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FACULTY OF MECHANICAL ENGINEERING

DOCTORAL THESIS STATEMENT

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DEPARTMENT OF MECHANICS, BIOMECHANICS AND MECHATRONICS

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New advanced methods in side crash testing

by
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Abstract

This work follows up the previous work regarding the used methodology in the field of passive safety, ie. crash testing. The work is based on experience gained in the Active Lateral Impact Simulator (ALIS) project and describes complete process. As the mechanical and geometrical parts have been already discussed in previous work, the main focus has been shifted to the fine-tuning of the boundary conditions and loading of the system in order to ensure correct biomechanical loads. It has been already decided that only pole strike is of interest and therefore the barrier strike will not be assessed and developed.

This work is to give an overview of current methodology and subsequently propose a new advanced approach of combined virtual and physical testing. The main idea is to reduce development time and associated costs by using sled testing which used to be used mainly for physical simulation of frontal crashes. Simulation of side crash in sled environment is not a brand-new topic, but certainly very complex one. This method is not really used on regular basis especially due to predictability issues and low accuracy. This work presents new approach of combination both virtual and physical testing. The whole process starts with full crash simulation, goes through conversion of virtual model to reduced sled model, sled testing and finally is wrapped up with full vehicle crash.

The new method uses mathematical-statistical method Design of Experiment, that offers many benefits for the physical test setup and furthermore the general overview of the sensitivity of system behaviour.

Keywords: crash test, finite element method, design of experiment, biomechanical loads, DYCOT, ALIS

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1. *Introduction*

Since the very beginning of the automotive era, the car has been mainly considered as a mean of a transport and as a scale of a social level. It has reached back as far as to the 17th century, to 1672 to be exact, when Ferdinand Verbiest [1] built the first steam-powered vehicle, however it has been intended to work as a toy. The first “real” vehicle was built in 1873, when Amédée Bollée built a self-propelled vehicle for transport of a group of people.

As cars were becoming complex and faster, safety issues have become more important due to the increase of fatal injuries among drivers and people around cars – pedestrians and members of traffic.

The first barrier crash test [2] was performed by General Motors in USA in 1934. In 1949 the first crash dummy, Sierra Sam, was created and used for evaluation of aircraft ejection seats on rocket sleds.

Principle of crash tests

The principle of the crash test is to understand kinematics and dynamics of the impact itself. With first crash tests in the second half of the last century, they have assessed structural behaviour of the vehicle only with output parameters such as deceleration and intrusion. Later on, the effect of the crash on human body has been put forward and so the first dummies have been developed. Nowadays there are many types of dummies. Each of them represents different “human body” and allows different biomechanical parameters to be measured and they are intended for different crash event.

Mandatory and consumer crash tests

Mandatory tests have been established by governments to ensure minimal safety and all vehicles have to meet their criteria. Each country/region has its own tests (e.g. EU, USA, China,…), nevertheless they differ only in several cases. The base is pretty much the same everywhere and so is the occupant protection. Mandatory tests have two results – pass or fail

Test facilities around the world

This chapter is to give a brief overview of current test labs around the world that actively use sled systems for side crash simulations. All labs have been using principles that are mentioned in Chapter Literature survey [20]. In Seattle USA, Seattle safety uses system as described by Dix et al. [19].

Another lab that is situated in USA belongs to Instron. It is not only manufacturer of the side crash sled system, but it is also manufacturer of the complete sled solution. Other labs are based in Europe. Continental in Germany uses exactly the same principle and adds the modification of the side door when it may deform in certain way via hinges and links.

There is another lab in Germany that offers side crash sled testing. It is ACTS GmbH, that is connected to the MAGNA Group. They use the principle as proposed Aekbote [13] with single hydraulic cylinder fixed to the door. Cylinder has got controlled displacement.

Finally, Austria houses DSD lab. DSD has developed known ASIS with principle proposed by Kinoshita [21] and also Kinoshita [23]. ASIS can use up to 9 cylinders and can be mounted on the sled. It is the closest device to the one TÜV SÜD Czech and ENCOPIM are developing.

