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Virtual Approach to Ground Armoured Vehicles Design

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Abstract:

The paper deals with computer based design tools and processes integration in the development of ground armoured vehicles. The general demands for ground vehicles and for their development are determined by the environment in which they operate. The paper aims at giving the design process of armoured vehicles overview as well as some insight into specific topics important in the process and describes the integration of modelling and simulation into the virtual process, vehicle dynamics, suspension design, mobility, and mine protection using new armoured vehicles.

Keywords:

Virtual prototypes, integration, design process, calculations, development process, modelling and simulation tools

1. Introduction

For many years, the development of armoured vehicles has been subject to the constraint of reducing development times; however the number of prototypes is being reduced at the same time. In this context, the employment of numerical simulations is gaining increasing significance. While only a few years ago the use of simulation techniques was confined to some niche applications, prototypes that are not backed up by simulation are no longer built today. The broad employment of numerical simulation in development processes has been made possible both by more and more effective software and further methodical software development. As a development method, virtual prototyping is gaining increasing importance. Virtual prototypes are capable of forecasting the result of the development and are thus an important decision-making tool within the development process. As the behaviour of the overall vehicle becomes predictable, sub-systems within the overall vehicle system can be validated and optimized early on in the process. To meet the requirements, the

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simulator must be better integrated into the development process so that the knowledge gained from simulations can flow into the development work in timely manner. In this context, the creation of efficient and effective simulation environments is becoming an increasing necessity.

2. Calculation in the Development Process

The development process can be divided into the following phases as shown in Table 1: Task definition, concept development, layout, detail design and engineering and further implementation. All phases are supported by specific calculation methods [1]. The calculation models used differ by type (rough, layout, optimization and recalculations), form (analytical formulas, differential equation systems, finite element methods and multi-body system simulations) and level of detail [2]. Simulation system and CAD tools are used for the following development tasks:

- Functional layout of structure, chassis, drive system, protection (bending, tensional rigidity, natural frequencies, axle kinematics, etc.);
- Data acquisition (problem of imprecise data, unclear interfaces);
- Assessment of vehicle concepts;
- Preparation and modification of vehicle concept models.

Table 1 Phases in the design process

Phases	**Result**
Task definition	List of requirements Action plan Cost targets
Concept development	Functional structure Principles of solution Concept Cost estimates
Layout	Construction Preliminary layout Total layout Cost calculation
Design and engineering	CAD drawing package Part lists Manufacturing and inspection Test specifications Recycling specifications Etc.
Manufacturing	Hardware prototype

In the development process, the concept definition phase is of great importance, as this is the period during which the concept of the vehicle, the functional structures and basic solutions are generated, which largely defines the performance capability and system costs of the vehicle. The workflows and processes are not much formalized during this phase and large amount of team consultation is required. In order to effectively generate new concepts and solution during this phase, there is a requirement for holistic thinking which can be achieved even with small interdisciplinary teams. In the final layout phase, the design solution is defined in what is referred to as the structural context and the fully designed parts, components and their interrelationships are defined relative to one another. In this phase, CAE tools are used mainly for the following tasks:

- Creation of detailed simulations models based on CAD data and review of design layouts;
- Final calculation with high forest quality;
- Optimization of design parameters (materials, technology, tolerances, etc.);
- Integration of external calculation capacity.

3. Virtual Prototypes in the Design Process

The concept and layout phase for new vehicles today includes systematic studies of the capabilities performance potential and technical limitations through simulation. This makes it possible to identify the key system components and assess them in terms of cost and risk. Simulation techniques are preliminary used in the following areas:

- Mobility (longitudinal, transverse and vertical dynamics);
- Structural design (stiffness) and ballistic protection (short time dynamics);
- Mine protection (short time dynamics).

A virtual prototype of the vehicle is generated from computation and CAD models as early as during the concept phase. Fig. 1 and Table 2 give an overview of the computation models and simulation tools used for this purpose.

