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Gas Jet Model for Airbag Inflators

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ABSTRACT

Simple, as well as more sophisticated empirical airbag models have been developed since the early seventies. By discretization of the fabric skin of the airbag in finite elements, phenomena like the inertia effects due to the motion of the different parts of the fabric, bag slap, and pressure forces on penetrating objects are accounted for, also during the deployment phase of the airbag.

In most cases relatively simple thermodynamics, i.e. a lumped parameter approach, can be used. For an out-of-position occupant however a complication can arise if the gas jet coming out of the inflator is directed towards the occupant. A relatively simple analytical model to account for the gas jet effects in combination with a lumped parameter approach is implemented in the MADYMO finite element module.

A model validation using a pendulum test with a passenger side airbag shows a good agreement between the measured and calculated results, only when the gas jet effects are included in the analysis.

INTRODUCTION

The rapid increase in car usage after the second world war led to a stronger emphasis on reducing the harm due to car accidents. Historically, the development process for the restraint design of passenger vehicles has relied heavily on physical testing of components and restraint systems. The use of computer simulation techniques in automotive crash safety design has rapidly increased in the past years. For the human body as well as for the car structure and restraint systems, like seat belts and airbags, computer models are becoming more and more realistic. The use of occupant simulation programs [1*] can save much time, especially during the early phases of the design process. Due to their limited CPU load and short turn around time these programs have proven to be very suitable tools for sensitivity analyses and design optimization studies.

MADYMO is a world-wide accepted occupant simulation programme. The programme has been designed especially for the study of the complex dynamical response of humans or human surrogates under extreme loading conditions [2]. But also for other dynamic events, like the simulation of vehicle riding and handling the programme has been applied successfully [3]. MADYMO combines multibody and finite element techniques with several force interaction models in one programme (Figure 1).

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* Numbers in parentheses designate references at end of paper

In the last two decades several empirical airbag models have been developed, among which is the MADYMO 2D model [4]. These models use rather simple approximations for the contact interaction between the occupant and the fabric skin. The properties of the gas inside the airbag are determined by using a lumped parameter approach [5]. During deployment the bag pressure is taken identical to the atmospheric pressure and bag inertia forces are neglected during the complete simulation.

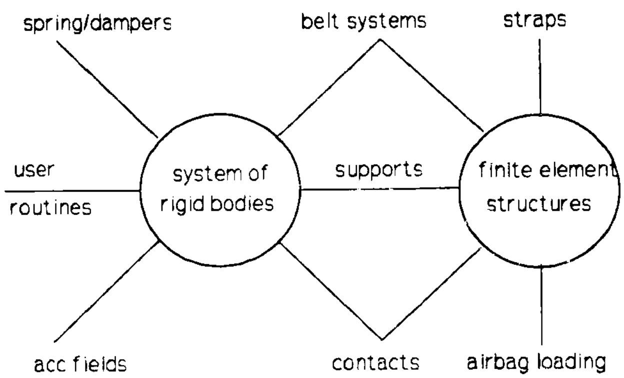

Fig. 1 MADYMO structure

With discretization of the fabric skin of the airbag in finite elements, the motion of the different parts of the fabric and the contacts with penetrating objects are described more accurately than with the empirical models. The inertia effects due to the motion of the different parts of the fabric, bag slap, and pressure forces on penetrating objects are accounted for also during the deployment phase of the airbag. Generally for finite element airbags a lumped parameter approach similar to the empirical models is used. For out-of-position situations, where the occupant comes into contact with the airbag during inflation, a complication can arise if the gas flow coming out of the inflator is directed towards the occupant. In such a case the inertia effects of the gas jet can have a significant influence on the occupant motion. This effect can be accounted for by using a three dimensional Eulerian discretization for the gas inside the airbag [6]. An other option is to use a relatively simple analytical model to account for the gas jet effects in combination with a lumped parameter approach [7]. The advantage of this approach to an Eulerian discretization is that the necessary computer time will only increase slightly, whereas using an sufficiently fine Eulerian discretization would increase the computer time with at least an order of magnitude.

The analytical gas jet model in MADYMO is the subject of this paper. First the MADYMO finite element airbag model, with special emphasis on the used lumped parameter approach and gas outflow models, will be presented. This is followed by a description of the analytical gas jet model. To illustrate the potential of the gas jet model for out-of-position situations, the experimental and numerical results for a pendulum tests will be compared. A discussion on the major findings of this study and the modelling of airbag unfolding concludes this paper.

MADYMO FINITE ELEMENT AIRBAG MODEL

In 1991 the MADYMO finite element airbag model [8] was released. The model is fully integrated in MADYMO and optimized for airbag simulations in a crash victim simulation environment. A tanktest analysis programme as well as airbag mesh generators, which generate the finite element input data for a driver or passenger side airbag in the design configuration, are provided with the programme.

The airbag skin is modelled with constant strain triangular membrane elements. Several material models suitable for fabric sheets can be applied. A "control volume" is continuously monitored and taken to be equal to the volume enclosed by the membrane elements used to model the fabric skin. The volume thus calculated only equals the volume inside the airbag skin if the elements form a closed contour. Therefore a special material type with negligible stiffness against elongation or compression can be applied for the modelling of exhaust orifices. Straps are modelled as massless linear springs.

