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FUTURE PERSPECTIVES ON AUTOMOTIVE CAE

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ABSTRACT – Computer Aided Engineering (CAE) is an integral part of today's automotive design process. Very often OEM's rely solely on software vendors to provide appropriate solutions. On the other hand, some companies still use in-house developed software for specific applications. It is, however, a combination of these two approaches that provides OEM's with optimal leading edge software technology. This paper will present an overview of several relevant automotive CAE-methods that will illustrate this approach. Four important automotive software areas will be considered: vehicle CFD applications, aeroacoustics, vehicle crash analysis and occupant / pedestrian safety. The first two topics, CFD and aeroacoustics, are extensive subject areas in themselves, but will be dealt with by considering two specific topics, namely, numerical aerodynamic / flow optimization and aeroacoustic sound propagation into vehicle cabins, respectively. A more detailed focus will be placed on the two safety application areas: vehicle crash analysis and occupant safety using Human Body Models.

1. INTRODUCTION

Automotive OEM's extensively use CAE-Methods in almost every aspect of the design and development process. Software companies supply OEM's with excellent simulation tools; however, some OEM's also use in-house codes for special applications. A combination of both approaches ultimately gives the OEM the competitive advantage. Moreover, no matter how good software is developed, CAE-analyst's quickly discover limits of the theoretical modelling and numerical approaches utilized for a given software. There are three levels of CAE from the OEM perspective: 1) basic algorithm modelling and numerical methods research, 2) integration of the CAE-method into the development process including the coupling CAE-software to optimization tools and 3) the active application of the CAE-method in the day-today design and development process. This paper deals with the first level, namely, CAE-methods research.

In order to conduct effective CAE-methods research, a first prerequisite is to have a team of technical experts for a given field that has both an excellent theoretical and numerical background but also has a solid knowledge of the underlying physics involved. This also includes knowledge of the experimental methods utilized for the validation of the CAE-methods themselves. Another important factor is support from leading technical universities, research institutes and programming experts. Critical issues include license fees for both sequential and co-simulation applications and for massive parallel HPC solver usage. The usage of open source software is an effective means to overcome expensive licence issues.

This paper will present CAE-methods research for four relevant automotive areas: aerodynamic optimization based on the adjoint method, aeroacoustic sound propagation into the vehicle cabin, vehicle crash analysis and vehicle occupant safety based on Human Body Models (HBMs). A theoretical overview of each of the mentioned areas, including examples of current applications and discussions of future perspectives associated with each topic will be presented.

Recent advancements of the adjoint optimization method have resulted in a new paradigm in the area of vehicle aerodynamic optimization. The adjoint method is a powerful tool for computing sensitivities which can be applied to both internal and external flows. An open source Computational Fluid Dynamics (CFD) code has been developed that allows both topology and shape optimization based on sensitivity maps. An overview of the adjoint method will be discussed along with several applications ranging from internal pipe flows to external vehicle aerodynamics. Validation of the numerical method based on experiments for the Volkswagen XL1 vehicle will also be presented.

When considering vehicle cabin acoustics, the effects of wind noise become dominant for the sound pressure level at mid to high vehicle speeds. Due to highly turbulent flow separations on the A-pillar and side mirrors, strong hydrodynamic and acoustic window excitation close to the driver's ear occurs. Recent experimental and numerical investigations have shown that there are two "types" of sources for the pressure loadings on the window: the hydrodynamic pressure which results from the incompressible high energy part of the turbulent flow field, and the acoustic pressure which is an exterior acoustic sound field caused by the compressible part of the turbulent flow field. An overview of current numerical methods available for simulating the combined acoustic loading mentioned will be presented.

The 3rd topic presented in this work focusses on the field of structural crashworthiness, where the demand for lighter vehicles drives the automotive industry to develop new materials and production processes. One of these recent innovations is the hot stamping process, which allows the production of partially hardened, advanced high-strength steel components. Due to the high tensile strengths of hot stamped materials, weight reductions are possible while maintaining, or even improving crashworthiness properties. By introducing regions of reduced strength and higher ductility, the energy absorption capacity and the risk of fracture can be locally improved. To be able to fully exploit the possibilities of these modern hot stamped steels, it is of paramount importance to attain accurate predictive models of their crash response. Therefore, a hardness-dependent material model is presented that is implemented in the Volkswagen Modular Material Model (MMM) framework for an explicit commercial FEM code. The model describes the crash-relevant material behaviour of tailored hardened components, including transition zones between more ductile and fully hardened areas.