Table 2 Computation models and simulation tools

Simulation	Model or Method	Design Tool
Mobility Wheeled Vehicle	Multi-Body System	Adams/Car
Mobility Tracked Vehicle	Multi-Body System	Recurdyn
Power Management	Longitudinal Dynamic	Matlab
Structural Analysis	Finite Element Model	Ansys, Pro/Mesh
Geometry/Assembly	CAD Model	Pro/Engineer
Human Dummy	Finite Element Model	Ls/Dyna
Blast Simulation	Finite Element Model	Autodyn
Ballistic Protection	Finite Element Model	Ls/Dyna, Autodyn
Mine Protection	Finite Element Model	Ls/Dyna, Autodyn

During the concept phase, the virtual prototype primarily consists of physical functions. As the development process progresses, geometries and components are increasingly added and detailed. The virtual prototype then describes the complete vehicle in geometrical, technical and functional terms. The geometrical CAD data, computation and simulation data of the virtual prototype are stored in a common product database which serves as a work platform for the various development teams. The digital mock-up of the vehicle can be generated with CAD models contained in the virtual prototype and the document structure. The digital mock-up models describe the vehicle topologically and technically and serve the entire product development and design process as a database, e.g., to conduct installation, ergonomics and crash studies. Concurrently with the development activities, the virtual prototype may be integrated into tactical and operation simulations conducted by the contracting authority in order to verify vehicle requirements. Figs 2 and 3 show possible uses of virtual prototypes within the development process.