The airbag inflation process is modelled as an expanding volume of gas, with mass and heat flowing into and out of this volume. Gas is blown into the airbag by the inflators and flows out through exhaust orifices and pores in the fabric (Figure 2). Thermodynamic quantities have been predefined as default values for those gases that are of most importance for airbag inflation. Multiple inflators can be applied. Each inflator can be activated by a combination of sensors using logical functions.

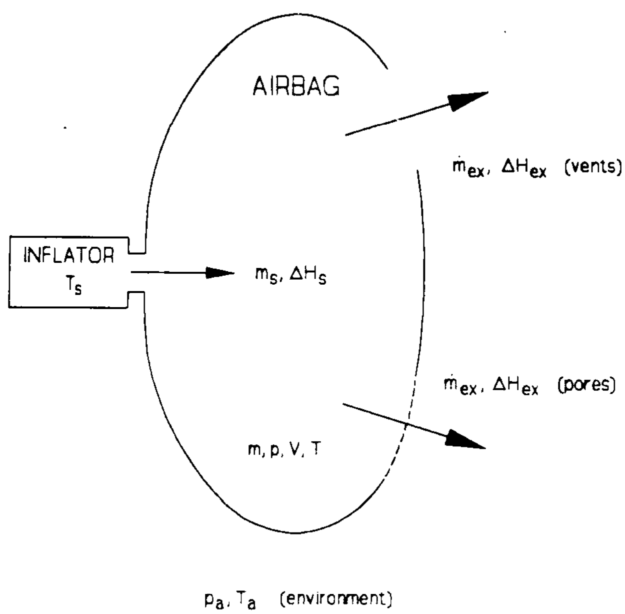

Fig. 2 Gas flow through the airbag

The gas mass in the airbag m is the difference of the supplied gas mass m_s and the exhausted gas mass m_{ex}. The change of mass in the airbag is therefore:

$$\dot{m} = \dot{m}_s - \dot{m}_{ex}$$

where the overscore . indicates the first time derivative. The gas inside the airbag is treated as a mixture of ideal gases and the state variables, pressure and temperature, are assumed to be uniform throughout the bag interior (lumped parameter approach). The ideal gas law for a certain gas volume V can be written as:

$$p\,V = m\,\underline{R}\,T$$

with p the pressure, T the gas temperature and $\underline{R}$ the gas constant. If the inflation process is treated as adiabatic, i.e. apart from the heat in the gas flows there is no heat transfer between the expanding volume and its surroundings, the first law of thermodynamics for a homogeneous steady-state flow process can be applied. In unsteady-flow, as is the case for the airbag inflation process the amount of mass in the system is not constant and energy may be accumulated or depleted. Neglecting the kinetic and potential energy, the net energy transport of the gas flowing into and out of an airbag equals the enthalpy difference of these flows [9]. The energy equation for the adiabatic unsteady-flow process may be written as:

$$d(mc_vT) + \Delta(c_pTdm) + pdV = 0$$

with c_p and c_v the constant pressure and constant volume heat capacity of the gas mixture respectively.

Gas can flow out of the airbag through venting holes and pores in uncoated fabric. The mass flow through venting holes is approximated by a one-dimensional, quasi-steady, isentropic flow model [5]. Combining mass conservation with the Poisson and Bernoulli equation yields:

$$\dot{m}_{ex} = A_e\left(\frac{p}{\underline{R}}\right)\sqrt{2\left(\frac{c_p}{T}\right)\left[\left(\frac{p_{ex}}{p}\right)^{\frac{2}{\gamma}} - \left(\frac{p_{ex}}{p}\right)^{\frac{(\gamma+1)}{\gamma}}\right]}$$

where A_e is the effective area, i.e. the product of exhaust area and discharge coefficient [10], of the exhaust orifice and γ the ratio of heat capacities. For subsonic flow p_{ex} equals the ambient pressure p_a, for sonic flow:

$$p_{ex} = p[\,2/(\gamma+1)\,]^{\gamma/(\gamma-1)}$$

Leakage through porous airbag fabrics is calculated using a model developed for gas flowing through a flat screen placed perpendicular to the flow direction [11]. The model is based on a resistance coefficient which for airbag applications can be approximated by the reciprocal square value of the porosity coefficient η. η can be specified for each membrane element separately. The resulting equation for the mass outflow rate is:

$$\dot{m}_{ex} = \eta^2 A_f \sqrt{2\rho(p-p_a)}$$

with A_f the total fabric area and ρ the gas density. To illustrate the different outflow characteristics for gas outflow through holes and porous fabrics, the mass flow rate as a function of the pressure difference for both models for Nitrogen of 673 Kelvin through an outflow area of 8,5 dm^2 is shown in Figure 3.