To sum all previously mentioned up, it is clear that this kind of side testing with controlled intrusion of the door trim is very demanding and no papers are currently presenting such complex approach that joins both virtual and physical testing. This work is to fill such a gap in publications and methodology. It is very important to quicken and to get cheaper the complete car development cycle while the restraint system tuning would be more accurate and convenient.

2. *Aims of the Thesis*

Due to large amount of physical crash tests there is a high demand on reducing the problem size. That would allow quicker and more accurate finite element correlation, restraint system tuning (airbags, seatbelts) and more convenient dummy positioning.

The main objective of the thesis is to develop virtual method of real side impact sled test with corresponding biomechanical loads that would reflect the full vehicle crash test. It should also shorten necessary development time and improve predictability and accuracy of both physical and virtual testing and hence significantly reduce costs associated with vehicle development. Finally, the output would enable complex tuning of restraint systems which are currently difficult.

Outcome of this work will be ALIS test setup and sensitivity study of the whole system behaviour.

2.1 Objectives

In order to reach main objectives, a new approach that uses virtual method and mathematical apparatus that would determine complex system setup has to be suitably implemented. It may use an advanced mathematical model for results evaluation and sensitivity and robustness studies. Following partial objectives are necessary to fulfil to reach the main objective (also shown on Figure 31):

1. Take over initial complete side crash simulation of virtual car
2. Evaluation of objectives and model size reduction
3. Creation of ALIS virtual model and setup
4. Initial determination of physical setup input parameters of ALIS via Design of Experiment (DoE)
5. Successful physical test
6. Comparison of sled test and full vehicle crash

Design of Experiment will be used for sensitivity study of the experimental design. The question is if we apply DoE to the virtual simulations, we expect to get rather detailed insight of the system behaviour and response sensitivities. The idea is to tune ALIS and sled control pulses so well that we will get the biomechanical results very similar to the simulation results of full vehicle.

3. *Method and experimental devices*

3.1 DYCOT

TÜV SÜD Czech has recently invested a large sum to test lab equipped with sled system (catapult) – DYnamic COmponent Testing (DYCOT) [5]. Sled test system consists of sled with grid holes and pusher sled, where all electronics and measurement equipment is mounted as also shown on Figure 1. The pusher sled is being pushed by CSA catapult, equipped with hydraulic piston that can accelerate the sled by up to 90G to total velocity of 100kph with payload of 1000kg. When fully loaded (payload of 5000kg), the piston is capable of accelerating the sled up to 35G. Maximum force is equal to 2.5MN. Maximum acceleration gradient is 14G/ms.

Figure 1: DYCOT sled test lab

It is usually used for frontal crash test where the occupant safety is being tested. It can also be used for testing of crash-landing of any small airplane that would fit in the lab. Latest addition to the service portfolio is battery pack testing for any battery packs up to 1000kg.

3.2 ALIS

The capabilities of DYCOT sled system have been significantly increased by adding ALIS into serie, right next to the sled platform. It uses up to 6 hydraulic cylinders in order to correctly simulate the door intrusion kinematics during the side crash. It enables one to use only small part of the car together with dummies and restraint systems and carry out simulation of the side crash with focus on restraint system and biomechanical loads.

The system may seem as a “train of trolleys”. The driven sled trolley is mounted to the main hydraulic system that generates the main acceleration pulse. ALIS is mounted on the separate trolley, attached to the sled. The whole structure is shown on Figure 2, where main components are identified. The lateral system consists of additional pneumatic system directly attached to several pneumatic cylinders, ALIS primary structure and control system, linear guiding system and “impact break-in structure”.

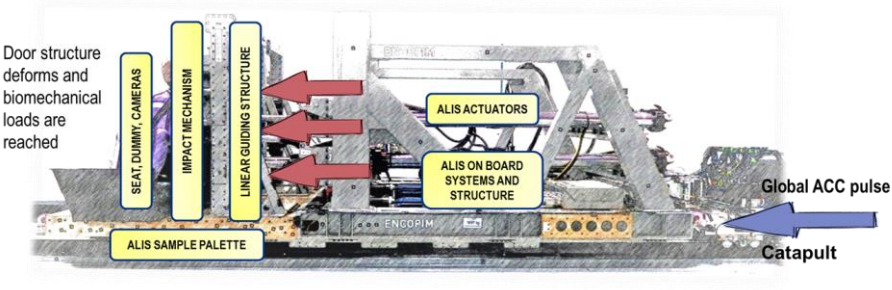


Figure 2: DYCOT + ALIS concept [A01]

3.2.1 Principle of ALIS [31]

The basic principle is to accelerate the sled with ALIS attached according to the real side crash pulse while the cylinders push forward through linear guide into the "impact structure". It should then cause exactly the same intrusion and kinematics of the door system, ie. biomechanical loads (=replication of the physical test). The source data will be extracted from full vehicle crash test and sled test simulations via FEM.