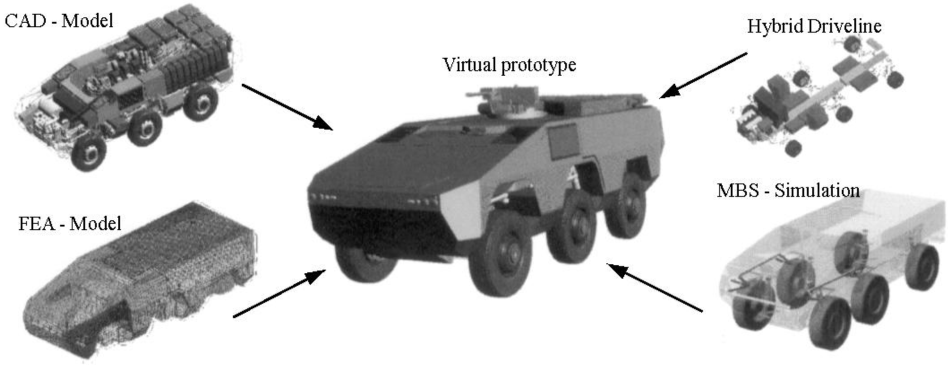

Fig. 1 Virtual prototype

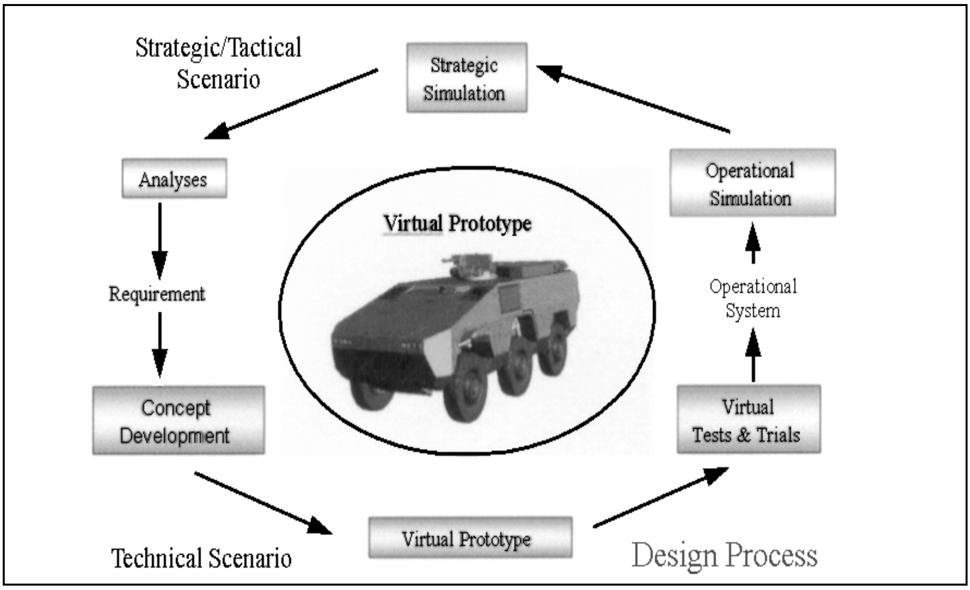

Fig. 2 Use of virtual prototypes in the development process

4. Structural Analysis and Design

Finite element models linked to the CAD model are used to design the vehicle structure. The meshing of the intermediate surfaces with shell elements is most conveniently carried out with the assistance of the mesh generator of the Pro/Mesh CAD software. For linear structural analyses and modal analyses with ANSYS, this mesh quality will normally be sufficient. For explicit non-linear Finite Element (FE) analyses, the model is meshed in the FE pre-processor in the order to obtain a better mesh quality. The global design of the structure is initially based on standard load cases which are derived from measured data. For the local design of load introduction points, e.g., the suspension, load data are used from mobility analyses conducted with Multi-Body System (MBS) model. In the case of soft load introduction points, elastic sub-structures from FE model are reflected in the MBS simulation. To optimize the structure in terms of stiffness and weight, mostly topology and parameter optimizers are used which are integrated in the FE software package. For non-linear optimization problems, e.g., optimization of structure and restraint systems for car crash or mine impact situations, special methods and software tools are used [3].

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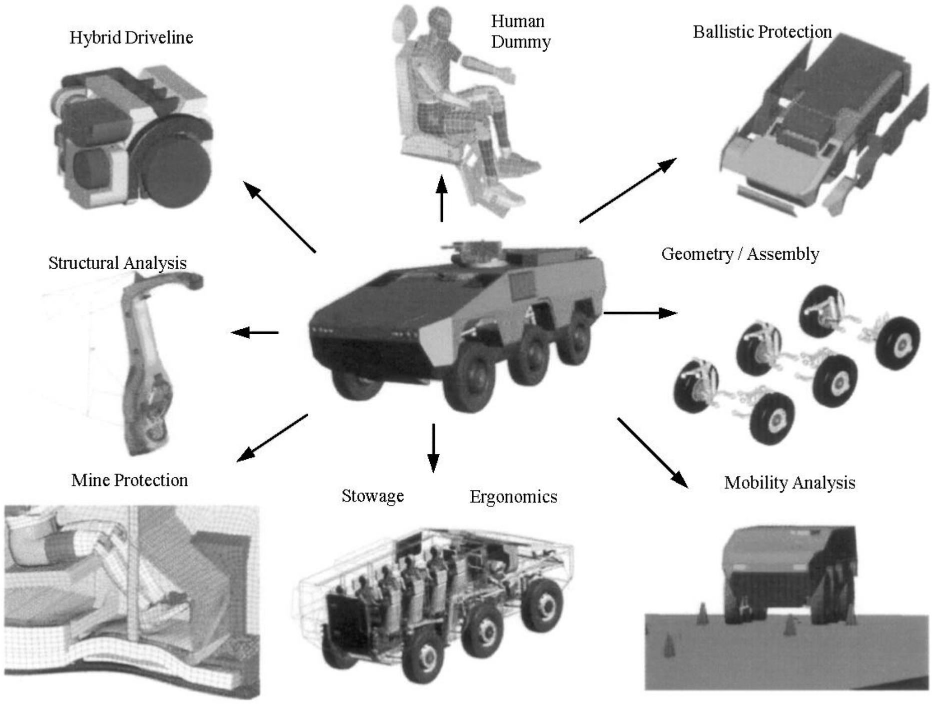

Fig. 3 Use of virtual prototypes in analyses and design

5. Suspension Analysis and Design

For the preliminary layout of the chassis concept, two different MBS tools are used for wheeled and tracked vehicles. For wheeled vehicles, the MBS software ADAMS/CAR specially developed for wheeled vehicle is used. For tracked vehicles, the MBS software RECURDYN specially developed for simulation of track and numerous contact conditions is used. Both MBS tools provide a library of chassis concepts and evaluation functions which permit efficient modelling and analysis. Initially, a simple MBS sub-model of the suspension is generated to analyze and design the axle kinematics and spring/damper system. The design and tuning of the spring/damper system to match a variety of operational environments and trackway conditions is a demanding optimization task. Basically, a high level of ride comfort requires soft suspension tuning, whereas driving safety relies on a stiff suspension setting. In order to resolve this discrepancy, simulations increasingly use active suspension elements [4]. The design layout of the suspension components is performed with assistance of CAD and FE models, see Fig. 4. The CAD model reproduces the axle kinematics in order to carryout crash studies and to generate the envelope curve for all wheel positions. The envelope curve describes the wheel arch contour and thus defines the interior payload area of the vehicle. The FE model equally reproduces the axle kinematics in order to take account of the influence of elastics and to optimize the component parts.

