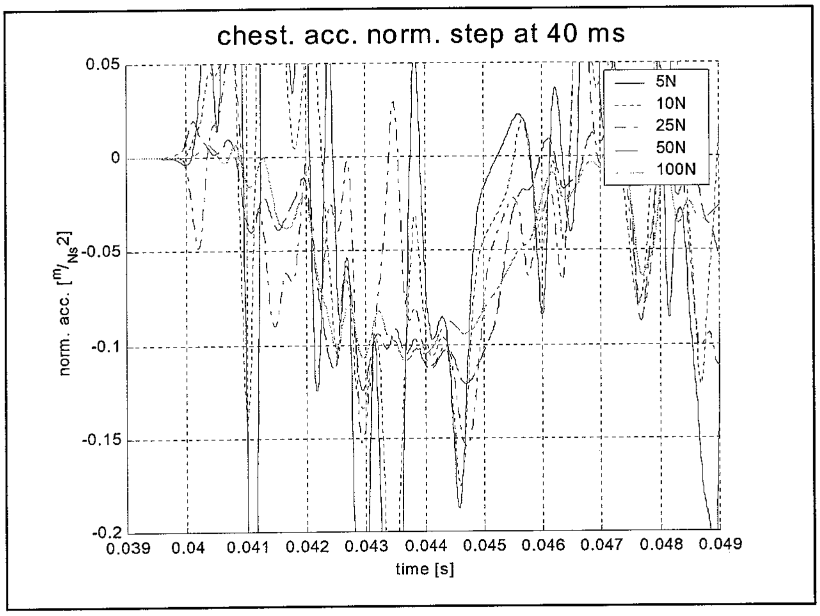

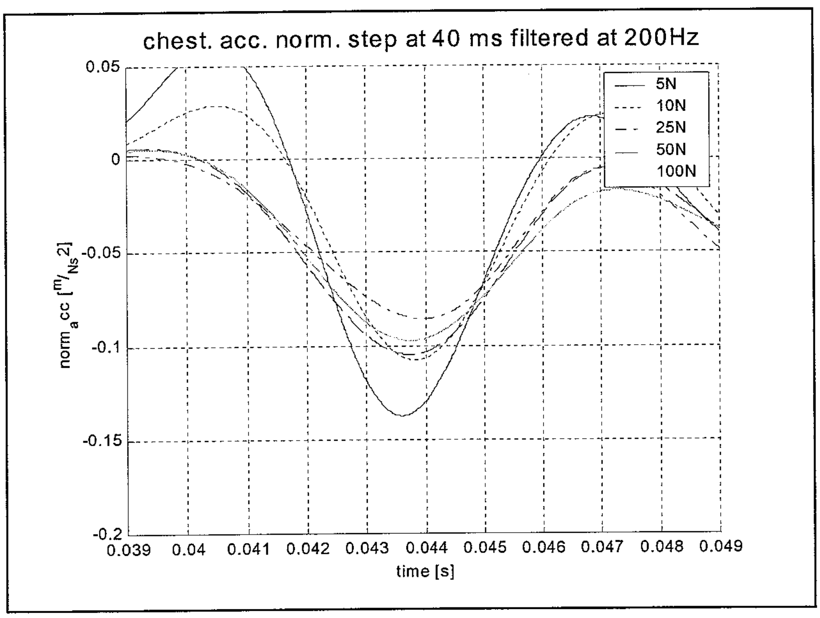

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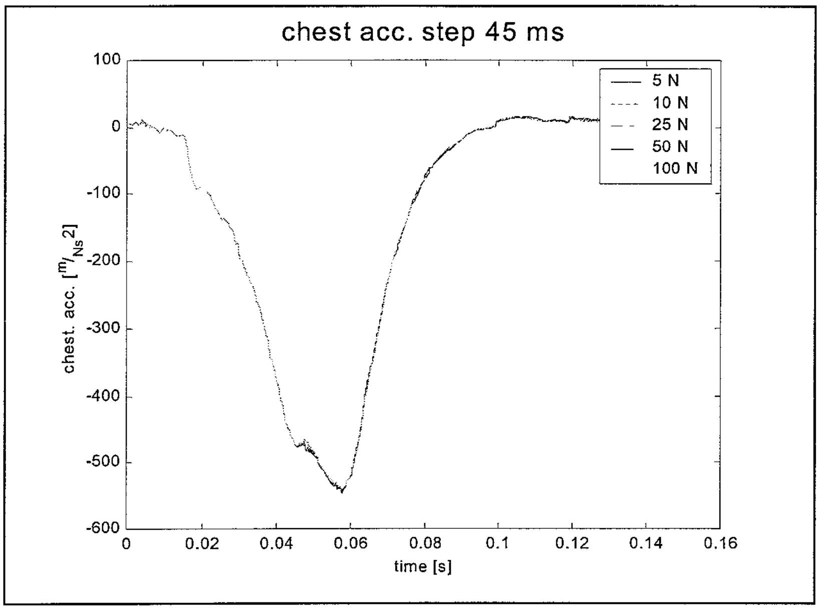

