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NUMERICAL ANALYSIS OF THE POSSIBILITY OF USING AN EXTERNAL AIR BAG TO PROTECT A SMALL URBAN VEHICLE DURING A COLLISION

This paper presents a three-dimensional model of an airbag located outside of a small city car at the front bumper, which is intended to protect the vehicle against the effects of road traffic collisions. Results of numerical simulations of airbag operation in case of collision with two types of obstacles are presented: a flat, vertical wall and a circular pillar with a diameter of 200 mm. The paper presents the physical model, which is the subject of simulation, along with its mathematical description and the numerical calculation scheme used.

1. Introduction

Airbags, besides items such as car seat belts or controlled crumple zones, are an important component of the features constituting vehicle passive safety. During a collision, the travelers' risk of injury and even loss of life depends largely on these features. A large inertial force acts during an accident on vehicle occupants, who may suffer from injury caused by impacting items and equipment (steering wheel, dashboard, etc). The task of the airbag is to quickly fill the space between the travelers and the vehicle's structural elements, to acquire the momentum, and to amortize the impact force, which results in a decrease in the load acting on the body of the passenger.

In this paper, we deal with a type of an airbag different from those being practically used in automobiles. There are already existing applications of external airbag systems, such as those protecting the crew escape module on the F-111 [8], emergency airbags attached to helicopter undercarriages [13], and those used to attenuate the landing of the spacecraft on Mars [3].

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It is expected that in the future, big five-four seat vehicles will be removed from city centers; they will be replaced with small single-double seat vehicles with much smaller dimensions and weights, probably electrically driven, and with the maximum speed limited by the design of the vehicle.

Due to the assumed low vehicle weight and its maximum speed limitation, it has become possible to consider the use of an external airbag as an impact energy absorbing device.

The length of such vehicles would represent half the length of the typical car which would allow two small vehicles to park in a normal parking space, thereby doubling the possible number of vehicles in the city. However, small, rather short vehicles have a small space allocated to energy absorption during a possible collision. To improve the safety of such vehicles while driving, it is proposed to use static airbags placed at the front and rear of the car. These airbags would be filled with air after the car leaves the parking space, creating a buffer zone in front of and behind the vehicle. This does, however, result in an increase in total length during vehicle operation. Airbags would be emptied and rolled before the vehicle would be able to park again, allowing for the use of small parking spaces. In the present work, to show the feasibility of such an airbag, the scope is limited to airbags placed in front of a light urban vehicle.

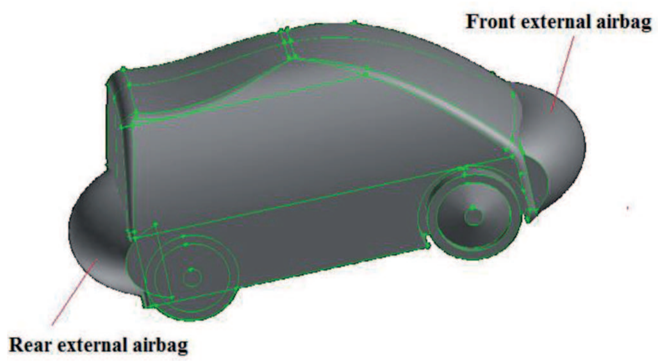

Fig. 1. Proposed locations of the external airbags on city car prototype

Fig. 1 presents a projection of an urban car to be developed at WUT and equiped with the external front and rear airbags protecting the car during a collision.

The proposed security system would consist of an external air bag, which is the first element of protection, a front swinging framework designed for the dynamic altering of force directions from a direct head-on collision into an oblique collision, and deformable suspension components of swinging frames around a rigid driver safety cage. The driver is additionally protected by a safety belt system. In the future, the use of air bags also protecting the driver (mainly his head) will be taken into consideration. The protection scheme is presented in Fig. 5. More details are included in chapter 4.

Different airbag models were used for simulation of different collision scenarios. One of the challenging tasks is the initial stage of airbag deployment. Many investigators [2,5,11,12,14,15] have paid attention to the situation called Out-of-Position, which takes place when a non fully extended airbag interacts with occupants. Typically, commercial codes are used for such investigations [9,10,17], however some investigators use their own codes [18].

