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A review of airbag test and analysis

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In recent years there have been many airbag-related injuries and fatalities. These have been due to the airbag interacting with the occupant during out-of-position (OOP) states. Numerical simulation of this situation is currently under investigation. This article reviews the mathematical models that have been developed and utilised for in-position (IP) occupant analysis, showing their capabilities in crash simulations and their inefficiency for OOP occupant interaction. The review then describes a new simulation technique, fluid structure interaction, which can possibly model the OOP occupant interaction. The capabilities of this new method are described and how it can be utilised for this type of simulation, along with recommendations of future work in this area.

Keywords: out-of-position; fluid structure interaction; control volume; airbag simulation; LS-DYNA; dummy interaction

Introduction

Airbags have been in construction since the late 1940s, when they had first been manufactured and investigated by automobile engineers. The first airbag to be installed in a vehicle appeared in 1971, in the 831 Mercury models that were manufactured by Ford [34], followed by General Motors offering frontal airbags as an optional extra between 1974 and 1976 [3]. In the 1980s, airbags were being mass-produced and by the 1990s they were accepted as an effective supplemental restraining system, along with seatbelts.

Even though airbags are accepted as aiding passengers in car accidents, they can cause harm of their own accord, the main problem being the deployment of an airbag with an out-of-position (OOP) occupant [8], which has long been identified as a potential problem of airbags.

The aim of this literature review is to identify all research information related to analysis of the OOP airbag deployment, covering all theoretical, numerical and experimental work in this field, from the first few initial mathematical models to all current research projects.

The review sets out to explain the early developments of airbag modelling, discussing the initial mathematical models that were created, which in turn leads to the development of the control volume (CV) method applied to simulate airbag deployment and is used in most airbag simulations at present. This is followed by details of the current work done on airbag crash simulation employing crash dummies. After this, the next section details the new numerical simulation methods that are being designed and utilised in the future to deal with OOP analysis, followed by a general discussion and areas of additional work that will be considered in this concluding section.

Initial Mathematical Models

One of the earliest studies on airbag modelling was conducted by Irish *et al*. [11] in 1971. They undertook a study on creating modelling tools for design of air cushion restraint systems, a study that was jointly conducted by Delco Electronic and General Motors Engineering Staff. The specific aims of the research were to investigate the verification of mathematical models of selected airbag restraint systems, to simulate the interaction of an airbag with an occupant during a collision and means to conduct trade-off studies of hopeful system concepts. This resulted in the development of a series of equations to mathematically model the motion of the airbag during occupant interaction and incorporate into the Cornell Occupant Kinematics Model, a computer program that can quickly process the data. The simulated data was compared against experimentally collected reservoir data, which was the most accurate parameter that could be measured, showing fairly accurate results of pressure, temperature and density at the supply reservoir, indicating a good correlation with the numerical data.

In 1972, King *et al*. [14] developed a mathematical model of an airbag for a three-dimensional occupant simulation that also includes the simultaneous collapse of the steering column, working in conjunction with a three-dimensional occupant model that had been developed by

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Robbins and Roberts [29]. The model was designed to assess the contribution of certain factors like the airbag size, airbag pressure, deployment rate, venting area, contact force, steering column collapse force and the distance available for the column to collapse have on the overall airbag restraint system. Through a set of simplification assumptions, the governing equations were derived instead of partial differential equations, taking into account these variables. These equations were written as part of a computer program that was merged with Robbins Roberts [29]. The model was validated by a number of experimental sled tests utilising a 50th percentile dummy, and comparing the kinematics of the numerical and experimental data showed a fairly accurate correlation.

Nefske [21] undertook a study on a basic airbag model, developing a mathematical simulation of the compressed-gas airbag system, on the basis of the work of Irish *et al*. [11] and King *et al*. [14]. An experimental model of a real airbag restraint system was built to verify the fundamental assumptions made in the mathematical models. Also, the interaction between the airbag and a single rigid mass was considered, as well as considering an application to model an occupant rebounding off an airbag. A comparison between the analytical data and the experimental data showed a reasonable correlation. To improve the accuracy, non-ideal gas effects, diffuser restrictions, bag stretch after the airbag volume is full and bag leakage had to be considered. The interaction of the single body mass with the airbag resulted in a correlation between the bag pressure and force it generated, which in turn allowed the evolution of a numerical model for obtaining the motion of a single rigid mass interacting with a moving vehicle that has a dynamically inflating airbag.