The main idea is to perform simulations before the physical testing loop to ensure the correct kinematics and structural behaviour reflect physical test. The simulation would determine parameters such as amount and position of cylinders used; timing, shape and magnitude of the pulses. These will be then used for the physical test of reduced model. The method is unique due to its limitless options of simulations. It will save time, money and help engineers with restraint systems tuning. Currently the process of tuning of side and curtain airbags is extremely time-consuming and expensive (painful). The approach is based on using only part of a car and it is a combination of physical and virtual methods. It is clear that every vehicle will require unique set of input parameters as well as impact structure.

3.2.2 Methodology

The whole process starts with FE simulation of full vehicle crash and is shown on Figure 3. Output is to be biomechanical loads, intrusion and kinematics of important structural parts such as doors, A- and B-pillars.

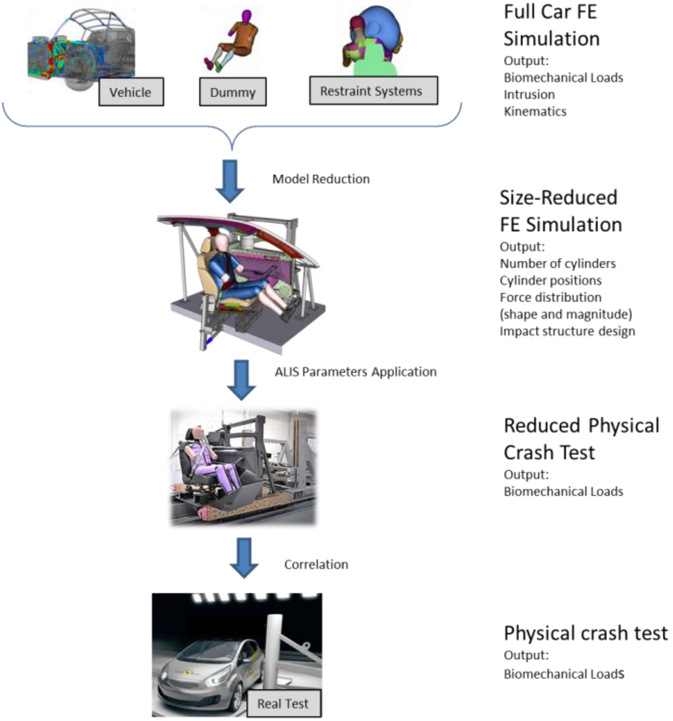


Figure 3: Real crash to ALIS reduction procedure [31] (Courtesy of Škoda Auto)

4. *Design of Experiment theory*

This chapter introduces methods used in this thesis for sensitivity study. It considers application of mathematical and statistical tools in right order and highlights the chosen options that are used latter in the thesis.

4.1 Introduction

Design of Experiment is a systematic process of understanding the effect between inputs and outputs, ie. parameters, variables and responses (results). It is a method that uses mathematical statistical-optimization apparatus to identify level of contribution of variables to responses. It is very common in many industry fields, where processes, design or simply anything that can be mathematically described are used. DoE enables one to study calculated and predicted responses based on variables within certain limits – design domain. It also allows one to understand mutual effect of any variable to any parameter and hence to understand the complete system behaviour.

The classical DoE has been developed by Sir Ronald Fisher in early 1920s, who was an agricultural engineer who conducted many experiments with various fertilizers on different lands. He has started to use DoE to differentiate effect of fertilizers and of other factors. Even though the DoE was developed almost a century ago, it has not been widely spread as one would anticipate. Nowadays it is not common to use DoE during development regarding products from a mass-production.

Many use DoE to understand very complex systems and their behaviour with wide range of input variables and responses. That leads to reduction of price and time as well as higher effectiveness of such processes, eg. quality of products.