The last topic presented here focusses on the field of virtual HBMs in Automotive Safety simulations. These models can be used as an additional tool to get more detailed information about the kinematics and injury effects on the human body. For the crash phase, the contribution of muscle activation is less; therefore, passive HBMs like the occupant and pedestrian Total HUman Model for Safety (THUMS), can be used for injury analysis. Muscle activation, however, must be taken into account to predict occupant motion in low g pre-crash manoeuvres triggered by assistance systems, for instance autonomous braking and steering systems. In this study, the passive THUMS was extended by active muscle models that are able to generate muscle forces. Hill-type elements are used to model the lumbar and cervical muscles as they are mainly responsible for the thorax and head motion control in a low g pre-crash manoeuvre. Pre-crash emergency braking simulations were performed with the finite element (FE) THUMS HBM. The study shows that changing the activation level of the lumbar extensor muscles can lead to different overall longitudinal kinematics of the model.

2. AERODYNAMICS / FLOW OPTIMIZATION

CFD is a central element of the automotive development process. Besides the classical use of CFD for the prediction of the performance of aerodynamic designs (e.g. drag and lift coefficients of vehicles, power losses of air ducts), there is also the need to apply procedures to improve and optimize the performance of those designs. The adjoint method has long been considered as the tool of choice for gradient-based optimization in CFD. The independence of the computational cost from the number of design variables is what makes it particularly attractive for problems with large design spaces. The first systematic application of adjoint methods in automotive CFD took place in the field of fluid dynamic topology optimization. To further drive the adjoint-based shape optimization methodology to the same degree of maturity and robustness and most importantly to new fields of physics such as thermal management, aeroacoustics and unsteady turbulent flows, new research collaboration between the academia and the car industry is needed.

2.1 Implementation of the adjoint method

The implementation of the adjoint method requires access to the source code either to implement the analytically derived adjoint equations into the code (so-called continuous adjoint) or to perform a manual or automatic differentiation of the primal code (discrete adjoint). The well-validated and versatile CFD solver OpenFOAM® was selected as platform to develop adjoint-based optimization methods for car applications. In addition to its open source character, OpenFOAM® comes with a high-level symbolic programming style, which makes it ideally suited to implement additional partial differential equations like the adjoint Navier-Stokes equations. For a detailed description of adjoint methods, the interested reader is referred to [1].

2.2 Validation and application examples

An application of the adjoint method in automotive CFD is the topology optimization of an engine intake port [2] in order to minimize the pressure loss between the inlet and the outlet and to increase the swirl inside the combustion chamber. Depending on the weighting of the two objectives, a reliable increase in swirl compared to a decrease or a relatively modest increase in pressure loss could be obtained. Moving to shape optimization, external aerodynamics is of particular interest through the computation of surface sensitivity maps. The adjoint method was first applied to the Volkswagen XL1, a dedicated low emission vehicle. Despite the already well optimized shape, the computed sensitivity maps suggested shape modifications, which further decreased the drag of the vehicle (Figure 1) [3]. Another field of growing interest is active flow control for aerodynamic improvement. Using the same vehicle as in the shape optimization case study, sensitivity maps have been computed, this time with respect to constant suction or blowing air jets normal to the car surface [4]. The application of jets in the indicated areas resulted in a 2% decrease in drag, a significant reduction for a car like the XL1.

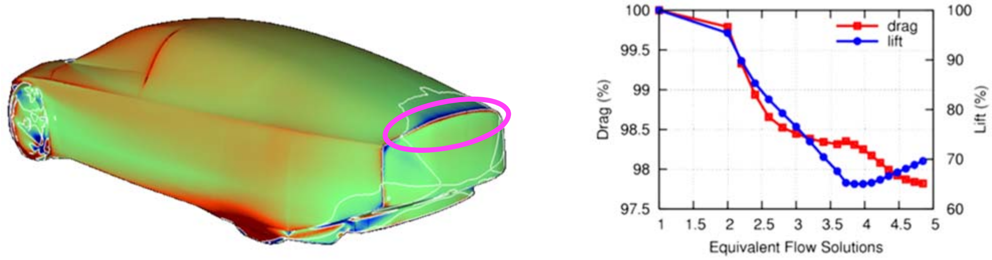

Figure 1: Shape sensitivities for drag of the Volkswagen XL1 model (left) and drag and lift reduction during optimization of the rear spoiler (right).