In 1988, Wang and Nefske [38] investigated and developed a generalised analytical airbag inflation model for the CAL3D occupant simulation program. The aim was to develop a general airbag simulation model which precisely calculates the airbag inflation and the interaction forces on the occupant. The model had to be general enough to be capable of being utilised by different airbag systems for a comparison analysis. The simulation model must also include representation of other sub-systems of the vehicle interior with which the occupant and airbag would interact. The article reveals a full set of equations that can be utilised to solve the thermodynamic state variables of the airbag inflation process, including accounting for airbag gas leakage and material stretch. These equations require prescribed inflator model inputs, the mass flow rate and temperature of the generated gas. These are obtained by performing a gas dynamic analysis of a tank test of a pyrotechnic inflator. With this calculated data, along with the thermodynamic properties of the gas, the airbag inflation process can be calculated. A comparison of simulation data was performed with actual 30 mph barrier test for a driver-side airbag system. The results showed good correlation, except for a time delay at certain stages. This was due to the bag shape changing in the real tests but remaining ellipsoid at all times in the simulation. This indicates that the model is ideal for in-position analysis when the forces created by the airbag on the occupant after it is fully inflated or OOP analysis where the forces created by the airbag as it first inflates are considered small. However, because it assumes a uniform pressure and temperature within the airbag, and also, because it does not consider bag slap and transient pressure forces on the occupant during airbag inflation, this model is not suitable for OOP airbag occupant analysis. For the same reasons, the previously mentioned mathematical models [11, 14] and [21], above, can also not be used for OOP occupant interaction analysis. This investigation plays an important role in all future airbag inflation simulation, since all future work especially OOP airbag occupant analysis will refer to the information collected from this study.

In 1995, Wang [37] furthered his research on airbag mathematical models by developing an analytical model for an airbag with a hybrid inflator, which consists of multiple gas sources. This type of inflator has the advantage of being able to easily adjust its output performance and outlet gas temperature compared to the pyrotechnic inflator. Also, observations from tank tests have indicated a smaller output variation over a range of ambient temperatures. The modelling of the multiple-gas-source has been done by treating each of the gases in the gas dynamic analysis separately. The resulting individual properties, like mass flow rate, can then be added together to find the appropriate ratios of the gas mixtures and the related thermodynamic properties. As in the previous article by Wang and Nefske [38], a set of equations is developed that can be utilised to solve the thermodynamic state variables of the airbag inflation process, including accounting for airbag gas leakage and material stretch. These equations require prescribed inflator model inputs, the individual mass flow rate and temperature of each of the generated gases, with the possibility of up to five gas sources for the inflation process available, providing this simulation model with some flexibility for further possible applications. The actual prescribed inflator model inputs are obtained by simulating a discharging hybrid inflator into a tank. The resulting data is adjusted from a non-adiabatic process to an adiabatic process to prevent the airbag overinflating via a computer program called HBFLOW, and then utilised as the prescribed inputs. With this calculated data, along with the thermodynamic properties of the gases, the airbag inflation process can be calculated. A series of simulations was performed to test the capabilities of the new model. They indicated the good correlation of the model with the single-source design, validating the model's equations, solution procedures and the prescribed inflator inputs. The simulations also indicated the greater accuracy of the multi-gas-source than the single-gas-source when used in a crash simulation. All these factors point to the overall superior potential of the hybrid inflation model.

Crash Dummy OOP Interactions

Since the enhancement of the Federal Motor Vehicle Safety Standard (FMVSS) 208 regulations, especially evaluating the risk of OOP interaction between the occupant and a deploying airbag, there have been various studies involving OOP analysis with hybrid dummies. Kamiji *et al*. [13] performed a series of parameter studies on the test methods for understanding injuries caused by airbag deployment and detailed certain factors affecting the testing procedure accuracy. The study explains the inaccuracies of the Hybrid III dummy for measuring chest injury criteria, due to the structure of the dummy's ribs, and how they can result in inaccurate measurements. Another inaccuracy is the fact that the dummy's chest position is dependent on other parts of the dummy (dummy's jaw), therefore is not always in the same position for each test. Also, another important factor is the build up pressure energy during the initial stages of inflation at the airbag cover seams, causing a slight change in dummy's reference position. All these factors increase the inaccuracy of the final results and add to the differences between repeated experiments. Other parameter studies showed that increasing the tear seam location of the driver module resulted in a decrease in chest deflection. Another method to evaluate the deployment force of the driver airbag was tested, producing good linear correlation with increasing speed. A series of parameter studies was also performed on the C3Y dummy for passenger side airbag deployment. The results indicated that different vehicle layouts and airbag configuration affected the accuracy of the results. The studies, in general, showed the inefficiencies of the Hybrid III and C3Y dummies. The inaccuracy is due to displacement being measured relative to the internal components surrounding the airbag and not the position of the airbag itself. Redesign of the dummies is required to better measure any displacements and improved positions have to be developed to wipe out any minor effects on overall consistency.