General information about methods used in investigation of fluid structure interaction can be found in [1].

As a part of this work, a method and a program have been developed to calculate pressure changes in the airbag and its shape deformation during a collision with an obstacle.

2. Concept of vehicle and pedestrian collision protection by an external static airbag

This study focuses on the application of an external airbag as an unusual protective element of the urban vehicle, which also acts as a device protecting pedestrians during a collision with this vehicle. The main feature of this airbag is that it is stationary. The airbag is filled with air in a static way at the time of vehicle departure from a parking space. A small compressor placed in the vehicle fills the airbag with compressed air to a preset pressure, thereby giving the airbag its expected shape. Before parking once again, the same compressor removes air from the airbag. The airbag fabric is pressed against the the vehicle surface, thus reducing the overall car length. A vehicle with a folded bag has a small overall size allowing two such cars to park in a parking space used by a single conventional car. An example of the placement of such airbags to protect the entire vehicle and pedestrians is shown in Figure 1.

The airbag would be pumped up through a small on-board compressor to a small initial pressure suitable for forming the proper shape of the bag. During collision, the airbag empties in a controlled manner through a set of valves, thus absorbing impact energy. To guarantee proper airbag operation in different situations, such as a collision with a large flat obstacle or a small round obstacle, it is proposed to construct a segmented airbag in which one or more segments can participate in the protection of the vehicle. The use of such an airbag during a collision as the main protection system of the whole vehicle (and pedestrians) makes sense only for cars with much smaller masses compared with the heavy vehicles produced today. When considering the construction of special one-two passenger vehicles for the use in inner city areas operating at speeds limited by the design of the vehicle rather than municipal rules, very light and durable bodies can be obtained by using unusual materials.

The overall collision protection model of the vehicle consists of three structures and their related mechanisms of action. The first structure is a rigid safety cage. The driver of the vehicle is attached to the frame structure by a five-point safety belt. The frame is broad enough to allow movement of the body of the driver which is delayed and controlled by these safety belts. In the front of the vehicle, a multi-element air bag is attached to the deformable elements of the outer frame. The frame is attached so that it can rotate around a vertical axis located in the plane of symmetry of the vehicle. In the event of a frontal, but not centered collision, the airbag frame should turn around the central pivot and allow for slipping between colliding vehicles.

It is expected that the external air bag will be the only protection element during a collision at low speeds (eg. up to 15 km/h). At higher speeds, the airbag will work during a collision at the initial impact, and after having exhausted its energy-absorbing potential, the structure between the frame and airbag will begin deforming, further protecting the rigid safety cage.

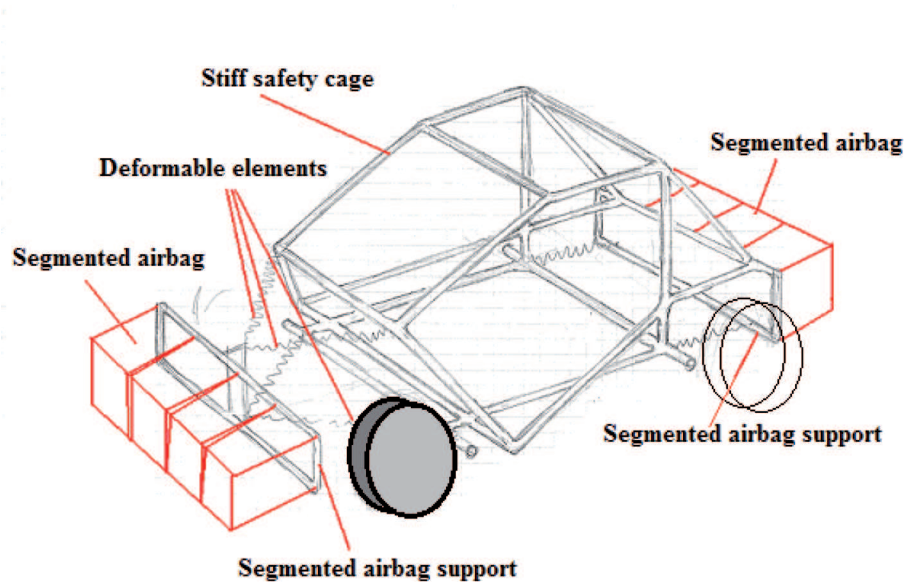

Fig. 2. Elements of an urban car collision protection system including external multi-chamber airbags

Figure 2 shows the assumptions for the construction of the vehicle structure and location of the external airbags.