5. Results

5.1 Results of DoE

As DoE is a multipurpose tool that identifies mutual effect of input variables/parameters and related responses. Durakovic [44] has presented a very good overview. It is regression analysis used for following tasks:

- Comparison – multiple comparisons for the best option selection that uses t-test, F-test or Z-test
- Variable investigation – defines and determines which variable has an (in)significant effect on overall performance and/or behaviour of the respective system
- Transfer function identification – it is not necessary to completely understand the complete process; the transfer function can be determined based only on input and output data. One does not have to get a complete overview and the "black box" is simply defined by a mathematical function
- Optimization – optimization of the system behaviour/performance via either ideal variable combination or optimized transfer function
- Robust design

5.2 Results of the virtual experiments [A04]

So far we have been preparing ourselves for the main task. To choose suitable variables from all available sources to achieve the intended responses. Now, when the response surface has been created and validated, the selection of variable that would fit the intended values follows.

The main reason of the virtual experiments is to perform sensitivity analyses that would later give a good knowledge of the system behaviour. This is particularly useful during the physical testing, when quick response to the current behaviour and recommendation of the next steps is highly expected and there is no time for further simulations. In order to get ideal pulse configurations for respective biomechanical responses, it is necessary to set the target. EuroNCAP assessment is based on scoring system of the maximal biomechanical loads.

For illustration there is a comparison of initial ALIS run, with all variables equal to 1, and full crash model shown on Figure 4.

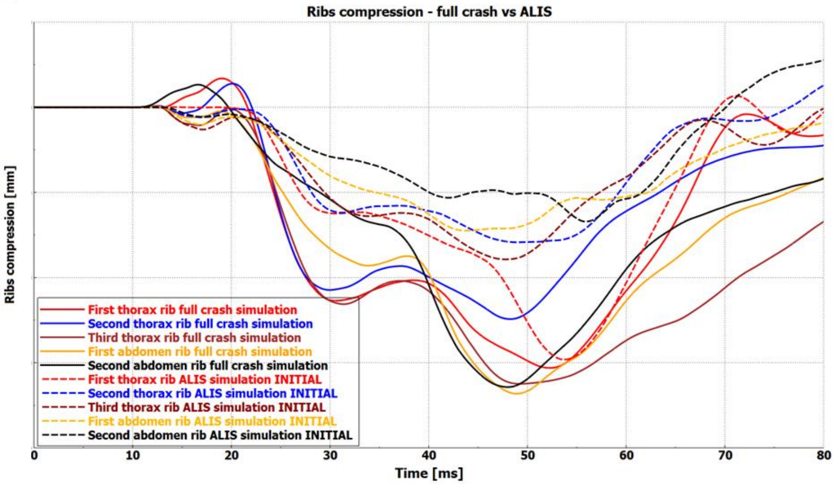
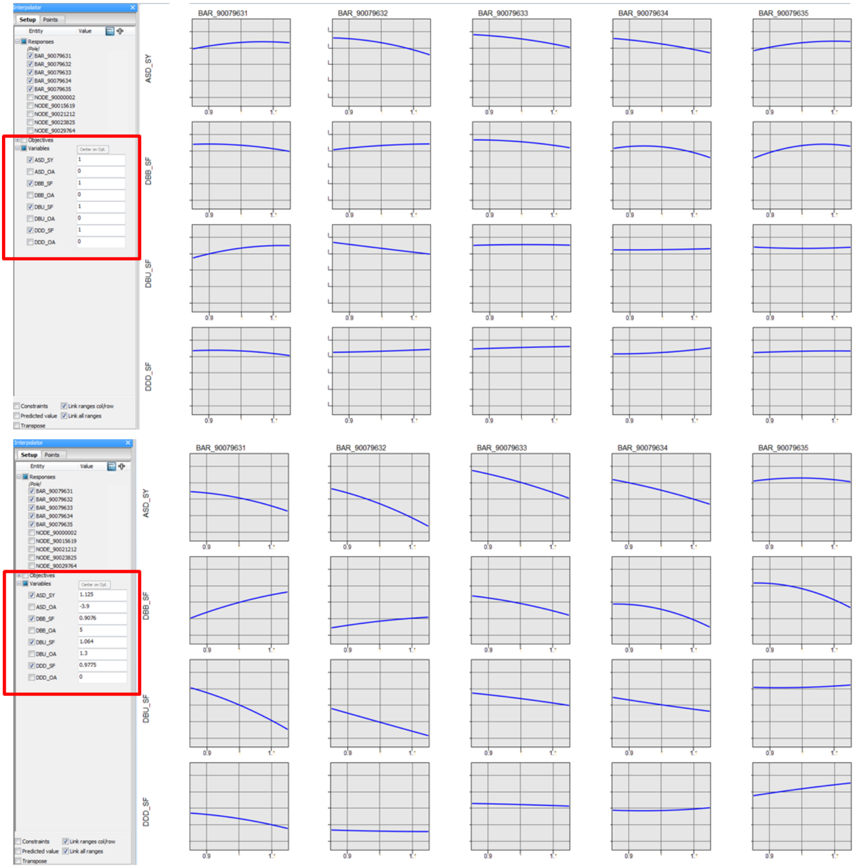