2.3 Future perspectives

The adjoint method has proven to be a powerful tool for fluid dynamic optimization and is being used extensively in topology optimization of ducted flows. Shape optimization combined with parameter-free morphing is also becoming productive for external flows. Efforts have now been focused on the inclusion of new areas of physics, such as thermal dissipation, a subject especially useful for optimization of internal combustion engines. Moreover, an extension towards inherently transient flow applications such as aeroacoustics, flow control and transient aerodynamics are the next steps to further the adjoint method.

3. AEROACOUSTICS / SOUND PROPAGATION INTO VEHICLE CABINS

For the prediction of interior noise in vehicle cabins arising from the sound radiation from a vibrating window, different physics from aerodynamics, acoustics and structural mechanics need to be incorporated to cover the whole transmission path. Prior studies ([5], [6]) have pointed out the importance of the acoustical fraction for the load on the side window, even if its amount of energy is magnitudes below its hydrodynamic counterpart. This highly increases the demands in accuracy for the CFD simulation of the flow. The reaction of the panel to its loading is a superposition of its excited modes. High efficiency of the excitation is mainly caused by the matching of wavelengths from the excitation spectra and the modes on the panel, which is much higher for the acoustic fraction. This can be calculated explicitly with structural solvers (i.e. FEM) or statistically with energy based methods such as Statistical Energy Analysis (SEA). Figure 2 provides an overview of different paths for simulating the cabin noise.

3.1 Implementation

In general there are two possibilities to capture the acoustic part. On the one hand, there are hybrid methods using acoustic analogies for propagating sound from equivalent sources calculated from an incompressible CFD solution. The second possibility is the use of a compressible CFD solver which inherently contains the hydrodynamic and acoustic part. For this purpose, an OpenFOAM® solver was modified to a weak compressible approach which exhibits the possibility to capture linear acoustics without solving an additional energy equation. For a one step-approach the Finite Area Method (FAM) from the OpenFOAM® Extended Project is used for solving the bending wave equation on the panel based on Kirchhoff-Love plate theory during the flow simulation. The framework is also able to use the resulting vibrations as a boundary condition for the radiation into the cabin. For this objective two methods are implemented: the solution of the wave equation and the evaluation of the Kirchhoff-Integral.

3.2 Validation and application examples

The validation is based on wind tunnel tests which were performed on a full-scale generic test body with a clamp mounted side window. For various settings the interior noise was recorded, providing a convincing database. The side window was replaced by a panel containing 96 flush mounted surface microphones for measuring the excitation force. For validation purposes, the hydrodynamic and the acoustic part can be separated by wave number decomposition. For further reference see [5]. The separated parts can be used for modeling the excitation forces in a SEA model. Results of this path indicated in Figure 2, were presented in [7] and revealed good agreement of the reverberant sound field up to 4000Hz compared to experimental results.