There are plans to use research results published in this work to build an airbag that protects an urban vehicle prototype built at the Faculty of Power and Aeronautic Engineering.

3. Airbag model

The considered airbag model has only two components (Fig. 3). It consists of a non-permeable fabric bag and an outlet valve. The valve is closed as a default and opens in an irreversible way after increasing the pressure inside the airbag to a predefined level.

The impact of transient effects on the work of the airbag during its dynamic opening has been analyzed in [16]. The motion of the airbag fabric delays due to the inertia of the air surrounding the airbag. In this case, the velocities of gas flowing from the gas generator and the airbag fabric in the initial period of its motion are considerable. The assumption of a uniform distribution of the instantaneous pressure inside the airbag is generally not true, and it is therefore necessary to model wave motion inside the airbag.

In the present study, an analysis was performed on the process of deformation of the airbag by an exterior obstacle in addition to the air outflow through an appropriate valve. The speed of the airbag walls and that of air in its interior are small enough, so that in this case it is possible to use the uniformly distributed pressure (UDP) model on the airbag. It was assumed that the airbag consists of four separately sealed chambers, each initially filled with air. Each of these chambers has an independent valve, which opens to allow air outflow when the pressure in the chamber during the collision exceeds the assumed value. The air filling the airbag chamber is compressed during the first phase of collision, and then fleeing through the open valve, absorbs impact energy resulting from a vehicle collision with an obstacle.

3.1. Elements of the airbag

A numerical simulation was performed for a small portion of space covering the airbag. The volume calculation is subject to discretization. This procedure is designed only to facilitate the calculation of the volume of the airbag because the uniform pressure distribution model is used. The fabric of the bag shell forms the boundary separating the high pressure area (inside bag) from the low pressure area (external environment) in which the assumption of gas parameters are constant. The bag surface itself is also subjected to discretization. Triangular elements were used here to allow the construction of a surface with complex geometry.

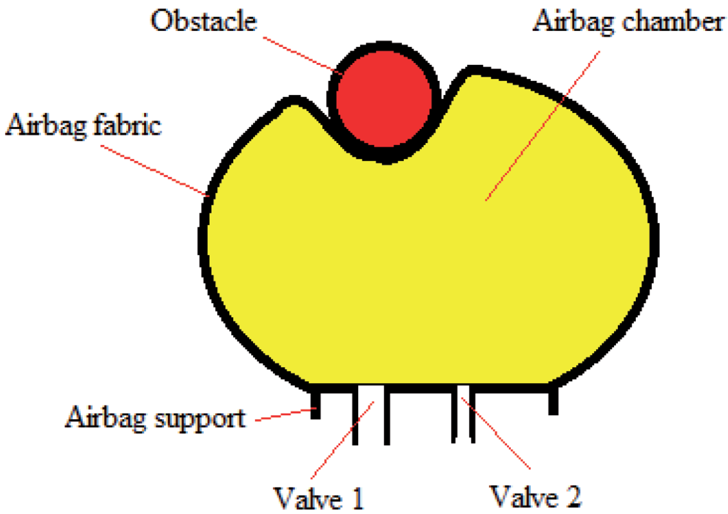

Fig. 3. Diagram showing elements of the airbag including the impacting obstacle and release valves

3.1.1 Model of the air compression process in the airbag chamber and air flow through the release valves

During a collision, the physical processes taking place in the individual gas chambers enclosed in a multi-chamber airbag occur in two stages. At the first stage, when the outlet valve is closed, the pressure and temperature of air inside the airbag increase to accommodate the same mass of air in the decreasing chamber volume. Pressure then exceeds a critical value, causing the valve to open. The second stage of airbag action then begins where the mass of air inside the bag is decreased due to the air outflow though the opened outlet valve.