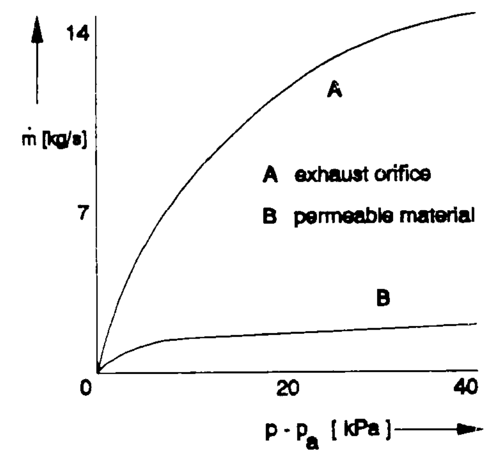

Fig. 3 Outflow through holes and fabrics

The ideal gas law, the energy and mass conservation equations and the equations to describe the gas flow through holes and fabrics in combination with specified inflator mass flow and temperature characteristics are sufficient to determine the mass, pressure and temperature of the gas mixture inside the airbag. The model has been applied to airbag systems in a car environment giving a good agreement between measured and calculated results [12, 13 and 14].

GAS JET MODEL

By adding gas jet effects the kinetic energy of the gas flow from the inflator, which is neglected in the lumped parameter approach, is taken into account. The behaviour of a non-buoyant incompressible steady state jet has been studied by Abramovich [15] for the case that the ambient gas and the gas in the jet have the same temperature. Idelchic [11] gives an overview of the parameters that define the shape of the jet for different outlet shapes.

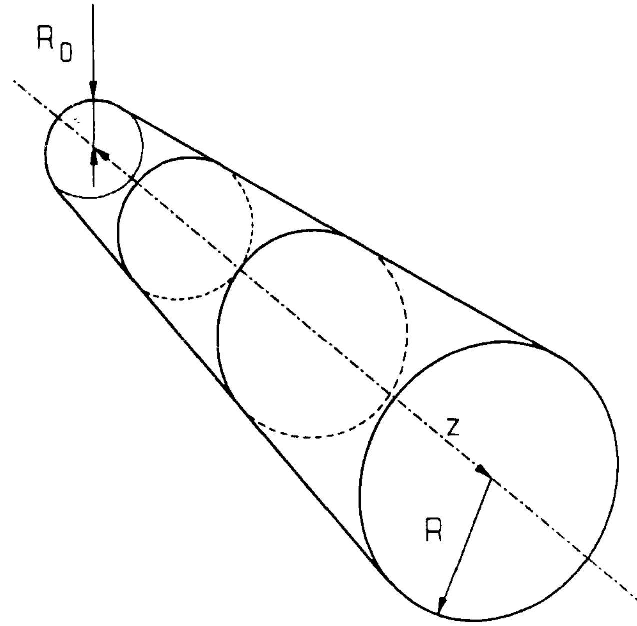

Fig. 4 Circular outlet: cone-shaped jet

For a circular outlet a cone-shaped jet is used (Figure 4). The maximum velocity V_{max} in each cross section of the jet is a non-linear function of the inflator radius R_0 and the distance of the cross section to the inflator outlet z:

$$\frac{V_{max}}{V_0} = f\left(\frac{z}{R_0}\right)$$

with V_0 the gas velocity in the outlet. The velocity distribution over the circular cross section is assumed according to a Gaussian profile (Figure 5):

$$V = V_{max}(z)\; e^{-\left(\frac{r}{R}\right)^2}$$

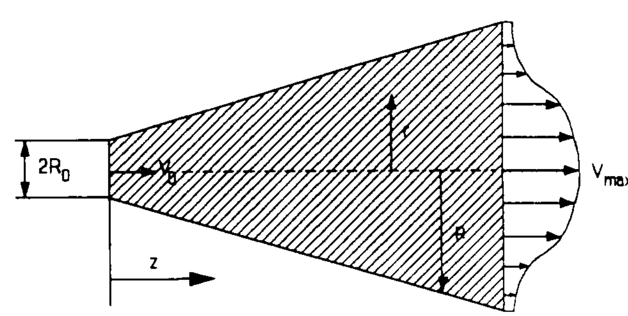

Fig. 5 Gaussian velocity distribution in jet

For a rectangular outlet a wedge-shaped jet is used with the width of the jet equal to the length of the longer side of the outlet (Figure 6). Only in the direction parallel to the shorter side of the inflator outlet a Gaussian velocity distribution is used.

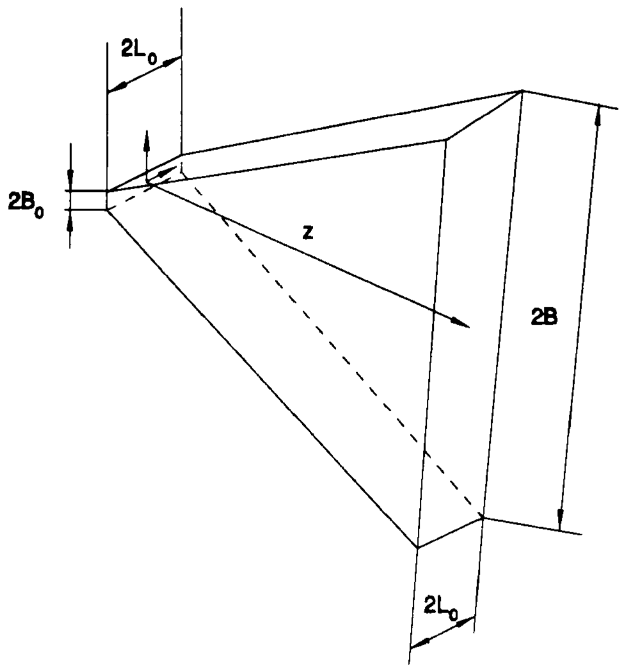

Fig. 6 Rectangular outlet: wedge-shaped jet

The flow in the inflator outlet is assumed to be sonic. Combining this with the ideal gas law and the energy equation for an adiabatic flow process leads to the following equations for the uniform gas velocity V_0 and the gas density ρ_0 in the outlet:

$$V_0 = \sqrt{(\gamma - 1) * c_p * T_s}$$

$$\rho_0 = \dot{m}_s / (A_i * V_0)$$

where A_i is the inflator outlet area. With these assumptions the velocity distribution in the jet is known. Based on this velocity distribution an analytical model to account for the inertia effects of a gas jet coming out of an inflator has been implemented in MADYMO. Above the pressure due to the lumped parameter approach an extra pressure is calculated for those membrane elements that are inside the jet region and which are not hidden behind other membrane elements. The pressure is calculated based on the gas velocity at the centre of the element and the density of the gas in the jet assuming an almost complete reflection of the jet by the airbag skin. The effects of the velocity of the airbag skin as well as the porosity of the fabric on the momentum transfer are not accounted for.

PENDULUM TEST AND SIMULATION

As stated in the introduction, gas jet effects can have a significant influence on the occupant motion for certain out-of-position situations. To illustrate the gas jet option, an out-of-position test with a passenger side airbag has been simulated. During inflation the airbag comes into contact with an initially stationary pendulum. The experimental set-up is given in Figure 7. The airbag was unfolded before inflation and fixed to a plate, which in turn was fixed to a rigid wall. A detailed description of the experimental set-up can be found in [16].

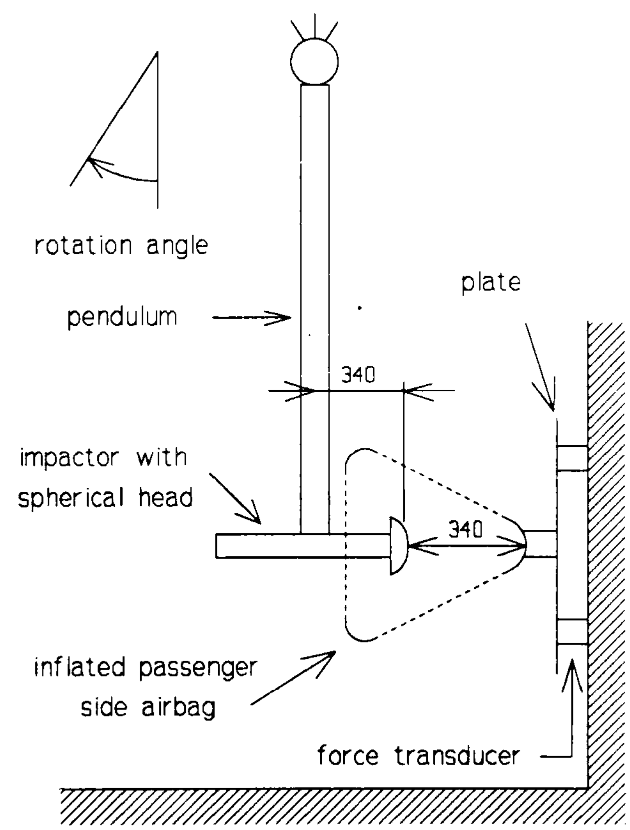

Fig. 7 Experimental set-up pendulum test

The pendulum was connected to a rigid structure with a revolute joint. The distance between the rotation axis and the centreline of the impactor is 1310 mm. The spherical impactor head has a diameter of 82 mm. The total mass of the pendulum is 10,9 kg. The mass moment of inertia with respect to the centre of gravity of the pendulum, located 245 mm above the centreline of the impactor, is 2,07 kg.m^2.