Figure 4: Comparison of initial ALIS vs full crash results (ribs)

The match is not ideal one at the moment and our goal is to get better match. Hence there has to be an update done of some or all available pulses (scale factor or offset). The suitable variable combinations can be found by user to achieve his requirements. LS-OPT can easily predict response values based when one changes the input variables. as indicated on Figure 5.


Top — Variables:
☑ ASD_SY 1
☐ ASD_OA 0
☑ DBB_SF 1
☐ DBB_OA 0
☑ DBU_SF 1
☐ DBU_OA 0
☑ DDD_SF 1
☐ DDD_OA 0

Bottom — Variables:
☑ ASD_SY 1.125
☐ ASD_OA -3.9
☑ DBB_SF 0.9076
☐ DBB_OA 5
☑ DBU_SF 1.064
☐ DBU_OA 1.3
☑ DDD_SF 0.9775
☐ DDD_OA 0

Figure 5: The response trends based on initial variable combination (top) and response trends based on update variable combination (bottom)

5.3 Results of the physical experiment

When to complete setup is ready, standing on sled tracks, fully instrumented and checked by test executive, the ALIS pneumatic tanks as well as the catapult get pressurized and ready for shot. Several learning shots have to be made in order to teach the system desired pulses. All the important happens within 0.1s. After the shot, technicians receive the raw data from all sensors and camera feeds. These data have to be post-processed as well. Complete relevant biomechanical results are shown on Figure 6.

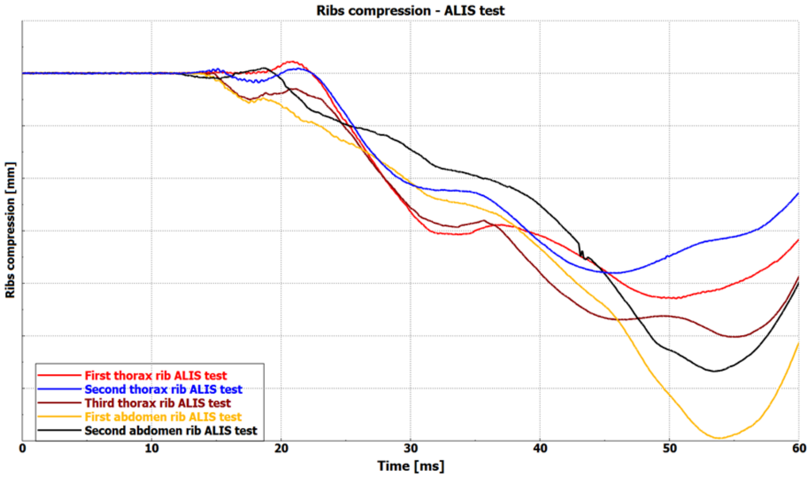


Figure 6: Biomechanical criteria tested on ALIS

5.4 Comparison

There is a last missing piece into the mosaic, and it is the overall comparison and evaluation. Since we have mixed several inputs and outputs, it should be mentioned once again what has been used and how it gets into the frame of complete process.