In 1999, Mu *et al*. [20] completed a series of tests on the relationship of a driver airbag design parameters to an OOP small female thorax injury. The study showed that the fluid/structure coupling is the most accurate method to model OOP interaction compared to other simulation techniques (in MSC/DYTRAN). The resulting tests were performed utilising the fluid/structure coupling simulation. It was found that deploying the lowest inflator pressure slope/mass flow rate and maximising the airbag-folding pattern will decrease the number of OOP thorax injuries. Other factors included the spacing between occupant and airbag module cover, steering wheel mounting flange design and inflator variability. All factors that are recommended for areas of further research since the simulation data indicate that by varying these components, the level of OOP thorax injuries can be lowered. It was also concluded that the inflator peak pressure, steering wheel rigidity, airbag and vent size, cover material, thickness, density, tear seam pattern and strength did not greatly affect OOP thorax injury. Overall, this study outlines the major factors that affect OOP interaction for small female thorax injury and can be used as a basis for future work in this area.

In 2000, Roychoudhury *et al*. [30] undertook an investigation of a computer simulation of a 5th percentile female driver interacting with an OOP airbag. The modelling consisted of finite element airbag module, steering wheel and test setup using HYPERMESH, a finite element folded airbag that was build in INGRID and the whole simulation was solved using LS-DYNA3D. LS-POST and HYPERMESH were used for post-processing the numerical results. The finite element 5th percentile female dummy that was created by First Technology Safety Systems was developed using HYPERMESH. With this simulation model, a series of tests was performed; a static airbag deployment test, an airbag force plate test, a dummy with the chest positioned on airbag deployment test (known as position 1 in the FMVSS 208) and a dummy with the neck positioned on airbag deployment test (known as position 2 in the FMVSS 208). The static airbag deployment simulation test showed good kinematic correlation between the simulation and test data, as well as confirming the module breakout movement. The force plate tests for the chest and neck interaction showed some reasonable correlation. The airbag design parametric study details the major factors that will affect the performance of the airbag during OOP load cases. The study indicated that in certain cases increasing the number of holes for venting in the airbag and utilising airbag materials which are more porous, thereby increasing the leakage of the inflating gas from the airbag will equal a change in the thorax injury criterion. Also, decreasing the fabric modulus and density does not affect the number of thorax injuries for certain inflator characteristics. The occupant position (position 1 and position 2) indicated that increasing the distance between the dummy and the wheel decreases the chest and neck deflection forces felt on the dummy. The results of the various tests indicated the effectiveness of the model but the investigation was fairly limited. Additional work in improving the model to increase the correlation with the experimental data is recommended by the authors, resulting in a computer aided simulation model that can be utilised for gathering information before availability of parts to perform actual testing.

In 2001, Mu [19] researched the techniques of developing advanced restraint system for driver OOP mitigating injuries. With the aide of computer simulation, Mu developed a coupled structural/computational fluid dynamics scheme, which he used in combination with laboratory tests, to illustrate the various OOP countermeasures possible. He concluded that an accurate simulation was not only down to accurate modelling of the dynamics of the gas and the airbag system model but also was effected by validating the mathematical dummy model and precisely modelling the position of the dummy and airbag in accordance with

OOP testing procedure. The computer simulations were compared against some experimental data, but some of the numerical data require more laboratory testing to be completed.

Duma *et al*. [5] investigated the injury potential to small female head and neck from an OOP side airbag utilising crash dummy and cadaver experiments. The tests concentrated on the worst case scenarios in terms of dummy and cadaver position during OOP interaction that were obtained from using a total body multi-body dynamics software package by Sieveka *et al*. [31]. The results indicated that for dummy and cadaver tests, the neck injury criteria remain below threshold. It was noted that bag geometry and inflator characteristics affect the potential amount of injury a female's neck can be faced with. All tests specified that the peak centre of gravity and neck acceleration correlated with inflator onset and peak pressure.