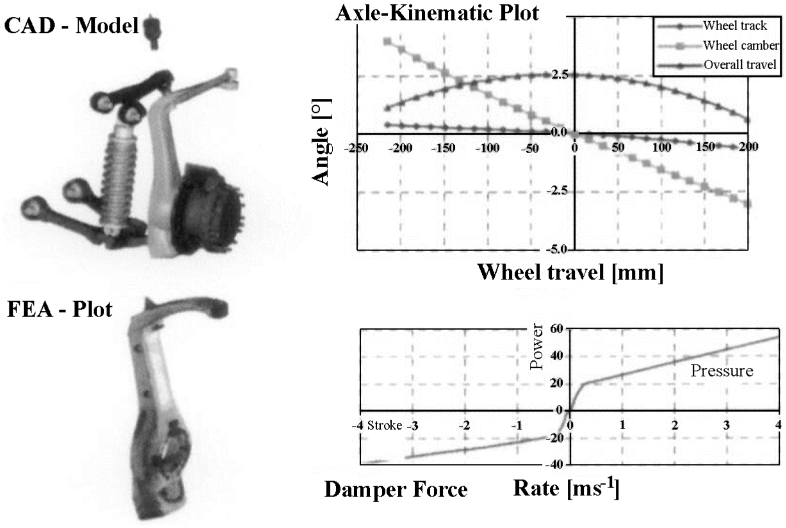

Fig. 4 Modelling and simulation in suspension design

Experimentally defined standard load situations are normally used to verify the strength of suspension components. A complete MBS vehicle model is generated to analyze the dynamic vehicle behaviour, see Fig. 5. The require data, unless already available, are derived from target value functions or measured data.

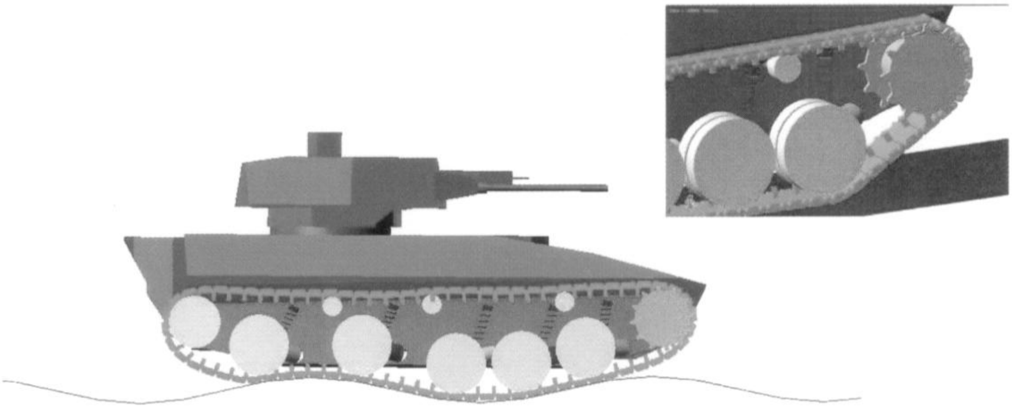

Fig. 5 Model of tracked vehicle on sine track

6. MBS Model of Vehicle Dynamic and Mobility

In the concept phase of vehicle development, driving dynamics and mobility analyses are of special importance in order to determine the loads, required spring travel and steering angels. The space claim of suspension and steering in turn determines the payload area in the vehicle interior and thus the total vehicle concept. Real test tracks are modelled to simulate and assess the mobility of the vehicle. The geometrical description and discretization of the virtual road and terrain profiles as well as single obstacles are performed with FE method. The surface characteristics, such as coefficient of friction and compliance, are allocated to the individual elements. In future, load cycles will also be determined on virtual test tracks in addition to mobility assessments. During the development, the calculated load cycles are to be used for structural analyses, computational component part life assessments to active test stands [5]. The fully parametric MBS wheeled vehicle model, see Fig. 6 is composed of the following sub-models and functions, using ADAMS/CAR:

- Chassis and suspensions components;
- Axle and steering kinematics;
- Drive model with differentials;
- Tyre model;
- Spring/damper elements;
- Active suspension elements with controllers;
- Driver model (steering and speed controller);
- Trackway profiles (terrain courses, bad roads, single obstacles).