There are following types of results in chronological order:

- Full virtual crash
- ALIS virtual test
- ALIS physical test
- Full physical crash

The example of results comparison is shown of Figure 7, where the thorax rib is compared among both virtual and physical tests. As most of the safety engineers are aware, side crash simulation has lower accuracy than frontal simulations. The final results can be only as good as good are inputs. This means, that there is a certain error in simulations compared to the physical test and everyone knows about that.

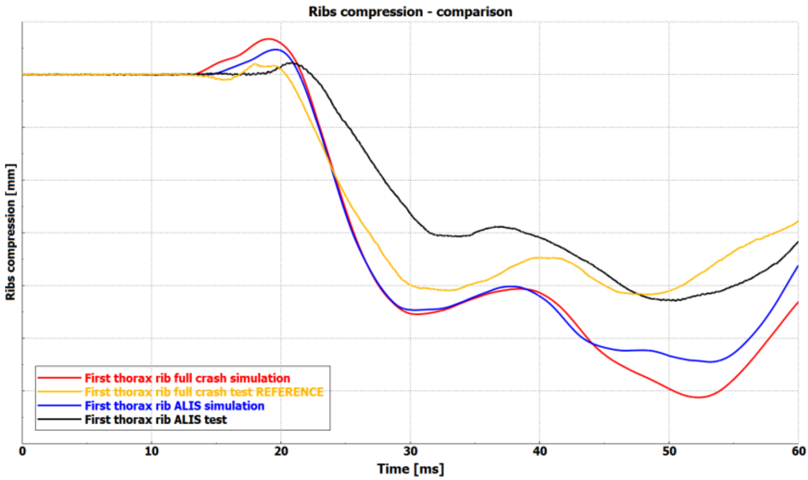
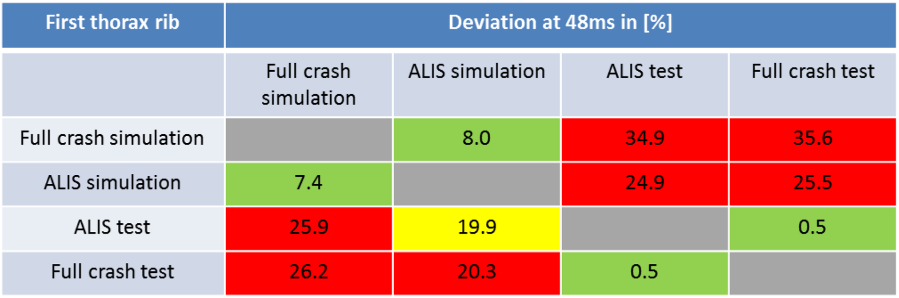


Figure 7: Comparison of rib compression – first thorax

For brief comparison, Table 1 presents deviation of all types of tests that are cross-table referenced.



First thorax rib	Deviation at 48ms in [%]			
	Full crash simulation	ALIS simulation	ALIS test	Full crash test
Full crash simulation		8.0	34.9	35.6
ALIS simulation	7.4		24.9	25.5
ALIS test	25.9	19.9		0.5
Full crash test	26.2	20.3	0.5	

Table 1: Comparison of the first thorax rib results

Comparisons however also show, difference between physical and virtual testing. On the other hand, the difference of full side crash simulation vs. physical test is fairly similar to the difference of ALIS simulation vs. ALIS physical test which is the main objective. This fact is also displayed in Table 2.

Name	Deviation of	Deviation at max value	Deviation of	Deviation at max value
First thorax rib	ALIS simulation vs full simulation	11.2%	ALIS test vs full crash test	3.2%
Second thorax rib	ALIS simulation vs full simulation	10.6%	ALIS test vs full crash test	7.4%
Third thorax rib	ALIS simulation vs full simulation	8.5%	ALIS test vs full crash test	37.4%
First abdomen rib	ALIS simulation vs full simulation	12.4%	ALIS test vs full crash test	7.5%
Second abdomen rib	ALIS simulation vs full simulation	1.4%	ALIS test vs full crash test	1.1%

Table 2: Quantified deviation between the test results

There are three ranges of acceptance:

- Green - Deviation within 10% is considered as a very good match
- Yellow – deviation between 10%-20% is considered as a decent match
- Red – deviation above 20% is considered as not good correlation with the physical test

It is also clear that not all of the absolute values have been reasonably achieved, except for the third thorax rib, but as ALIS is only a sled reduced representation of the full vehicle crash, there is no such ambition. It is obvious that ALIS has got only several actuators that try to generate the same conditions, whereas in full crash there are unlimited “actuators” and therefore it is impossible to replace crashes fully by sled testing only. Sled testing is only an add-on to the full crash testing. This is also why no legislation, nor consumer tests allow purely sled testing. Simply it cannot substitute the full vehicle crash tests.