A research program was undertaken by Hollowell *et al*. [10] in 2002 to evaluate the capabilities of a prototype dual stage passenger airbag in terms of aggressivity to occupants of varying size and general restraint system performance. The evaluation was based upon varying the partition of a two-stage inflator, the size of the vent holes of the airbag cushion and deploying time between the first and second inflator. These variations were conducted upon high speed unbelted sled tests for 50th percentile male and 5th percentile female Hybrid III dummies at 30 mph, as well as belted sled tests at 35 mph. Also, low risk OOP deployment tests with a 3-year old, 6-year old, 5th percentile female Hybrid III and 12-month Child Restraint Air Bag Interaction (CRABI) infant dummies were conducted to evaluate airbag aggressivity. The study results indicated that the 60/40 and 70/30 inflator partitioning and a 10 ms delay met all injury criteria for the 50th percentile male dummy in 30 mph sled tests. The low risk OOP deployment tests for the 6-year-old and 12-month CRABI dummies were satisfied, for position 1 (dummy chest against airbag) and position 2 (dummy neck against airbag). The 3-year-old-dummy only satisfied position 1. The 5th percentile female Hybrid III failed in the unbelted 30 mph sled tests. The results in general indicated that the dual stage inflator had an improved performance over the baseline single stage inflator but further work is still needed to verify and vindicate this project.

A number of simulation and experimental tests, including OOP interaction with a 3-year-old dummy were performed by Park and Hong [24]. The numerical analysis was done utilising MADYMO (Mathematical Dynamic Modelling). A body block test was done to verify airbag cushion correlation. The resulting data indicated that the body block test simulation is affected by the inflator model and the friction between the airbag and body block but the door does not need to be simulated at all. A pendulum test, to analyse opening stiffness correlation, confirmed again the importance of the inflator model, as well as indicating that simulation door strength is an important factor in this type of analysis. Finally, the dummy OOP low-risk deployment test for a 3-year-old dummy was performed, verifying again that the greatest factor of importance is the inflator model, then the door strength, followed by friction coefficient between the dummy and airbag.

New Numerical Simulation Techniques

Lasry *et al*. [15] performed a study of numerical analysis of a fully folded airbag and its interaction with occupants, using PAM-SAFE, a program for analysing occupant study. The investigation completed a validation study of a driver side airbag, with the experimental results showing good correlation with the simulation, which was initiated with a fully folded airbag. The method of inflation was via the uniform gas pressure method. This would normally represent a weak comparison, but the reason for the similarities is the position in which the pressure was recorded, near the base of the airbag. If the comparisons were made near the airbag surface, the results may not have been as accurate with the experimental data. The article also describes an OOP interaction of the passenger side airbag, but there are no experimental data to make a comparison.

This investigation by Mestreau and Lohner [18] is concentrating on the accurate simulation of the fluid-structure interaction during airbag deployment, utilising a loose coupling of PAM-CRASH TM, a computational structural dynamic program and PAM-FLOW TM, a computational fluid dynamic program. It is felt that this will accurately predict the interaction of the airbag during deployment with an OOP occupant because it will simulate the jet effect visible at the earlier phases of inflation. It is this jet effect that is responsible for the numerous injuries occurring to drivers positioned close to the airbag during inflation. The aim here is to utilise the advantageous parts of both programs to solve numerical problems that could not be done by using each program separately, such as airbag simulation. It is difficult to simulate the airbag simulation in computational structural dynamic program due to flexibility of the boundaries and large changes in the topology. However, coupled with the computational fluid dynamic program, which uses an automatic remeshing technique, it can deal with changes in the topology. This enabled the simulation to be performed in this manner, although there were no experimental data to compare the accuracy of the simulation. Also, the simulation was done using a flattened airbag; therefore, further research needs to be done on simulation of folded airbags. The authors also accepted the need to utilise an improved interpolation method between the fluid and structure.

In 2000, Rieger [27] looked at gas flow modules in order to obtain and develop an understanding of the gas flow dynamics, concentrating upon acquiring the correct accuracy for given boundary conditions for gas flow calculations and being able to numerically depict the local effects like pressure waves. First a tank test was performed using the

MADYMO gas flow module, with two different combinations of the mass flow, temperature and gas mixture – a detailed inflator model and the Average Temperature Method, with the detailed method indicating the more accurate results, especially for OOP analysis. Next, a flat driver airbag simulation was computed and a comparison with experimental data showed that neither inflow modules accurately modelled the test data. The research indicated that further work is needed in obtaining the perfect Euler grid resolution for the flat driver airbag and that using two CPUs instead of one may result in non-identical results.