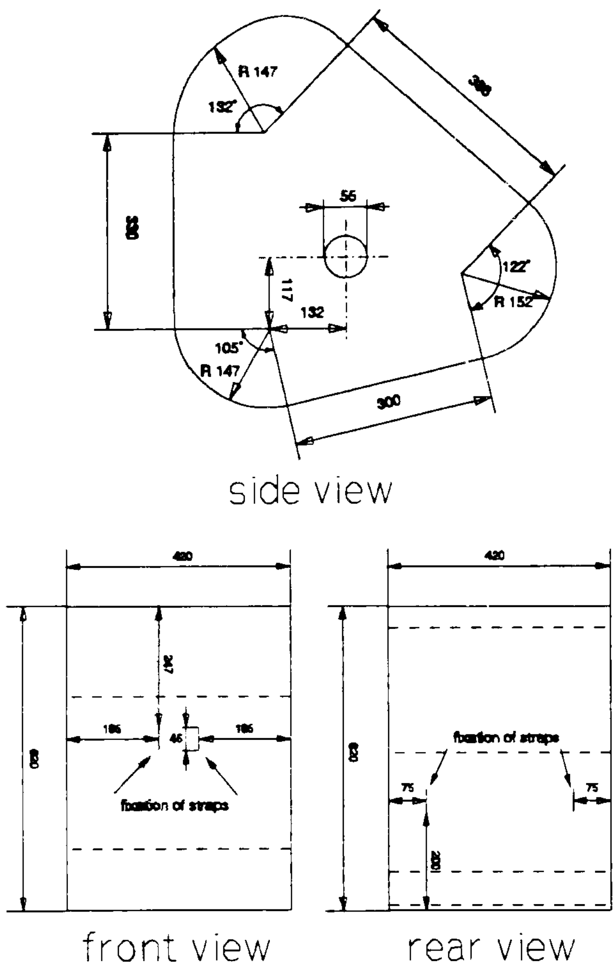

Fig. 8 Diagram passenger side airbag

The 120 litre passenger side airbag (Figure 8) is made of non-coated nylon 66. It has one exhaust orifice at the right hand side. Two straps connect the front side with the back side of the airbag. The airbag has been modelled using 2744 membrane elements with a linear elastic isotropic material behaviour:

Young's modulus	60 N/mm^2
Density	620 kg/m^3
Poisson ratio	0,3
Thickness	0,5 mm
Porosity	0,05

Each of the two straps is modelled as a massless spring between two nodal points. The untensioned length of the strap is equal to 620 mm, The strap material is assumed to be the same as the airbag skin material, resulting in a stiffness of 4500 N/m.

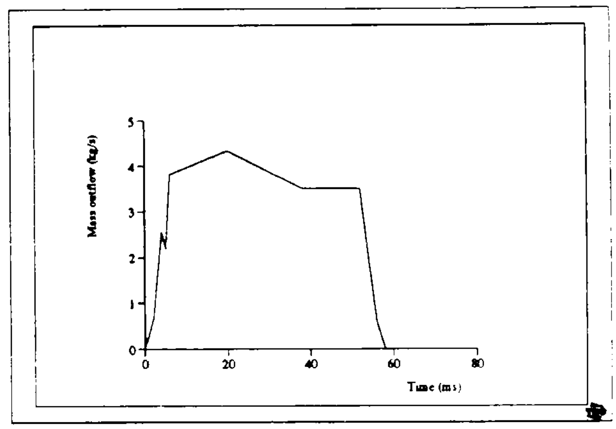

Fig. 9 Inflator mass flow rate

As a consequence of the used aspirating inflator system, considerably more ambient air is sucked into the airbag than hot gas produced directly by the inflator. The total inflowing gas is modelled as pure Nitrogen with a temperature of only 406 Kelvin. The total inflowing mass flow rate is presented in Figure 9.

For reasons of comparison a simulation with and without gas jet effects has been performed. The airbag geometry and pendulum position at different times are presented in Figure 10 and 11 for a simulation with and without gas jet respectively. By comparing these figures, the gas jet effects can be identified clearly. Figure 12 contains the rotation angle of the pendulum as a function of time as resulting from the experiment and the simulations with and without gas jet effects. Figure 13 contains the acceleration history of the pendulum c.g. as resulting from the experiment and the two simulations. From these figures it can be concluded that a much better correlation with the experiment is obtained if the gas jet effects are included. The computer time necessary was 3803 s and 2072 s on a Silicon Graphics 400 series for the simulation with and without gas jet respectively.