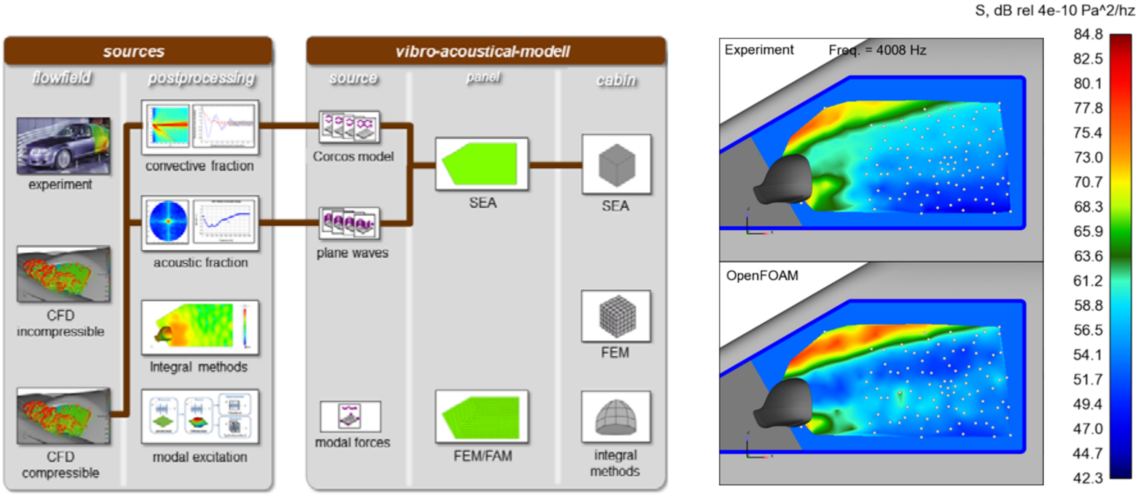

Figure 2: Overview of simulation paths for cabin noise (courtesy of ESI Group) (left) and PSD spectra of fluctuating surface pressure on the side window of the generic test body, comparison of experimental and numerical data (right).

Hammershock tests on a clamped glass panel were also performed for validating the OpenFOAM® FAM solver for the initial response of the panel due to excitation. The accelerations are predicted with high accuracy until reflections from the boundaries reach the measurement position. To capture these reflections further improvement of the FAM solver is required.

3.3 Future perspectives

The presented OpenFOAM® framework is able to fully capture the transmission path of sound into the vehicle cabin. For the prediction of the long term behaviour of the excited panel, additional damping terms need to be included [8]. A lumped spring model [9] will be implemented for reproducing the influence of more complicated mountings found in production vehicles.

4. VEHICLE CRASH ANALYSIS

The hot stamping process is gaining popularity as a production method for crash-relevant structural components in vehicles. Due to the high tensile strengths of hot stamped materials, weight reductions are possible while maintaining, or even improving crashworthiness properties. Some crash-critical components, however, are found to benefit from regions of reduced strength and higher ductility. The B-pillar shown in Figure 3 is an example of such a part. For optimal performance in a side crash, the bottom part should show a high energy absorption capacity, while the upper part should ensure a high intrusion resistance [10]. To be able to fully exploit the possibilities of these modern hot stamped steels, it is of paramount importance to attain accurate predictive models of their crash response. In the present study, three sets of quench-hardenable boron steel 22MnB5 were heat treated such that their as-treated microstructures cover the full range of hardness values from 165 HV in the soft ferritic/ pearlitic state to 477 HV in the fully hardened, martensitic state. These three variants form the corner stones of a hardness dependent constitutive model consisting of an extended Swift hardening law and a strain-based fracture criterion.

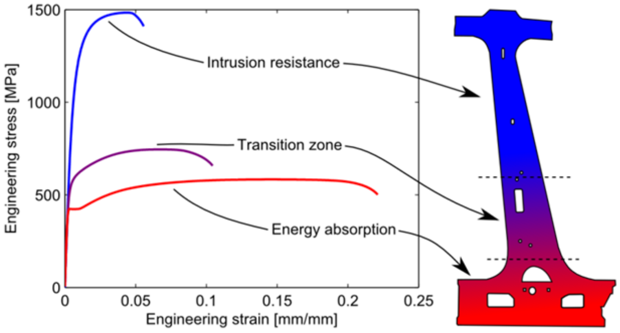

Figure 3: Tailored B-pillar with corresponding stress–strain curves.

4.1 Experimental work and model calibration

Standard uni-axial tensile tests according to DIN 50125 were performed with three resulting hardness grades. The resulting stress-strain curves are shown in Figure 4. The softest ferrite/pearlite and the hardest martensite samples show tensile strengths of 600 MPa and 1500 MPa, respectively. The intermediate bainite grade has a tensile strength of 750 MPa. After converting the engineering stresses and strains from Figure 4 to true stresses and true plastic strains and fitting an extended Swift hardening law, a fracture model was calibrated. Four different fracture tests were carried out for all three 22MnB5 hardness grades in order to collect data for the stress triaxiality and Lode angle dependent modified Mohr-Coulomb fracture criterion [11]. The four fracture specimens were designed such that fracture occurs at locations with well-defined and constant stress states throughout the experiments: uni-axial tension, plane strain tension, simple shear and equibiaxial tension. For a detailed description of specimen geometries, experimental procedures and model calibration, the interested reader is referred to the work of Eller et al. [12].