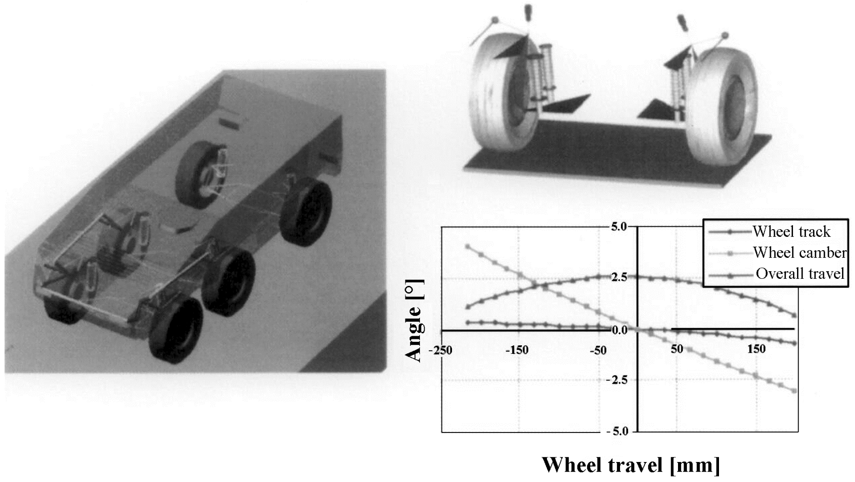

Fig. 6 MBS model of 6x6 off-road vehicle [1]

The individual axle system is built up from the kinematics points, the structures, joints and force elements. The spring/damper system can be replaced with active elements using control algorithms. In the case of the tyre model, the measured data of the tyre manufacturers are used in the special format. It is possible to provide a 3D contact between the contact path and road profile. The various 3D trackways are reproduced with triangular elements. The driveline is reproduced from the wheels to the transmission output shaft. Lockable transversal and longitudinal differentials are used. The torque acting on the transmission output shaft is controlled by the driver

model. The driver model is an intelligent model and controls the steering angle, input torque and brake forces. The individual systems are easy to replace and modify. During the concept phase, it is possible for example to assess and select centre-of-gravity positions, wheelbases, different axle concepts and suspension systems.
The fully parametric MBS tracked vehicle model, see Fig. 7, is composed of the following sub-models and functions, using RECURDYN:

- Chassis and suspension component;
- Suspension kinematics;
- Drive model with superposed steering (torque control);
- Track (double pin track and rubber pads);
- Active suspension elements with controllers;
- Driver model (steering and speed controller);
- Trackway profiles (terrain courses, bad road, single obstacles);
- Soft ground.

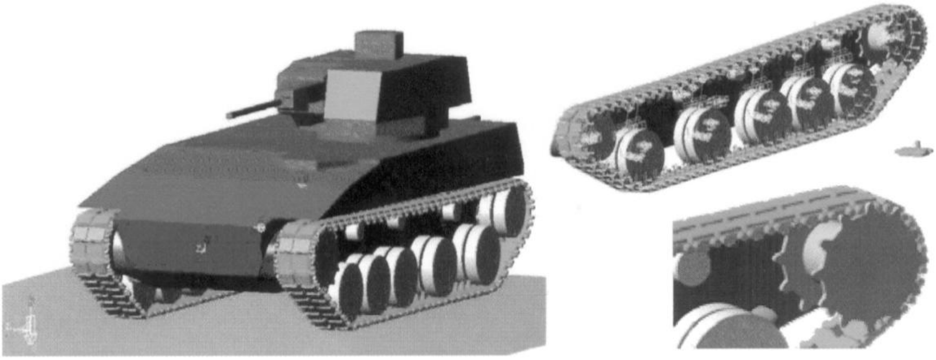

Fig. 7 3D MBS model of tracked vehicle

The right and left parts of the drive structure are built up from the kinematics points, the structures, joints and force elements. The spring/damper system is modelled with passive and active controlled elements. The track is built up with single bodies and links. The coupling of the bodies is modelled with force elements using measured data of the track manufacturer. RECURDYN is using recursive algorithms and therefore analyses of tracked vehicles can be carried out efficiently. The driveline is reproduced with the drive torque on the Sprocket. The steering torques is superposed to the drive torque. The torque is controlled by the driver model. The driver model and the ground profiles are similar to the MBS model of wheeled model.