Improvements in driver safety were researched in Spain by Alcala *et al*. [1]. The research concentrated on developing new airbag shapes and systems that held the inflated airbag in the newly created positions, then analysing the effect the new airbag shapes had on the head and thorax injuries, concentrating on crashes with steering wheel movements. This was to be accomplished by reducing the kinetic energy of the occupant at the initial stages of a crash, thereby advancing the driver restraint as well as preventing the harsh interaction between the steering wheel and the occupant's body. The results indicated a very noticeable improvement in all criteria that were analysed, with the main improvement being due to the restriction of the arm movement early on in the crash due to the new shape of the airbag. However, this is not the case for various different steering wheel positions and is an area that requires more investigation, along with the wheel being set at different rotational positions.

As a result of the revised regulations in FMVSS 208, Kamiji and Kawamura [12] undertook a study of airbag interference with OOP occupant by computer simulation. The first part of the study compares the two different methods of numerical analysis of airbag deployment, the CV method or a general Euler-Lagrange coupling method. The comparison shows the deficiencies of the CV method, mainly its ability not to model the compressible fluid during inflation. This is especially critical during OOP analysis, where the membrane force of the airbag is vital due to its interaction with the OOP occupant. Other deficiencies in the CV method are its inability to reproduce the thrust of the gas from the inflator and the uneven pressure distribution inside the airbag, unlike the Euler-Lagrange coupling method. The study also considered the effects the friction force of the airbag fabric had on the occupant during OOP interference, leading to the conclusion that the dummy's head twists in the transverse direction when there is no friction and in the direction of the airbag fabric when friction is introduced. The final part of the study detailed a comparison with experimental results, showing reasonable correlation. The problems realised from this study were that to accurately analyse OOP occupants using the general Euler-Lagrange coupling method, a more accurate model of the friction force will have to be developed and improvements in the simulation of the folded airbags, so that no penetration may occur between the fabric of the airbag during a model calculation.

A new airbag simulation capability was developed for the MADYMO simulation program and utilised by Fairlie and Steenbrink [6] in 2001. The simulation runs computational fluid dynamic techniques to numerically model, with great accuracy, the airbag's interior volume. The pressure field in the airbag is coupled to the standard MADYMO FE model of the airbag. This setup allows the airbag's acceleration and movements during all stages of inflation to be predicted more precisely. The technique is simulated and compared against the standard isobaric simulation method. The coupled simulation inflation plots indicate that the pressure distribution within the airbag has significant effects upon the airbag shape, especially compared to the standard isobaric simulation model. This means that this simulation method would produce more accurate results in OOP occupant interaction. Investigation of how the new simulation method would compare against experimental data is required.

Marklund and Nilsson [17] examined the simulation of an inflating airbag interacting with an OOP head form using a coupled fluid-structure approach based on an algorithm developed by Olovsson (Arbitrary Lagrangian Eulerian, ALE) [23], which uses a Multi Material Euler approach along with a penalty contact algorithm in LS-DYNA. Experiments were also performed using a simplified setup in order to reduce sources of error and bases of comparison. The simulation and experimental results illustrated a good correlation, also showing that at the initial phase of the airbag inflation there is a high-pressure zone between the head form and the inflow into the airbag. This signifies that the difference in pressure between the inflow into the airbag and the high pressure is too low for *a priori* assumption of sonic flow at the airbag inlet position. This problem could easily be overcome if the head form was placed further away from the inlet, leading to the assumption that the inlet is sonic. The only other significant discrepancy was a peak in the acceleration time history near the end of the simulation, which may be linked to the head form being constrained to move only in the z-axis direction in the numerical simulation.

A study performed by Rekveldt *et al*. [26] undertook a phased approach of modelling airbag inflation with calibration against tests which increased in complexity. Also, the investigation carried out an advanced testing procedure on the airbag fabric, to obtain the temperature on the surface of the airbag during inflation, via a high-speed infrared camera. The first step involved analysing the inflation of an unfolded airbag model using the CV method, the MADYMO/gas flow model and an actual static airbag deployment test. The results showed good correlation between all three sets of data, except at the early stages of inflation, where the CV method did not show a sharp peak in acceleration. The second part of the study was concentrated on folded airbag model, again with similar results as in the first part of the study. The next stage, the

OOP testing, was not possible, since no simulation results could be achieved. The investigation looked at a method to measure the airbag fabric temperature during inflation via a high-speed infrared camera and compare against simulation results. The results would not be exact, since the simulation model is calculating the temperature on the inner surface of the airbag, whereas the infrared camera is concentrating on the outside surface of the airbag. It is possible to use the experimental data and then calculate the temperature on the inside of the airbag by utilising a heat transfer equation, but the results would not be accurate, since the airbag surface is partially transparent, so the measured temperature is not the exact outer surface temperature.