At the time of collision with an obstacle, and with the valve closed, there is a gradual but rapid decrease in the volume of the airbag shell, and therefore the volume of gas contained within it, without changing its mass (the shell is sealed). We assume that the process is so fast that there is no energy loss due to conduction of heat to the external environment. Therefore, this process can be considered as adiabatic (without heat exchange with the environment). The ideal gas compression is described by the following dependencies:

$$\frac{p_2}{p_1} = \left(\frac{V_2}{V_1}\right)^k \tag{1}$$

$$\frac{T_2}{T_1} = \left(\frac{V_2}{V_1}\right)^{k-1} \tag{2}$$

where:
T_1, T_2 – gas temperature inside the bag at the time t_1 and t_2 respectively
V_1, V_2 – gas volume inside the bag at time t_1 and t_2 respectively
p_1, p_2 – gas pressure inside the bag at the time t_1 and t_2 respectively
k – is the gas constant
The situation changes when it comes to opening the valve, which leads to air outflow from the airbag shell.
In the case of subcritical flow of expenditure, the volume flow through the nozzle valve is calculated from the relation

$$Q = \alpha\beta A \frac{p_0}{\sqrt{T_0}} \sqrt{\frac{2k}{R(k-1)}} \sqrt{\left(\frac{p}{p_0}\right)^{\frac{2}{k}} - \left(\frac{p}{p_0}\right)^{\frac{k+1}{k}}} \tag{3}$$

where
- p ambient pressure
- p_0 pressure inside the bag
- T_0 temperature inside the bag
- k isentropic exponent (ratio of specific heats)
- R Air gas constant
- $\alpha\beta$ coefficients of contraction and loss of speed
- A valve cross-sectional area

At a pressure ratio $\frac{p}{p_0} < \frac{p_*}{p_0}$ where $\frac{p_*}{p_0} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$
it is necessary to use the relation describing critical flow. Critical flow rate is defined by the equation

$$Q_* = \alpha\beta A \frac{p_0}{\sqrt{T_0}} \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{4}$$

Changes of pressure inside the airbag chamber can be calculated from the energy equation:

$$\frac{dp}{dt} = \frac{k-1}{V} \sum_{i=1}^{N} \alpha\beta\rho_i u_i A_i \left(\frac{kRT_i}{k-1} + \frac{u_i^2}{2}\right) \tag{5}$$

where
- V is the instantaneous volume of the chamber
- ρ density of the departing air
- u air outlet speed
- T air outlet temperature

and N is the number of chambers within the airbag.

It is assumed that the valve opens when a specified pressure is exceeded inside airbag and that it stays open until the end of the airbag emptying process.

3.1.2 Model of airbag fabric dynamics

It was assumed that the dynamic model of the airbag fabric takes into account the inertia of the fabric, its elasticity, the pressure forces acting on the fabric, and the forces of fabric contact with an obstacle. It is assumed that the obstacle is rigid, and that during contact with an obstacle the fabric takes the shape of the obstacle(s) in the contact zone. Furthermore, the fabric can be dragged around the obstacle causing the occurrence of frictional forces between them.

The lumped parameter model was applied in this case (Fig.4). Airbag fabric is discretized using triangular elements. The fabric is modeled as a set of masses connected with their neighbours by springs. It is assumed that the whole mass of an element is concentrated at its vertices (it is 1/3 the mass sum of triangular shell elements surrounding the node), and thus motion of the fabric as a whole is the result of the movement of its vertices. For each triangular element, pressure forces acting on the fabric surface are calculated, taking into account pressure differences across the fabric and element surface, which are then redistributed to the element vertices (Fig. 5). Tensile forces generated by deformation of the fabric surface are calculated on the basis of vertex motion and change of the relative distance between neighbouring vertices. Friction forces during the contact of contact with an obstacle are calculated taking into account vertex velocity relative to the obstacle. Interactions between fabric – fabric contact are resolved from rebound forces generated in the case when the distance is too close between non-neighbouring vertices.