7. Use of Simulation for Mine Protection Development

The design of mine-protected vehicles places high demands on development engineers. If a mine detonates under a vehicle, the duration of the introduced shock pulse is to be extended by the affected lower floor structure in order to be able to absorb as much energy as possible by the floor structure. The absorption of the introduced kinetic energy with less deformation in the crew compartment requires a high level of stiffness of the floor structure. On the other hand, the structure must not be so stiff that material failures cause cracking up and collapsing of the floor structure. The seat system itself and its connection to the vehicle structure must be of certain compliance in order to keep the loads imparted to the occupants by forces and shocks as low as possible. All measures taken to protect the occupants must be highly responsive. After 0.3 milliseconds of a mine blast, the floor structure will already show local deformation. After 10 milliseconds, initial movements of the dummy caused by the introduction of forces and shocks can be observed. Initial vehicle movements occur after approx. 30 milliseconds. In the area of vehicle development activities, mine protection measures generally relate to the following areas:

- Structural measures (floor deformation, introduction of forces and shocks, penetration behaviour);
- Occupant protection systems (seats, footrests, airbag, energy-absorbing elements);
- Interior equipment (padding, mounting of personal equipment, spall liner);
- Measures to preserve residual mobility.

In designing mine protection systems, all measures must be well balanced. Computer simulation has proved to be an effective tool in developing mine-proof vehicles. The numerical simulation of the dynamic effects of a mine blast on the vehicle structure makes it possible as early as during the concept phase to predict the structural behaviour and to assess the effectiveness of different design approaches and their effects on the occupants.

7.1. Assessment Criteria

A key objective in vehicle development is the fulfilment of the occupant protection requirements in mine blasts. Generally, the following criteria are used to assess the mine protection level of a vehicle:

- Probability of occupant injury (DRI, dummy values, loads, forces);
- Hazards caused by local failures (e.g., fuel leakage);
- Hazards caused by flying debris (secondary projectiles);
- Residual mobility.

The probability of occupant injury is determined from stress values calculated in simulations with the assistance of dummies or in mine blast tests. The dummies used during these tests included the Hybrid III 50th dummies, which were developed and validated for the motor industry. Fig. 8 shows the stress values of a dummy which are today evaluated with respect to the probability of injury.

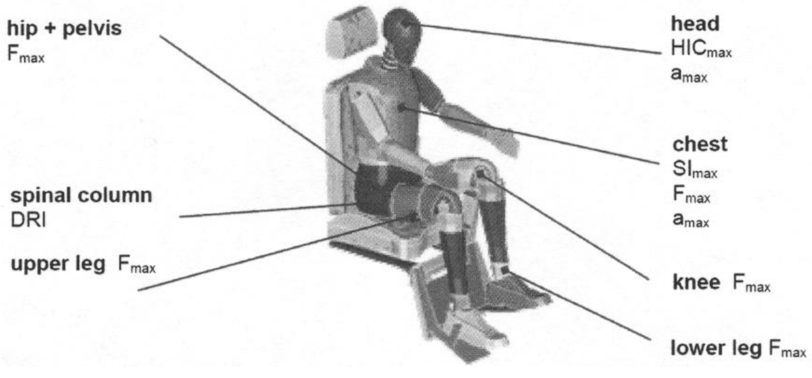

Fig. 8 Stress value used to assess the probability of occupant injury.

7.2. Model Harmonization with Blast Tests

Mine protection development activities include numerous blast tests conducted to verify and harmonize the simulation models. The data and models obtained can be used to perform complete vehicle simulations for the purpose of verifying and optimizing mine protection. A comparison of the dummy stress values obtained with complete vehicle simulations with the values measured during qualification tests shows a high level of agreement. Fig. 9 shows a comparison of the calculated and measured vertical loads acting on the pelvic area of a Hybrid III dummy during a mine blast under a vehicle.