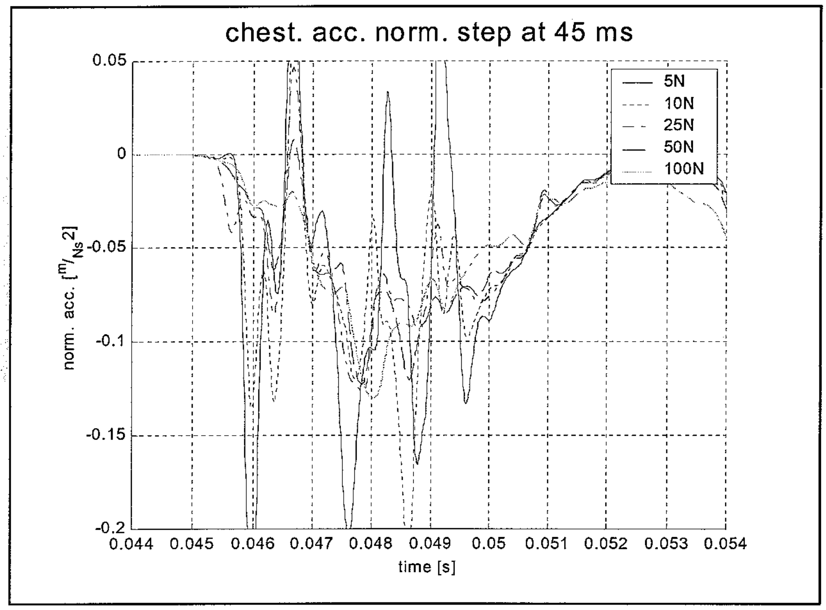

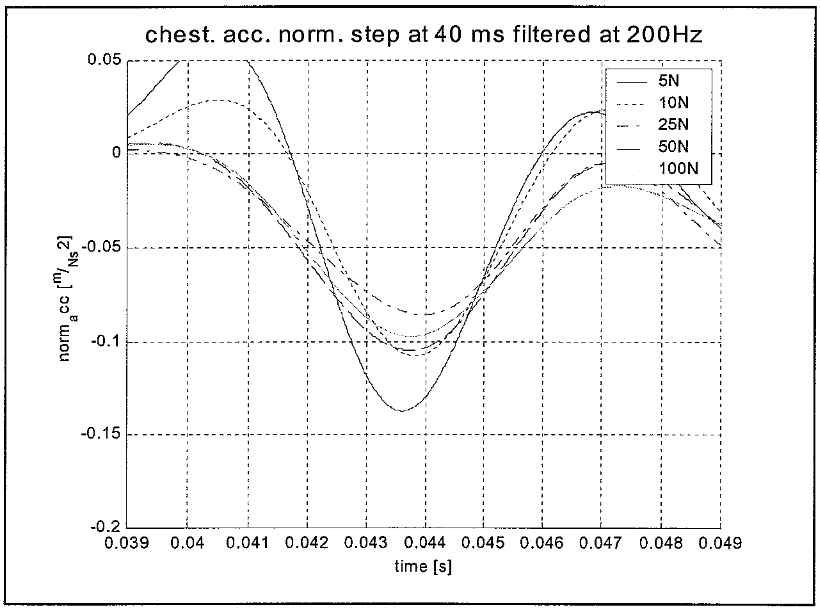

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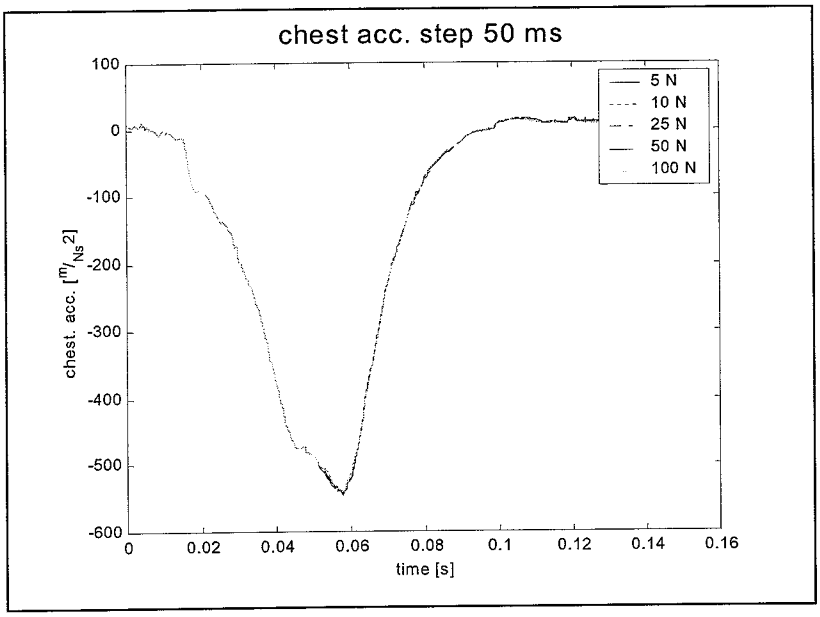