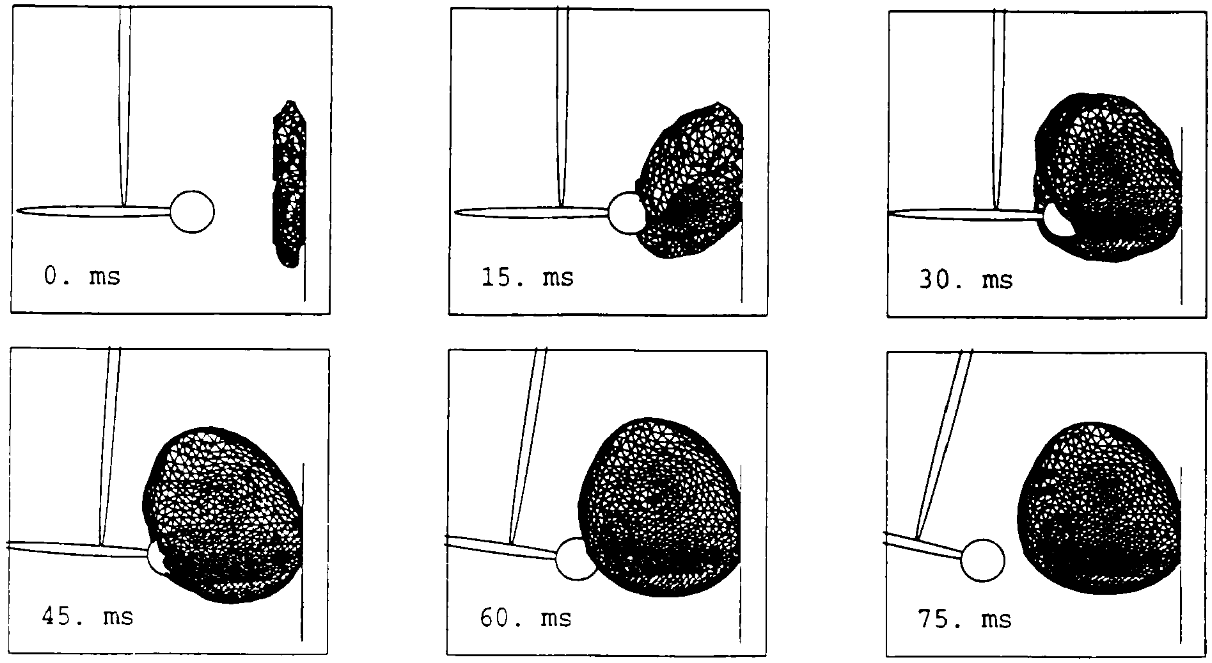

Fig. 10 Calculated kinematics with gas jet

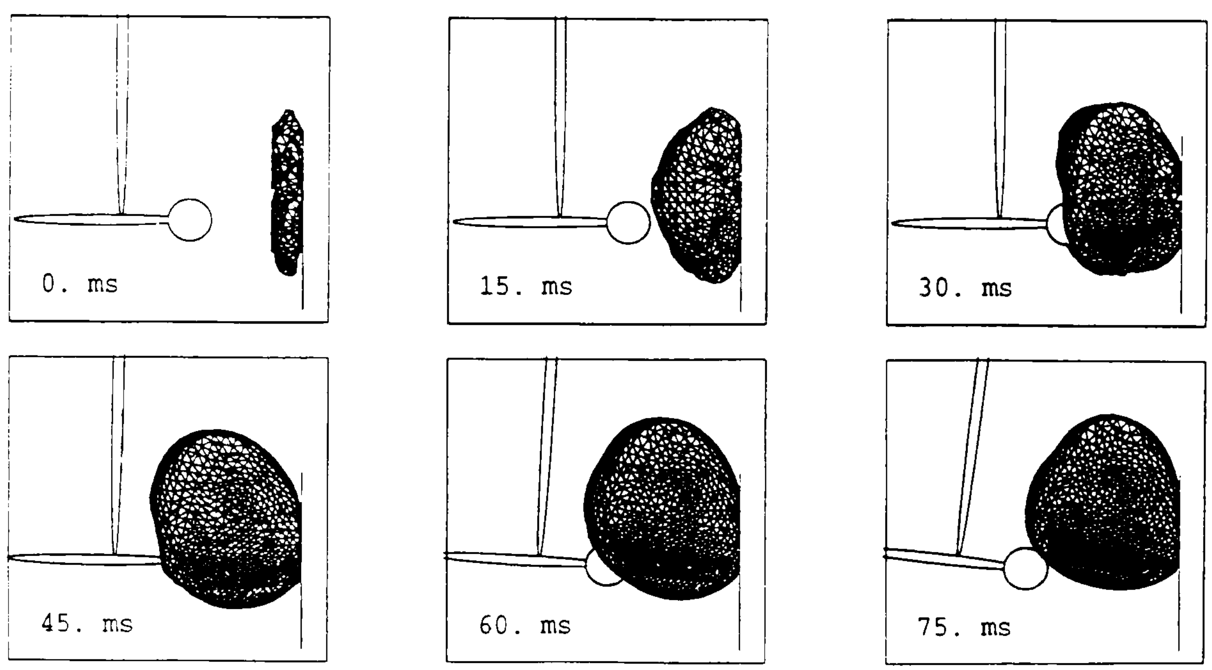

Fig. 11 Calculated kinematics without gas jet

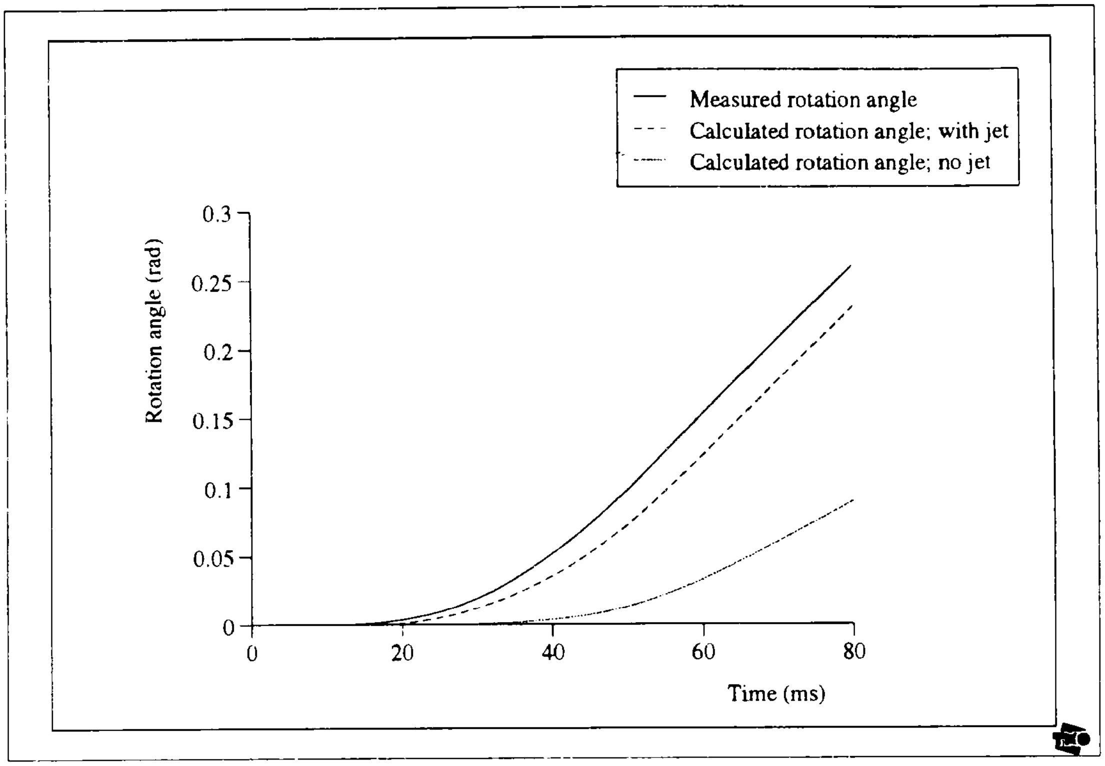

Fig. 12 Pendulum rotation angle time history

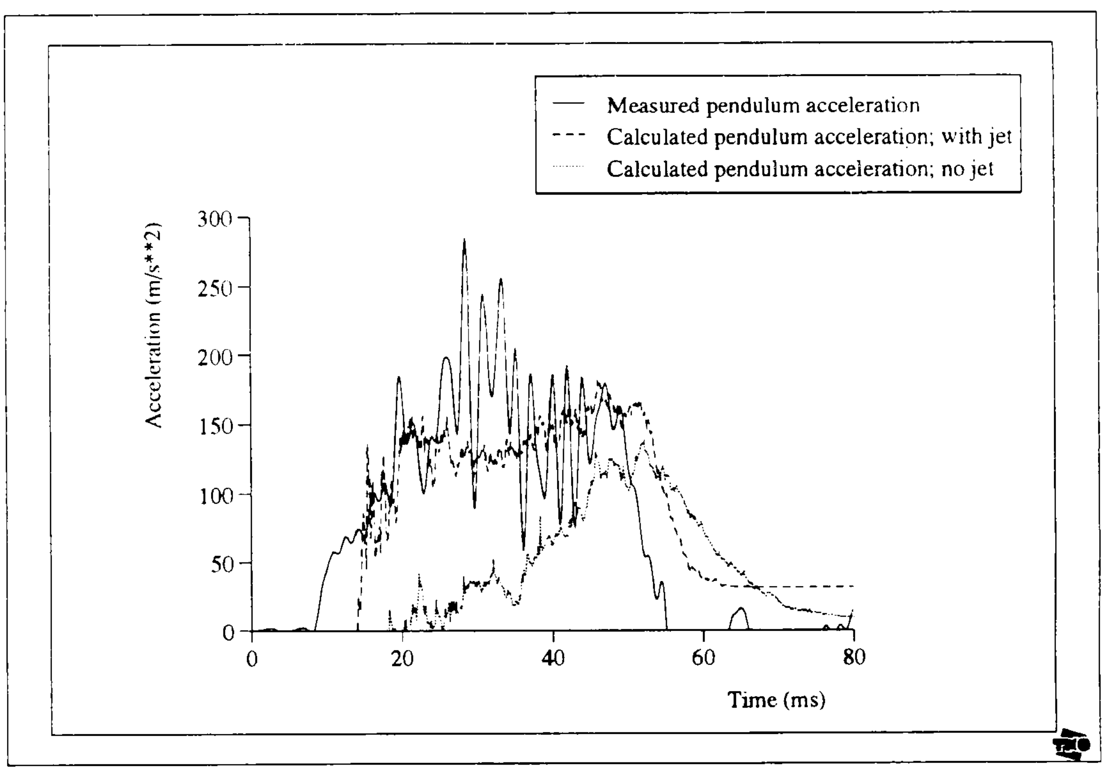

Fig. 13 Acceleration history pendulum c.o.g.

DISCUSSION AND CONCLUSION

Since its appearance on the market MADYMO has been continuously modified and improved [2]. The MADYMO finite element airbag model was released in June 1991. In the recently released version 5.0, friction in contacts between nodes and planes and ellipsoids as well as tyings between nodes and belt segments can be applied. With these options parts of a belt system can be modelled with finite elements allowing sliding over dummy surfaces. Currently a geometrically non-linear triangular thin shell element is being evaluated in a in house version of MADYMO. The shell element is based on the combination of a hybrid stress plate bending element and a constant strain triangle and has only twelve degrees of freedom, namely the displacement components of the three vertices and a rotation about each element side. The element proved accurate and effective for dynamic geometrically and physically non-linear shell analyses. Combining multibody models with finite element discretizations of parts of the restraint systems, car interior structures or dummy parts that undergo large deformations allow detailed analyses of the behaviour of those parts under dynamic loadings in an effective way.