Before proceeding with the numerical simulation, the free (initial) distance between the neighbouring vertices is determined for each element. This is the state in which the shape of the airbag is defined without the presence of elastic forces. For each element of the airbag fabric, forces that arise on that element as a result of the pressure difference between the gas inside the bag and the external environment are calculated.

In the first stage of each time step of the integration procedure, the function calculating an element surface area and its spatial orientation is called. In the next step, the value of the pressure force acting on the element is calculated.

To be able to designate the pressure inside the airbag, its volume at any given time needs to be known. The airbag shell is mowing inside space

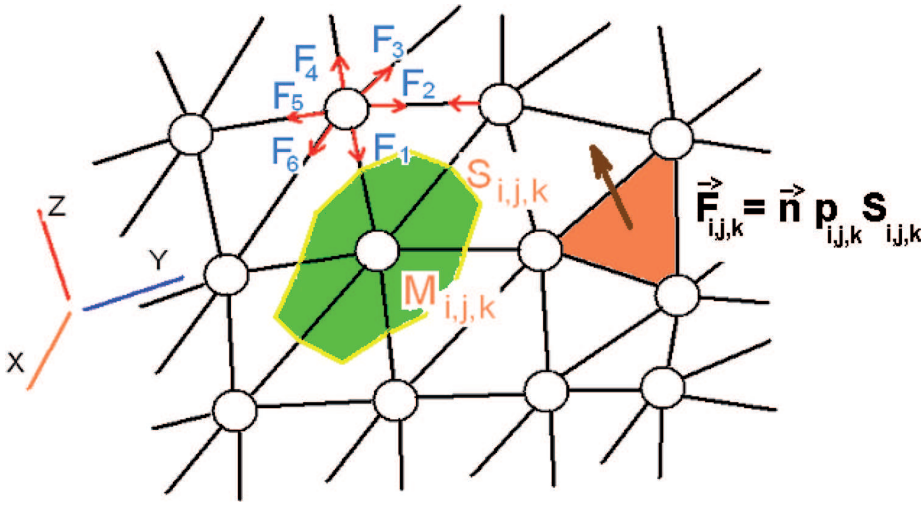

Fig. 4. Schematic description of lumped parameters model used in investigation of airbag dynamics

divided into small hexagons. To determine the volume, a procedure taking into account the location and spatial orientation of the shell elements marks hexagons containing shell elements. In that way, the boundary between the internal and external airbag space is determined. After counting the internal hexagons, their number multiplied by an elementary volume of a single hexagon defines the airbag's internal volume. As previously mentioned, the shell model of the airbag fabric assumes that it is built of triangular, flat elements. The entire mass of the element is redistributed and accumulated in the corners (nodes), which are connected by edges of the element. Changes in distance between the vertices (nodes), and therefore deformation of the sides of triangles give variation of elastic forces acting between vertices (nodes). Therefore, the airbag fabric can otherwise be described as a collection of material points (vertices of triangles) connected by elastic massless elements (Fig. 4). The forces acting on the shell defined as the entire grid will introduce vibration. To ensure that the model provides a more accurate reflection of reality, in addition to element elasticity, element damping must be introduced, which causes quenching of excited vibrations. The real airbag fabric is formed by the crossing of filaments. During fabric tensing (stretching), there exists friction between crossing filaments. Frictional effects are calculated using an appropriate procedure in the program. The essence of its operation is based on determination of the relative speed with which the nodes belonging to one shell element move relative to another, and on this basis facilitate the calculation of damping forces, whose values are directly proportional to the relative node velocity.