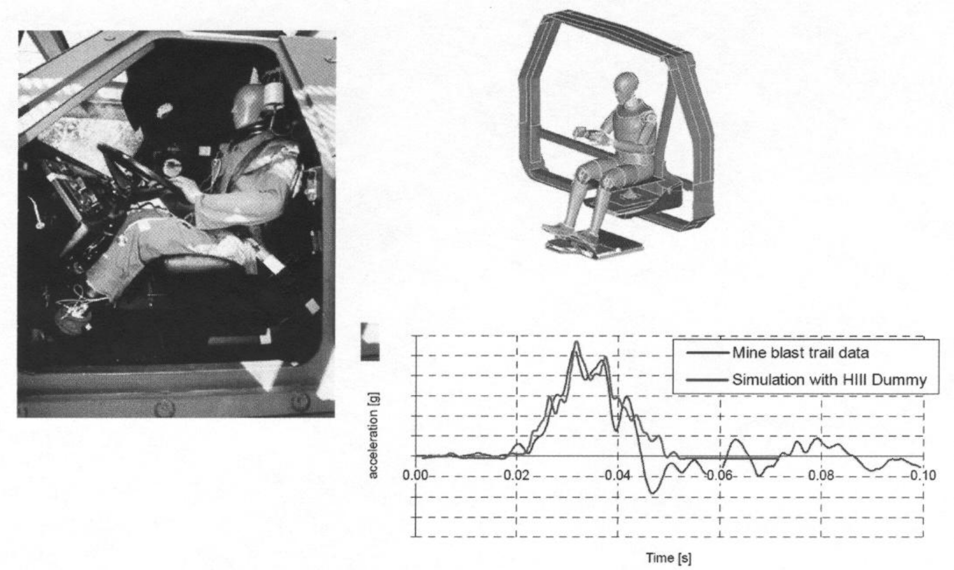

Fig. 9 Comparison of calculated and measured vertical loads in the pelvic area of a Hybrid III dummy

7.3. Mine Simulation

An FE computation model is based on a CAD model of the vehicle structure. During the development phase, the calculation engineer and design engineer consult each other to make sure that the CAD model of the vehicle structure can be meshed easily. In this way, it is possible to avoid the frequently considerable effort required to generate an intermediate surface model capable of being meshed. The generation of intermediate surfaces from the ProE data is possible with the assistance of the ProENGINEER module ProMECHANICA. For meshing and the further set-up of the computation model, the FE program ANSYS is used under the ANSYS/LS-DYNA user interface. This is where the vehicle equipment relative to mine protection (e.g., floor liner, stiffening profiles, tank, transfer boxes, etc.) is added, the contacts of the component parts among one another are defined as well as loads are applied and further boundary conditions defined. The installation of the dummy in the model as well as the correct orientation of the limbs is part of ANSYS. A great deal of attention must be given to those components which are located between the inner and the outer vehicle floor. These components, such as the transfer box, tank or floor liner, reduce the load on the mine protection floor by their mass (shock absorption) when they are hit and accelerated by a dynamically denting floor structure. These components must therefore be included in a simulation. However, in conjunction with the simulation, they also represent a good opportunity for design and optimization.

For the actual calculation of the model, the explicit, non-linear equation solver LS-DYNA is used. For the usual model sizes of 100,000 to 300,000 elements, LS-DYNA requires approximately 20-30 hours on a workstation (SGI OCTAINE2) for a computation period of 20 milliseconds, depending on mesh refinement and model structure. Owing to the relatively small storage capacity requirement of LS-DYNA, such an analysis can also easily be performed on a well-equipped PC. The evaluation of the computation results is subsequently carried out in the LS-POST processor. LS-POST also includes the output and evaluation of the dummy stress values. The FE model for the explicit dynamic analysis shows a very high level of detail and a high mesh quality. This FE model can therefore also be used without any major effort to conduct implicit static structural analyses or modal analyses.

7.4. Load Introduction

The level of protection of the vehicle is normally specified by the contracting authority. It can be used to calculate the effective energy, the local and time-related impulse of the mine and to derive load conditions for the simulation. Loads created by a mine blast are introduced into the vehicle structure in the form of a pressure distribution on the vehicle floor variable in terms of time and location. In this case, time-variable pressure loads are applied to the vehicle underfloor in a radial pattern starting from the centre of the blast, see Fig. 10. The pressure distributions over time are determined as a function of type of mine, type of laying, soil condition, vehicle ground clearance, shape of vehicle underbody and radial distance from the centre of explosion. The explosion is calculated in accordance with a formula by the Jones-Wilkins-Lee and Euler codes are used for the propagation of the blast wave [1].