With the plasticity and fracture models of the three individual grades calibrated, piecewise linear interpolation based on material hardness is applied to create a model that can be used to approximate the behavior of arbitrary grades. Interpolation will take place separately for the calibrated strain hardening equations and the calibrated fracture criteria. After implementing the model in the Modular Material Model (MMM) framework [13] for an explicit commercial FEM code, tensile tests were simulated for several interpolated material grades (see Figure 5). The value of X_b represents the fraction of bainite being added to the model: $X_b = 1$ is a fully bainitic material and $X_b = 0.6$ in the upper hardness range represents a mix of 60% bainite and 40% martensite. The results seem plausible, because the fracture points all correspond to the typical strength-ductility banana shape for metals.

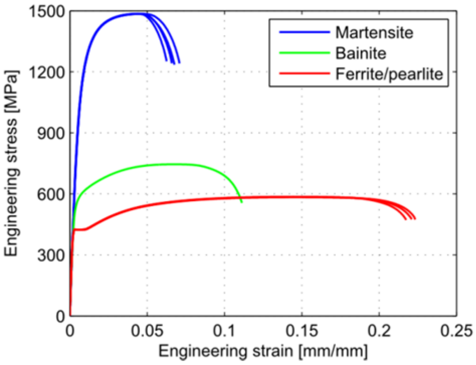

Figure 4: Engineering stress-strain curves of the three hardness grades of 22MnB5.

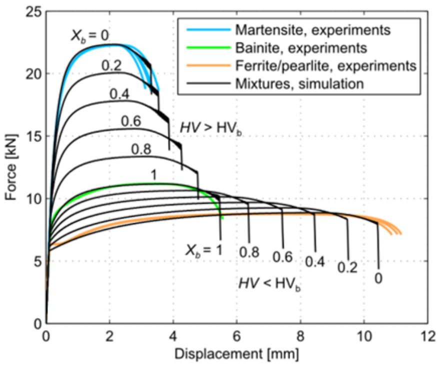

Figure 5: Simulation results of the standard tensile tests for several interpolated material grades.

4.2 Model validation

In order to validate the proposed hardness dependent material model, a tapered tensile test specimen with hardness transition zone in the gauge section, of which a schematic is shown in Figure 6, was designed and tested. Hardness measurements taken along the longitudinal axes of three specimens show a steep transition from 465 HV to approximately 250 HV over a range of 150 mm. If width *d* on the right-hand side of the gauge section would be equal to the width at the left-hand side (28 mm), the tapered tensile specimen would reduce to a standard uni-axial tensile specimen. With a hardness transition zone in the gauge section of a standard uni-axial tensile specimen, the specimen would always neck and fail in the softest area. To avoid this trivial solution, width *d* was reduced: the smaller width *d*, the further the necking zone moves to the right.

A total of six experiments were performed for two specimen variants (*d* = 14 mm and *d* = 18 mm), and confirmed excellent repeatability considering both the fracture location and the force-displacement curves. The experimental and simulated force-displacement curves are shown in Figure 7. It can be seen that the newly developed model predicts the experimental curves with good accuracy, both for the narrow and the wide specimen.

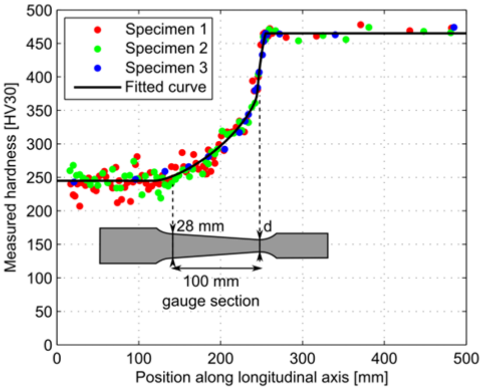

Figure 6: Hardness measurement results along the longitudinal axes of the specimens.

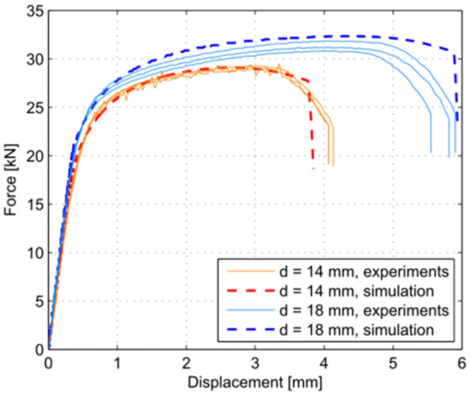

Figure 7: Force-displacement results of the tapered tensile test specimens.