An article written by Zhang and Cooper [39] in 2002 describes a new method of folding the airbag for simulation purposes by Breed technologies. The new method reduces the time to fold an airbag considerably compared to conventional folding methods like the Mapping Method and the Scrunch Fold Method. Breed's method is also of a high quality and can be done using the current existing tools in either MSC-Dytran or TNO-MADYMO. The new technique can be utilised for all types of airbag analysis, including OOP analysis since it does not require a tough contact algorithm to handle the intricate airbag contact issues when the airbag is folded and there is self-contact of the airbag material, and also, there is no initial node or element penetration. The study indicates that simulation tests of this type of modelling have been performed with good correlation to other procedures for airbag folding, such as detailed above, but no actual results were presented in the study.

In an article written by Olovsson [22], a new technique in LS-DYNA, using the new model keyword *MAT_GAS_MIXTURE, was developed to model the gas mixture for airbag application, especially for OOP situations where the current methodologies of the CV technique were limited and produced inaccurate results compared to test data. This new procedure explicitly models the gas flow and the resulting interaction with the deploying airbag material. This approach models the gas flow utilising an Eulerian or ALE formulation, with the gas being able to be coupled to a Lagrangian model via a fluid-structure interaction algorithm. The main advantage this method has over other techniques is that the kinetic energy that is lost via advection will not occur with the ALE solver because the kinetic energy is automatically transformed to heat, thereby satisfying the conservation of energy. The article briefly details a comparison of this new procedure against the CV method via tank tests, with the results showing the tank pressure time histories. The small differences in the results are put down to fluid-structure interaction algorithm numerical errors, with the author suggesting a comparison of the procedures with experimental data.

Van Der Veen and Sadeghi [36] investigated a new simulation method for airbags with multiple compartments. The model consisted of a multi-compartment airbag, with each compartment modelled with a separate Euler domain, using MSC. Dytran. The method is analysed by working on three test problems, two theoretical and the last a real airbag simulation. The analysis shows the advantages of using a multi-compartment model over a single compartment model. There is also a comparison with an airbag deployed using a uniform pressure, again showing the accuracy of the multi-compartment airbag. The next stage would be to obtain experimental data to compare and further validate the numerical analysis.

The study undertaken by Fokin *et al*. [7] concentrates on simulating a thorax side airbag in LS-DYNA using the ALE method, creating a gas generator so precise that validation of the finite element airbag model against standard test results can be avoided. Since this is rather difficult to model using the current tools in LS-DYNA, this investigation develops a simplified gas generator with an explanation of the boundary conditions and the properties of the inflating gas. The study explains why the gas velocity cannot be used as an independent boundary condition and illustrates a method to prescribe the gas velocity to the inflator nodes, so numerical discontinuity will be small and at the same time the mass flow rate that is desired can be provided. A body block test is done to compare the ALE method with the CV method and experimental data. The results show a good correlation between the ALE calculation and the experimental data. The small differences are due to the inaccurate leakage model utilised. A comparison between the kinematics of the ALE and CV method shows the differences in the pressure distribution of the airbag at the early stages of inflation. The CV method applies a uniform pressure to the airbag fabric, where as the ALE method applies the pressure wherever the gas from the inflator flows. This difference diminishes as the airbag inflates, until the behaviour of the airbags becomes virtually indistinguishable. Also, the outside pressure in the ALE method is not constant and varies as the airbag inflates. Finally, the investigation does a push-away test, comparing the ALE airbag method with the CV airbag method. The comparison shows that the results are similar, with the CV method having larger accelerations in general. This is because the CV method overestimates the initial acceleration according to research performed at Altair Engineering. The reason being that due to the uniform pressure assumed by the CV method, the acceleration on the rigid body is larger than using the ALE method, where the only pressure felt by the rigid body in the early stages of inflation would be where the airbag is in contact with the inflator.

Souli and Olovsson [33, 32] wrote a couple of articles about the industrial application of fluid-structure interaction utilising LS-DYNA. The article describes the use of a new Eulerian-Lagrangian coupling algorithm based on the penalty method, along with the improved multi-material capabilities of the latest version of the software, which enable the modelling of various new applications with a much higher success rate in terms of kinematics and simulation data.

One of the important parameters in OOP occupant interaction is the accurate modelling of folded airbags. In 2004, Rieger [28] undertook a research study on the capability of simplified folded airbag models in gas flow simulations. He studied three different methods of gas flow, (radial inflow, vertical inflow and flow through a two chamber airbag) using the Leporello folded airbag. The results indicated no clear kinematic correlation with hardware tests for any of the three simulations. The vertical inflow formulation mimicked the hardware test the best and as a result was utilised for simulation purposes. The investigation also indicated increasing the gird size of the simulations does not directly lead to improved results. Some analysis was also performed of the compression folded airbag, but it was not possible to obtain some hardware results to validate the model. It is believed that further examination is needed in this area to better understand the modelling of the inflow.