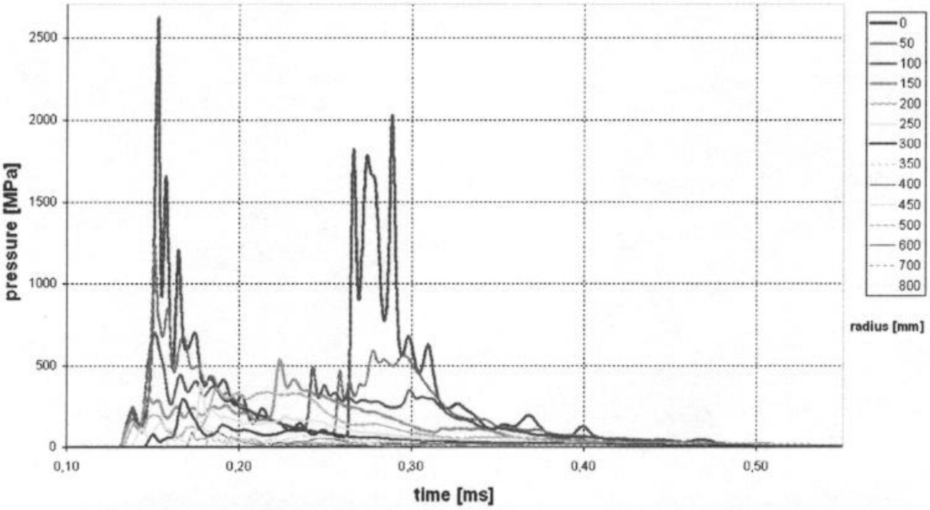

Fig. 10 Pressure distribution of a mine blast at 500 mm distance from the floor (freely positioned in a steel collar).

The calculated mine load cases have been validated through simulated blast tests with steel plates and vehicle structures. In the complete vehicle simulation, the decoupling between the load simulation and then structural response analysis is possible, in those cases where loads occur instantaneously as in the case of mine blasts, when boundary conditions (ambient geometry) vary only slightly during the period of load introduction. While the dynamic vehicle floor deformation takes on the maximum value after approximately 1.5 to 3 ms, the pulse load of a mine laid on the surface will have reached almost its final value after 1 ms. The peak pressure at the centre of the blast even has only an effective period of up to 0.3 ms after the start of the blast. The interaction between the propagation of detonation fumes and deformation of the underbody can therefore be neglected in the first approximation. This permits a separation between load simulation and simulation of the structural response. However, if the propagation of the blast wave is disturbed or influenced by structural geometries, for instance in the wheel arch, coupling of the Euler and Lagrange networks in the FE simulation makes sense in order to better identify pressure distribution and the interactions.

8. Conclusion

Modelling and simulation today is an integral part in the development process for new armoured vehicles. The use of modelling and simulation tools makes the result of development predictable and design solutions can be verified or changed or optimized early on in the program. The identification and qualification permit fast decisions and trade-offs between different approaches. This article shows the importance of virtual prototypes in the development process to reduce development cost and times. Owing to more stringent protection requirements, the design and optimization of new armoured vehicles is possible only with the assistance of complete vehicle modelling and simulations. The design of suspension assesses vehicle mobility, simulation runs are conducted with verified vehicle models and virtual test tracks. The plans for the future are to replace partial qualifications of vehicle variants with modelling and simulations in order to further reduce the number of required prototypes. At this time, it is not yet foreseeable that prototypes will become totally unnecessary, as numerical simulations can only answer questions that are explicitly factored into the model. No direct statements can be made on manufacturing influences, spreads in material characteristics and test conditions. The reliability of the solutions calculated can however be assessed with stochastic simulations, e.g., based on the Monte-Carlo method etc.

References

[1] SEHRA, A., REED, J., HOENLINGER, H., LUBER, W., STODOLA, J. et al. *Integration of Tools and Processes for Affordable Weapons* [Final Report of the NATO RTO Research Task Group AVT 093]. Paris : RTO NATO, 2006. 324 p.

[2] SHALKE, E. and ELSENHANS, H. *Integration of Innovative CAE Tools in the Concept Stage of Vehicle Development* [VDI Report No.1559]. Düsseldorf : VDI, 2000, p. 481-498.

[3] MEYWERK, M. *Optimization in Automotive Industry: Methods and Applications* [VDI Report No. 17801], Düsseldorf : VDI, 2002.

[4] HÖNLINGER, M. and GLAUCH, U. Mobility Analysis of a Heavy Off-road Vehicle Using a Controlled Suspension. In *Structural Aspects of Flexible Aircraft Control.* Paris : RTO NATO, 2000, paper 23. ISBN 92-837-0014-7.

[5] NOVOTNÝ, P., PÍŠTĚK, V. and STODOLA, J. Virtual Engine – a Tool for Military Truck Reliability Increase. *Advances in Military Technology*, 2006, vol. 1, no. 1, p. 49-69.

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