5. OCCUPANT SAFETY ANALYSIS USING HUMAN BODY MODELLING

5.1 Introduction

Vehicle safety is becoming ever more important due to the increase of governmental and consumer requirements. Passive safety describes the measures contributing to the occupant and pedestrian protection after a crash has already occurred. Active Safety is helping to avoid a crash, while triggering different measures in the Pre-Crash phase. Integrated safety combines the active and passive safety measures to further improve occupant and pedestrian safety. This is a major step towards a total safety strategy where the goal is the complete elimination of road fatalities.

When active lane change and/or braking assistance systems autonomously trigger an evasive manoeuvre, the occupant will change to a new position differing from the initial position. Current crash tests used for the optimization of trigger times and air bag shapes, are done with well-defined initial positions. In the future, nearly every car will be equipped with autonomous braking and steering assistance systems which influence the posture of the occupant significantly. For an optimized restraint system, the offset positions need to be considered. Crash test dummies, also called anthropometric test devices (ATDs), are equipped with sensors to measure the loads on different parts which can be used to calculate the injury severity. To predict injuries, numerical simulations with virtual dummy models are performed before real crash tests are conducted. Unfortunately, dummies cannot be used for analysing the posture change or maintenance in a pre-crash phase as described above. On the one hand their structure is to stiff and on the other hand they are not able to brace the muscles needed to change the posture or to stabilize the body. Volunteer tests have to be performed and new simulation methods including new models have to be developed which better represent the real human body compared to the dummy.

Virtual Human Body Models (HBMs) become more important in a wide field of virtual product development. Simulations tools like virtual test dummies are mainly used to evaluate the safety of passenger cars. In the field of ergonomics, HBMs are also used to evaluate comfort. There are two modelling approaches of HBMs: the finite element (FE) based method and multi body based models. The application of these models depends on the analysis requirements. Multi body models are an assembly of rigid elements of defined dimensions and masses. If it is necessary to perform the analysis of stresses on a tissue level, a deformable FE based model is required. The disadvantage of the FE model is the increased computation time compared to the multi body model. One early multi body based model was proposed by [14]. It was a child model consisting of nine rigid bodies connected by eight kinematic joints. Today's mostly widely used multi body based model is a MADYMO model. [15] presented a multi body model which represent a 50th percentile male; this model consisted of 24 rigid vertebra, seven flexible bodies for the thorax and multi-part extremities. With regards to FE models, some of the HBMs available are: the HUMOS model presented in [16], the THUMS model [17] and the Global Human Body Model Consortium (GHBMC) model [18] and [19].

A representation of the THUMS model is shown in Figure 8. It has been used in a number of published studies attempting to reproduce injuries in car collisions [20]. [21] proposed a multi body HBM that contains controlled active behaviour of the neck, spine, elbows and hip. [22] analysed the effects of muscle tensing in bracing on impact responses of driver's lower extremity in frontal impact using the THUMS version 3.0. The model consisted of muscle elements modelled by Hill-type elements with a prescribed activation level. [22] proposed an active HBM also based on the THUMS version 3. The model was equipped with 1-D Hill-type elements for the trunk and neck musculature, where the muscle activation levels were calculated by using a feedback control method.

Figure 8: Representation of THUMS version 3.

5.2 Numerical Method

As just mentioned, in order to represent muscles which are able to contract, Hill-type elements are often used as a mechanical simplification in FE models and are presented in Figure 9. Hill-type elements are based on the ideas proposed by Hill in 1938 [24] and describe a muscle in terms of its macroscopic elongation, shortening/lengthening velocities (deformation rate), and neural excitation level. Different reformulations of the classical Hill-type model were proposed by [25], [26], [27], [28], [29] and [30].

The Hill-type muscle model used in this study consists of a contractile element (CE) which accounts for the active force generated by a muscle, a parallel viscoelastic element (PE) which simulates passive muscle properties and a series elastic element which represents the lumped series elasticity of a muscle and a tendon. The parallel viscoelastic element consists of a nonlinear spring PE and a linear Dashpot DE. The total muscle force F_m is described as:

$$F_m(Z, x, \dot{x}) = F_{CE}(Z, x, \dot{x}) + F_{PE}(x) + F_{DE}(x) \qquad \text{Eq. (1)}$$

where the force response of the contractile element F_{CE} is a function of an instantaneous muscle length x, its instantaneous elongation/contraction rate $\dot{x}$, and the instantaneous value of the active muscle state $Z(t)$. Moreover, F_{CE} is also represented by:

$$F_{CE}(Z, x, \dot{x}) = F_{max}\, Z(t)\, F_l(x)\, F_v(\dot{x}) \qquad \text{Eq. (2)}$$

where F_{max} is the maximum isometric muscle force, $F_l(l)$ is the muscle force-length characteristic and F_v is the force-velocity characteristic.