Zhang *et al*. [40] investigated the three major commercial crash simulation software packages that are used in the automotive safety industry, LS-DYNA, MADYMO and PAM-CRASH. The aim of the study was to evaluate and compare the three different computational analysis tools. The study showed that all three software packages showed good correlation of both airbag deployment kinematics and pressure distributions. MADYMO had the quickest model setup and run time, PAM-CRASH showed the best kinematics and LS-DYNA gave the greatest amount of control over the model. The accuracy of the results is largely down to the inflator inputs, which were calculated from tank pressure based on some over-simplified assumptions. An improved procedure of ensuring the correct inflator gas characteristics is an area that requires intensive research work, to further improve the quality of the numerical solutions. Another area that requires extra effort is the folding patterns of airbags. This introduces large element distortions and packed layers in a small volume. The software packages need to spend some time on a smooth unfolding process for airbags with various folding patterns.

In 2004, Haufe and Weimar [9] performed a study on airbag simulation using a fluid/structure interaction method in LS-DYNA. The aim of the article was to compare the standard method of airbag simulation, the CV method with the ALE technique, discussing the advantages and disadvantages of the former process. The analysis consisted of the comparison of three different modelling techniques: the ALE technique, the CV method without jetting effects and the CV method with jetting effects in two separate simulations, a flat airbag interacting with a rigid tube and crash simulation using a three-year-old Hybrid III child dummy model. The comparison indicates that the CV method with jetting effects overpredicts the initial accelerations of the interaction and the CV method without jetting effects has quicker volume growth in the initial stages of interaction. The ALE technique has a larger final acceleration value that is closer to actual experimental data. This method is more demanding in terms of detailed simulation and analysis time, but analysis of the fluid flow and gas flow interaction effects produces much more reliable results compared to the other methods.

Utilising a deploying flat airbag as a possible example, Cirak and Radovitzky [4] presented a strong computational method for the coupled simulation of an extremely flexible thin-shell structure (airbag fabric) with a compressible high-speed flow (inflating gas source). The coupling is based on a Lagrangian-Eulerian combination. The deformations of the shell elements are formulated using Lagrangian theory and the compressible flow equations are solved using Eulerian finite volume method. The interesting aspect of this methodology is the coupling procedure, which is centred on level sets. The resulting airbag simulation shows the robustness and the general success of the simulation procedure; however, the coupling modelling technique is only first order accurate and not conservative, which means the accuracy in the results will be greatly affected, especially in the early stages of inflation when considering OOP cases and this process does not consider the effect of permeable membranes.

A flat airbag model was created in MADYMO to simulate the inflation process in order to observe and compare the airbag oscillation frequency to hardware tests [25]. The model was of a simple folded driver airbag with a pendulum positioned just on top, while also considering the effect the surrounding air of the simulation would have on the damping force. The initial results indicated that there was initial correlation with the hardware tests, which worsened due to bag oscillation between the airbag and pendulum. Further analysis indicated that the reflections of shock waves play an important part in the deployment process and need to be considered in future simulations, which is possible in MADYMO since it is able to accurately model such matters. The analysis also showed that a small amount of energy was dissipated by the shock waves and their reflection significantly increases the internal airbag pressure. Another important factor is creating a model with high number of elements, which will be possible with the next version of MADYMO since the current version cannot handle a very large number of elements without extremely large costs in terms of computational time and calculation.

An important consideration for OOP airbag simulation is the procedure utilised to fold and store the airbag, especially in the early stages of inflation, where the folds affect the speed and shape of the deploying airbag. This process also involves creating folded meshes of the airbag, which is a time-consuming chore, which is why Thornton *et al*. [35] performed a study into the rapid development of multiple fold patterns for airbag simulation in LS-DYNA using Oasys Primer. Normally, the mesh must be created from the start each time a different fold pattern is utilised, and the process itself is a tedious one involving an iterative time-consuming method of meshing and then folding the airbag. With Oasys Primer, mesh-independent folding is possible, saving large amounts of computational time. The investigation gives an example of using this new procedure, resulting in the creating of a star-folded airbag that was created in approximately 20 minutes. The resulting model was then simulated using both the CV and ALE procedures. The results indicated that the ALE procedure was more accurate since it correctly predicted the non-uniform deployment of the airbag due to the airbag folds acting as barriers, whereas, as expected, the CV method applied a uniform pressure to the whole airbag, resulting in an unrealistic airbag deployment shape.