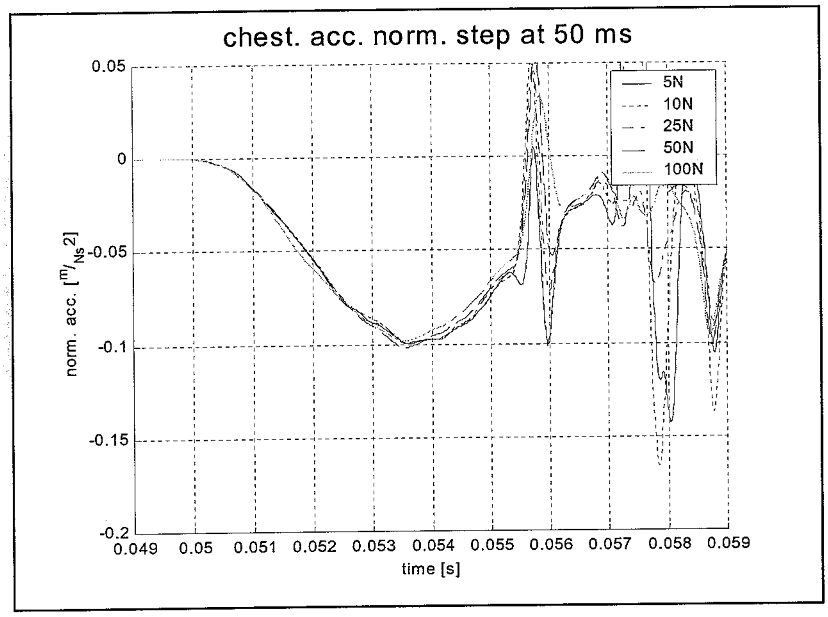
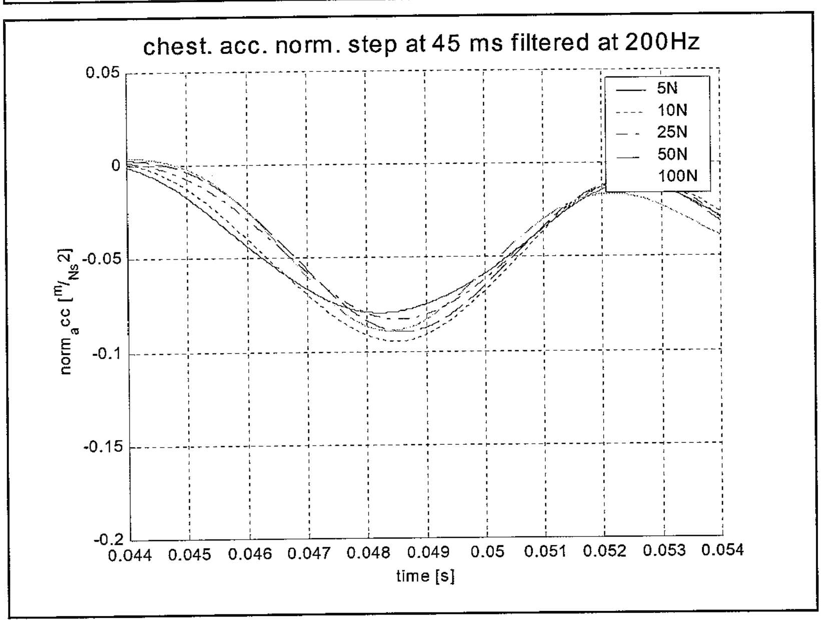
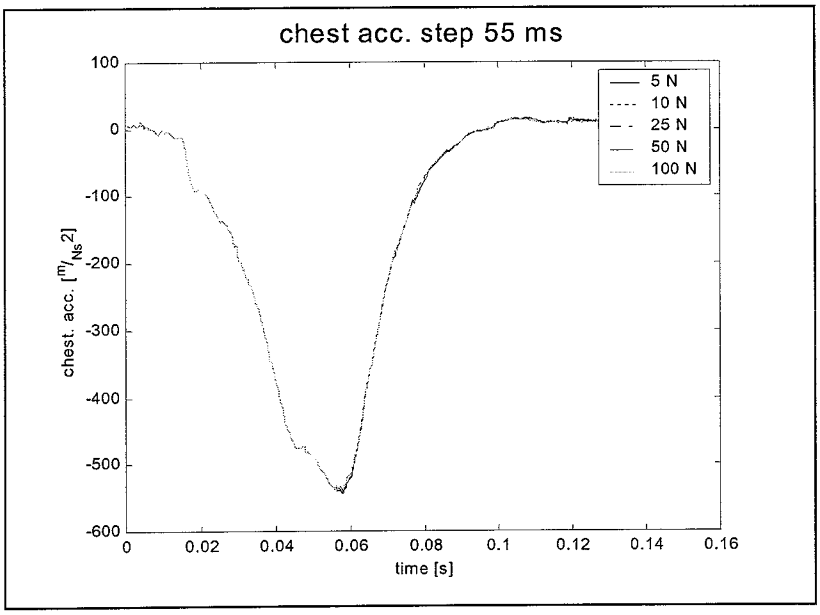
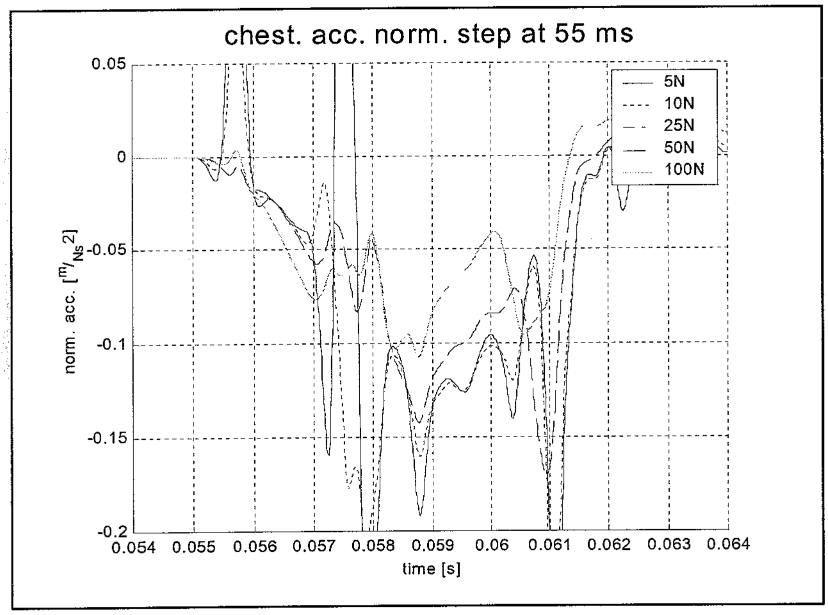