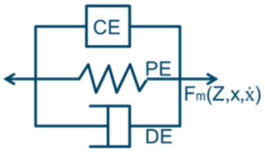

Figure 9: Representation of a Hill-type element.

THUMS version 3 was originally used for applications in the crash phase, where loads from 30 - 40 g can occur. and represents a 50th percentile male (175 cm, 77 kg). The application of the THUMS in the pre-crash phase needs an extension of the model to achieve bracing or stabilizing as a consequence of muscle contraction. Hill-type muscle elements were introduced for trunk and neck muscles to the THUMS according to the model of [22], which is shown in Figure 10. Origin, insertion and the muscle parameter were defined according to [22] as well. The pre-crash simulation was done using the commercial FE code PAM-CRASH and represented an emergency braking case from 12 km/h with a peak acceleration of 1 g. The seat was modelled as a wooden material to avoid possible influences of the foam and the occupant model was restrained by a lap belt only.

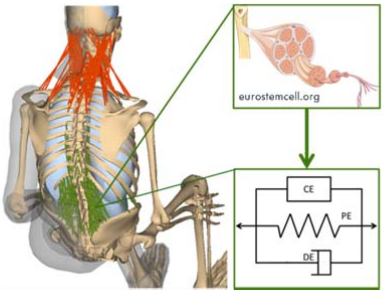

Figure 10: Hill-type elements implemented on a THUMS HBM.

The lumbar muscles of the THUMS model were activated and compared to the kinematics of the THUMS model without muscle activation. Figure 11 shows that the activation of the lumbar extensor muscle can change the overall kinematics of the model significantly under low g load case conditions.

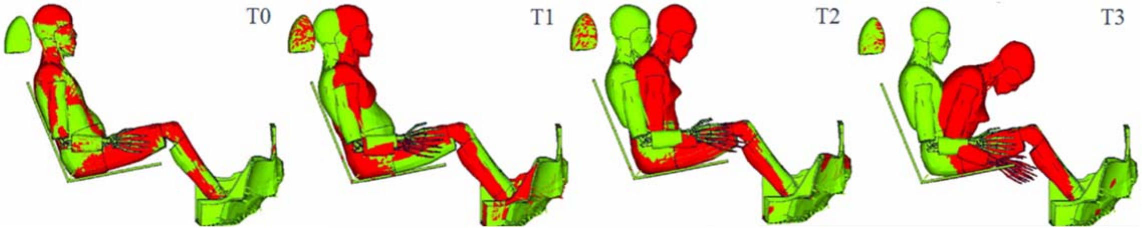

Figure 11: Kinematics of the THUMS model for a pre-crash load case at four time periods (red: passive; green: active lumbar extensors)

5.3 Future perspectives

The activation of muscles in the lumbar area can lead to different kinematics of the THUMS model in the load case which was analysed in this study. Limitations of this model are the prescribed and constant activation of lumbar extensor muscles. In the future, the different algorithms for muscle activation and recruiting methods should be implemented in the passive THUMS model. This will then allow the ability to brace and react against external forces or to simulate target-oriented movements.

6. CONCLUSIONS

This paper presented an overview and discussion of future perspectives in several areas of automotive CAE-methods research: aerodynamic optimization, aeroacoustic sound propagation into vehicle cabins, vehicle crash analysis and occupant safety analysis using Human Body Models (HBMs). In the area of aerodynamic optimization, the advantages of the adjoint method were discussed for both sensitivity map and topology optimization applications relating to internal and external flows. For the area of aeroacoustics, it was shown that numerical simulations allow the determination of both the hydrodynamic and the acoustic pressure components of sound propagation. The advantages of using an open source CFD code was illustrated for both the areas of aerodynamic and aeroacoutic simulation. With regard to vehicle crash analysis, a novel hardness-based methodology was presented for the evaluation of crash relevant structural safety for partially hardened high-strength steels. Finally, the application of HBMs in the pre-crash phase using active muscle modelling using Hill-type models was discussed showing an overview of the theoretical modelling involved as well as the advantages of simulating muscle activation.

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