A study performed by a working group of the German automobile industry in 2004 [2], consisting of Volkswagen, DaimlerChrysler, Porsche, BMW and Audi, undertook an investigation to find out the current capabilities of the current crash and occupant simulation software tools for OOP airbag deployment by utilising the gas dynamics of the process. The research concentrated on the three main industrial software packages, PAM-CRASH, MADYMO and LS-DYNA. The working group first established the need for a flow-based approach to the simulation process. This is achieved by comparing the kinematics of the CV method in LS-DYNA with the ALE method, ALSO in LS-DYNA. The kinematics of the two procedures shows how the CV method first underestimates the airbag velocity, then overestimates at later stages of deployment. The ALE method deviates from the test results that occur after 35 ms and are of appreciably smaller quantity compared to the CV method simulation. Also, the CV method does not model relevant OOP effects, including unsteady gas dynamics and the general thermodynamic processes of the airbag. The investigation now consisted of testing the capabilities of the three main crash and occupant simulation software packages by a series of basic tests of varying complexity in order to make an accurate comparison between each program. Certain tests were selected from a wide range that were conducted and detailed in this article. The first comparison was of a hemisphere impacting with a flat airbag. The results indicated that MADYMO overestimates significantly the airbag simulations in terms of kinematics and actual simulation data, namely the velocity and acceleration. PAM-CRASH is much better, with a smaller overestimation of the hemisphere velocity and much improved kinematics. The most accurate results were obtained by LS-DYNA where overestimation of the results is half as high as PAM-CRASH. The next test considers a hemisphere impacting with a Leporello folded airbag, concentrating on folding techniques and its associated problems. This test again shows how MADYMO overestimates the results, which is also how the PAM-CRASH simulation reacts. LS-DYNA again is the most accurate, comparing very well with the test data. The final test is a dummy impact simulation. Here the dummy injury criterion is analysed for each program. MADYMO is still the worst of the three, again overestimating the results. Both PAM-CRASH and LS-DYNA are within the test variations, even though there is a small overestimation of the chest load data utilising PAM-CRASH. The article indicated the importance of flow-based simulation for OOP airbag deployment, the need to precisely model the interior of the airbag into which the gas flows and the capabilities of the different software packages. Overall, LS-DYNA has proven to be the most precise, followed by PAM-CRASH and then MADYMO. The working group's next target is utilising more complex models. This will further validate the current techniques and result in more complex analysis to verify the methodology.

A joint investigation by Coventry University [16], TOYODA GOSEI Europe NV and TNO Automotive UK Ltd looked at simulating airbags for OOP cases, in particular, the low-risk deployment tests for the 5th percentile dummy in static OOP positions as detailed under the FMVSS 208 regulations, utilising the MADYMO software. The project involved simulating a flat and folded driver airbag and correlating it to experimental work, utilising the gas flow and CV method in MADYMO. By analysing the results, a good correlation can be seen for both the flat and folded airbag simulation when compared to experimental data and the kinematics as well, especially when modelling with the gas flow procedure. The next stage of the investigation is to further validate the models, including adding a pendulum head form, accounting for material permeability and airbag models with holes.

Summary

This literature review summarises the advances and accomplishments of airbag OOP simulations, covering the origin of the first mathematical models, leading to the model created by Wang and Nefske [38], which is able to accurately model airbag simulations for in-position analysis, and also the improved model by Wang [37] that has greater functionality and is equally accurate, both utilised as the basis of modelling techniques in LS-DYNA, commonly referred to as the CV method. The inaccuracies of this method compared to fluid structure coupling method for OOP interaction are also detailed. Kamiji *et al*. [13] indicated the inaccuracies of the dummies, thereby specifying that the experimental data may not be good enough to be used for comparison with any numerical simulation results. The fluid structure method has greater controllability of the gas dynamics, which is particularly important in the early stages of airbag deployment and this is why it is being utilised in OOP interaction load cases [9, 4, 25, 35], but still there are areas of improvement employing this technique.

Future work in this area will involve further analysis of the fluid structure coupling method to gain an understanding of how the process works and the many different variations of this technique. The method also has known deficiencies like correct unfolding airbag procedures, good contact algorithms during the unfolding process and unwanted leakage. These are certain areas that need to be improved to aide in the overall accuracy of the method, leading to a greatly enhanced fluid structure coupling numerical simulation techniques which can be utilised for OOP loads cases and a range of other possible situations.

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