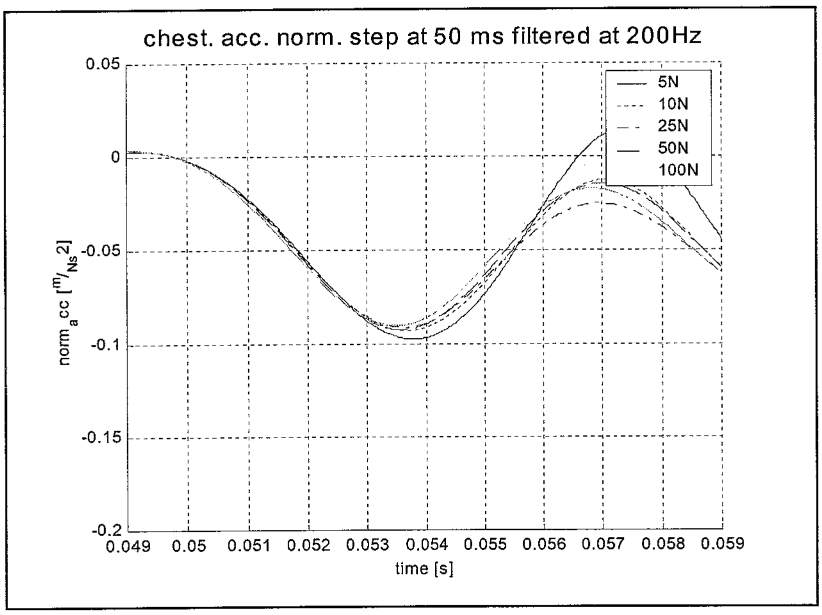




Supplement b, all stepresponses for the 5% dummy with airbag







Supplement , all stepresponses for the 5% dummy with airbag