The airbag model proved a versatile and user-friendly simulation tool. This is especially true for the thermodynamics due to the predefined gases, the different outflow models, and the jet model. In an earlier publication [8] the simulation of two tests, in which a driver side airbag comes into contact during inflation with an initially stationary pendulum or 50^{th} percentile Hybrid III dummy, have been described. A good agreement between measured and calculated results was found using the lumped parameter approach and outflow models as described in this paper. The passenger side airbag test presented in this paper however shows a good agreement between the measured and calculated results only when the gas jet effects are included in the analysis.

The gas jet implementation is based on a simple analytical model, assuming among others a steady state flow process, which is a crude description of the actual gas jet phenomena. Despite these excessive simplifications it has been applied successfully for the analysis of the pendulum test with quite reasonable CPU times. To include the gas jet model in the simulation the user needs only to specify the position and geometry of the inflator outlet next to the mass flow rate and temperature time characteristics. The mass flow rate and temperature characteristics can be calculated with the MADYMO tanktest analysis program using the average temperature [5] or dual pressure method [17]. It was chosen not to use the inflator pressure time history as input due to the uncertainties in the dual pressure method.

The gas jet model should be applied for those out-of-position situations where jet effects are expected to have a significant influence on the occupant motion. As long as the occupant only interacts with the airbag after unfolding, the initial configuration of the airbag will have a limited influence on the occupant motion. The laborious creation of a folded airbag configuration is than superfluous. A suitable initial airbag configuration can be obtained from a pre-simulation using a finite element model of the airbag in the design configuration. However if there is contact before complete unfolding, contact forces could be generated during unfolding of which the magnitude largely depends on the airbag initial folding pattern and unfolding mechanism. In order to be able to include these effects, as well as other contact interactions between finite element structures, an additional contact algorithm will be implemented in MADYMO. It is expected that the gas flow through the folds has to be modeled using an Eulerian discretization in order to obtain realistic results. A very fine three dimensional Eulerian mesh, resulting in very large CPU times, would then be necessary. The value of such analyses should be considered in the knowledge that real airbags differ from each other due to manufacturing tolerances, through ageing and as the environmental temperature and pressure change.

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DISCUSSION

PAPER: **Evaluation of Gas Jet Model for Air Bag Inflators**

PRESENTER: Henk A. Lupker, TNO

CO-AUTHOR: Mr. W. E. M. Rruijs

QUESTION: N. Rangarajan, GESAC

Henk, I guess you use some kind of unbounded jet theory to represent the gas flow.

ANSWER: Um mm

Q: How did you transfer the momentum from that jet onto a folded bag or a non-folded bag.

A: They are two different phenomenons. The unfolding of the air bag deals with the contact interaction between the folds and folding, and what I presented here is that the gas jets seize a certain element. The velocity, that element is known, from that you know a momentum transfer. The momentum transfer translates into a pressure working on this element and then this element starts to move. During unfolding, it will be prohibited to move more, that is prohibited due to the inertia of the other elements, but these are two separate effects, so if you model one and you can include the other in your model, then those effects are accounted for. So it is more or less independent.

Q: Thank you.

Q: Guy Nusholtz, Chrysler Corporation

Just sort of a comment to back up one of the things that you mentioned about the grid size. We did a full boiler and equation gas jet and we found we had to go to one millimeter grid size to match our experimental data and that takes an incredible amount of time to compute sixty milliseconds.

A: OK. Thank you and I think also if you have a folded air bag, if you want to account for the flow of gas through all the folds, you even need much finer mesh, so during the computing time you cannot deal with such kind of phenomenon.

Q: T. C. Low, Ford Motor Company

I have a question about an assumption that you make on your computation? If you use uniform gas dynamics to model your bag inflation process, you're introducing a assumption by yourself, you only have a jet velocity profile that you have to introduce some pressure gradience, it looks to me like the two assumptions are contrary to each other. Can you elaborate on that a little bit more?

A: I don't think that there are contradictions there. If you specify the inflator output, so it means that you specify the mass flow as well as the temperature, actually you define the mass coming into the air bag as well as the energy or the NLP coming into the air bag and what I assume at is some kind of momentum transfer, not mass, not energy, only momentum transfer due to the velocity of the gas, so I didn't include any new turbo-dynamic energy, only energy due to the velocity of the gas so I think it is reasonable to do that.

Q: Chris O'Connor, Ford Motor Company

I had a few questions. When you transfer the momentum from the jet to the fabric or whatever your impacting, what kind of co-efficient of restitution do you apply? Is all of the momentum transferred or is some of it rebound?

A: Almost all the momentum is transferred by that. Be assured that also the gas jet is inverted in direction.

Q: OK. The other thing is, one problem we found is the jets reflecting off of a canister wall on the passenger-side inflator. Will this be able to handle some redirection of momentum or loss of momentum due to impacting a wall?

A: As I said, we don't account for the velocity of the elements, but what we do account for is the direction of the element. We calculate the velocity of the certain point, apply the pressure, perpendicular to the element, so the forces working on the nodes are perpendicular to the element in geometry. So in that way, you account a little bit for the direction of the elements.

Q: Of course. What I'm talking about more is that if you have a fixed inflator wall, the jet will hit that and rebound it, then hit the bag. How would we handle that with this model?

A: This is not incorporated in this model. It is just the jet is in one direction. You assume there is no rebounding whatsoever, so it is not in the model.