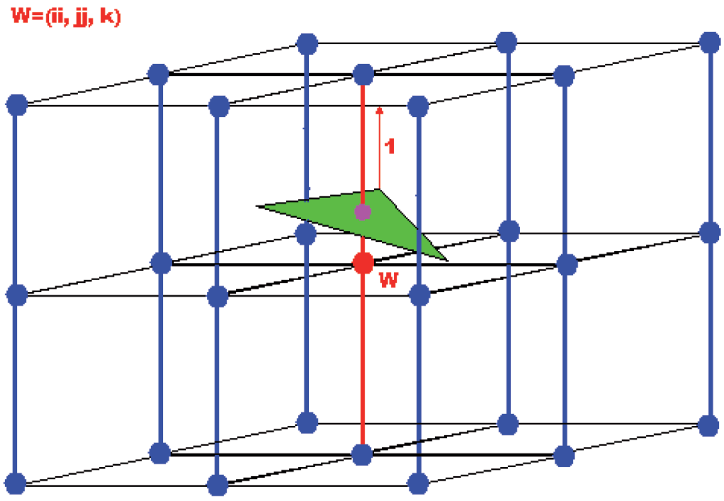

Fig. 5. Part of a gas grid with the selected nodes: internal (lying inside the shell – red), possible external (blue) and potential directions of spatial orientation shell element (direction = 1... 6)

All the calculated forces, after being assembled into components, are stored in an array for later use in the program.

3.2. Numerical algorithm

The movement of the mass centered in each node is the result of the sum of the forces on the node originating from the differential pressure acting on the elements of the shell near the node, the elastic forces of the coating determined by the movement of neighboring nodes, and the damping forces based on the velocity of moving nodes. The node coordinates determining the position and velocity of the shell can be obtained by integrating the appropriate equations of motion.

For each node, there exist three equations of motion for each different direction:

$$
\begin{aligned}
m_i \frac{d^2 x_i}{dt^2} &= \sum_{k=1}^{Mt} S^i_{nX}\left(p^i_{wew} - p^i_{zew}\right)/3 - \sum_{k=1}^{Kw} K\left(\frac{(\Delta d_k)}{\left(d_k^{ref}\right)}\right)_x - \sum_{k=1}^{Kw} C\left(\frac{(\Delta d_k)}{\Delta t}\right)_x \\
m_i \frac{d^2 y_i}{dt^2} &= \sum_{k=1}^{Mt} S^i_{nY}\left(p^i_{wew} - p^i_{zew}\right)/3 - \sum_{k=1}^{Kw} K\left(\frac{(\Delta d_k)}{\left(d_k^{ref}\right)}\right)_y - \sum_{k=1}^{Kw} C\left(\frac{(\Delta d_k)}{\Delta t}\right)_y \\
m_i \frac{d^2 z_i}{dt^2} &= \sum_{k=1}^{Mt} S^i_{nZ}\left(p^i_{wew} - p^i_{zew}\right)/3 - \sum_{k=1}^{Kw} K\left(\frac{(\Delta d_k)}{\left(d_k^{ref}\right)}\right)_z - \sum_{k=1}^{Kw} C\left(\frac{(\Delta d_k)}{\Delta t}\right)_z
\end{aligned}
\tag{6}
$$

where

$\sum_{k=1}^{Mt} S_{nX}^{i}\left(p_{wew}^{i} - p_{zew}^{i}\right)/3$ – means the sum of the component pressure forces acting on surface elements adjacent to the node (summing the elements of the next adjacent node).

$\sum_{k=1}^{Kw} K\left(\frac{(\Delta d_k)}{\left(d_k^{ref}\right)}\right)_x$ – means the sum of component elastic forces derived from the change in the distance d from neighboring nodes (aggregation after successive nodes adjacent to node).

$\sum_{k=1}^{Kw} C\left(\frac{(\Delta d_k)}{\Delta t}\right)$ – means the sum of component damping forces derived from the change in the distance d from neighboring nodes and the speed of its evolution over time (adding up the successive nodes adjacent to node).

Initial conditions:

$$\begin{array}{ll} x^{i}(t) = x_{p}^{i} & \left.\frac{dx^{i}}{dt}\right|_{(t=0)} = 0 \\ y^{i}(t) = y_{p}^{i} & \left.\frac{dy^{i}}{dt}\right|_{(t=0)} = 0 \\ z^{i}(t) = z_{p}^{i} & \left.\frac{dz^{i}}{dt}\right|_{(t=0)} = 0 \end{array} \tag{7}$$

These express the state of stillness before the start of the airbag operation simulation.

The system of second-order differential equations written for all nodes describing the airbag fabric motion can be transformed into a two-times larger system of first order differential equations that can be numericaly integrated using the Runge-Kutta method.