6. *Results for science and praxis*

6.1 Results for science

The main accomplishment is combination of newly developed methodology with DoE application into the automotive industry. It opens broad options for other applications.

6.2 Results for practice

Main advantages for the practice can be seen in less time demanding and so less expensive development and swifter testing. Also, less prototype parts for the testing are required. Should the approach be used in broader scale, it may get cars and other vehicle affordable to more people.

7. Conclusions and future work

7.1 Conclusions

In this work the ALIS has been introduced as well as current car development cycle. It has been showed how ALIS can speed up the development while decrease costs. Several nowadays solutions for sled have been presented. The literature survey has clearly implied that there is a similar approach for physical testing, however with very little computational effort. ALIS potential has been presented and new methodology suggested. Fundamentals of Design of Experiment have been selected and presented. DoE approach has been then applied during the computational part in order to determine ALIS physical setup and also to prepare sensitivity study for later testing. Finally, the results from all testing phases have been extracted and compared.

This work is to give an answer to the question, whether computational testing can support the physical testing with sufficient accuracy and predictability. It has been proven that DoE approach is able to assess the necessary data from experiments and turn them into physical test inputs.

To sum all up, the evaluation of all partial objectives is below and chapter numbering is referring to the thesis content:

- Stage 1: Take over initial complete side crash simulation of virtual car – All information and solutions are available in the Chapter 5.1.1. This stage is completed.

- Stage 2: Evaluation of objectives and model size reduction – This stage is completed, and all information and details are in Chapter 5.1.2.

- Stage 3: Creation of ALIS virtual model and setup – Chapter 5.1.3 is dedicated to this stage. Several sub-tasks were defined and also this stage is completed.

- Stage 4: Initial determination of physical setup input parameters of ALIS via Design of Experiment (DoE) – Chapter 5.1.4 is the backbone of the thesis and gives comprehensive information about the overall solution. This stage is completed.

- Stage 5: Successful physical test – This stage is described in chapter 5.1.5 and its status is completed.
- Stage 6: Comparison of sled test and full vehicle crash – Final results are presented in chapter 5.1.6, where all four models are compared, and conclusions are presented. This is also completed.

This work is also summarized and published in ACTA Polytechnica [A03] and International Journal of Crashworthiness [A04]. Furthermore, it will be presented on global engineering conference FISITA 2021 [A05] held in Prague.

7.2 Discussion

During the writing the thesis I have realized how many enhancements and additional topics this work generates. It has been purely focused on implementation of DoE into presented methodology. It should be noted that our assumptions are based on only one experiment and one analysis. It would be very useful to get more experiments and get better statistics.

As crash engineers may be also interested in biomechanical distribution over time and not just maximal values, it can be of interest to apply so-called curve matching function/algorithm, that would further improve the pulse settings and hence whole accuracy of the ALIS.

Additionally, implementation of curtain airbag, which is integral part of the testing seems necessary to offer even more accurate overall results.

It also leads to further work regarding angle of impact for side pole loadcase. It may turn out that currently used 15° is not the ideal for sled system and the optimum can be between 0-15°. This work also opened new questions, regarding localised floor wrinkling and hence lateral tilting of the seat and dummy.

The Design of Experiment is currently being used mainly in aerospace industry. From my point of view, it is very powerful tool for automotive sector as well due to many combinations of restrain system that is fine-tuned to its perfection.

This work should inspire any engineer to adopt DoE in their own work to push the limits of simulations and physical testing and find the good weighing out between them as they have to always go together in parallel to get best results.

The thesis proved that suggested approach is feasible. It is possible to use model reduction approach together with mathematical apparatus to solve side crash test on sled device. There are a lot of areas of the reduced model representation to be improved, such as design of mechanism, including rigid bodies and more accurate boundary conditions and so on to achieve better representation of the full crash model.

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