4. Numerical simulations

4.1. Preliminary analysis of the vehicle stopping process

A drastic reduction in vehicle mass from a typical car mass of 1000-1200 kg to 200 kg for urban cars has made it feasible to consider the possibility of using an external airbag to stop such a vehicle. The idea of an external airbag's application requires the estimation of the range of its applicability.

Assuming the vehicle mass m = 200 kg, and vehicle stopping distance = 0.6 m, one can calculate deceleration values for different initial vehicle velocity. The results of these calculations are presented in Table 1.

Table 1.

$g = 9.81\ m^2/s$
$s = 0.6\ m$
$m = 200\ kg$

a/g	a [m^2/s]	v [m/s]	t [s]	F[N]	F[KG]	v [km/h]
1	9.81	3.431035	0.349749	1962	200	12.35
2	19.62	4.852216	0.24731	3924	400	17.47
3	29.43	5.942727	0.201928	5886	600	21.39
4	39.24	6.86207	0.174874	7848	800	24.70
5	49.05	7.672027	0.156412	9810	1000	27.62
6	58.86	8.404285	0.142784	11772	1200	30.26
7	68.67	9.077665	0.132193	13734	1400	32.68
8	78.48	9.704432	0.123655	15696	1600	34.94
9	88.29	10.2931	0.116583	17658	1800	37.06
10	98.1	10.84988	0.1106	19620	2000	39.06
11	107.91	11.37946	0.105453	21582	2200	40.97
12	117.72	11.88545	0.100964	23544	2400	42.79
13	127.53	12.37077	0.097003	25506	2600	44.53
14	137.34	12.83776	0.093474	27468	2800	46.22
15	147.15	13.28834	0.090305	29430	3000	47.84
16	156.96	13.72414	0.087437	31392	3200	49.41
17	166.77	14.14652	0.084827	33354	3400	50.93
18	176.58	14.55665	0.082437	35316	3600	52.40
19	186.39	14.95553	0.080238	37278	3800	53.84
20	196.2	15.34405	0.078206	39240	4000	55.24

When analyzing the results shown in Table 1, we may note that allowing for the structure of the car (without occupants) to have a deceleration of only 10 g, the vehicle can be stopped in a distance 0.6 m from a speed of 39 km/h by a force of 2000 KG acting on the protecting structure. The driver would be additionally protected by safety belts and his deceleration would be even lower.

The car's protective structure has three safety barriers. The first is formed by the external airbags, the second is of the form of the deformable structure, and the third is the stiff safety cage with safety belts as support points.

The analyzed multi-segment external airbag forms the first element of system protection and vehicle stoppage.

The following airbag model has been adopted (Fig. 6). The airbag consists of a number of independent segments. The airbag shell is made of a durable fabric. Inside the shell, there is a deformable, air-impermeable rubber coating. The airbag is inflated initially to a certain pressure. The airbag is equipped with a system of two safety valves with different flow cross-sections and different opening pressures. During a collision, one or more segments of the airbag deform. In the deformed segments, air pressure increases and reaches a value at which one or both valves will open. The air flows out through the valves, thereby maintaining the interior airbag pressure that had initially changed as a result of deformation due to the impacting of obstacle(s) while accounting for vehicle speed, motion, and interaction with other segments of the airbag.

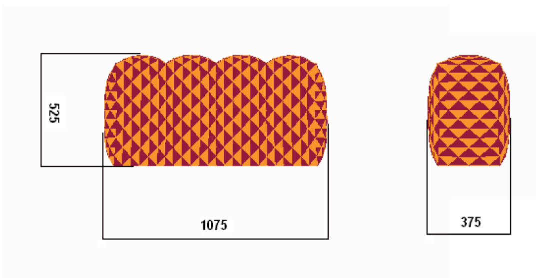

Fig. 6. Basic geometry of the segmented, four chamber airbag

The operation of the external airbag consisting of four independent chambers arranged side-by-side has been analyzed numericaly. Two scenario variations of airbag operation have been considered. One was a collision with a large flat obstacle. The second was a collision with a small circular obstacle (Fig. 7).

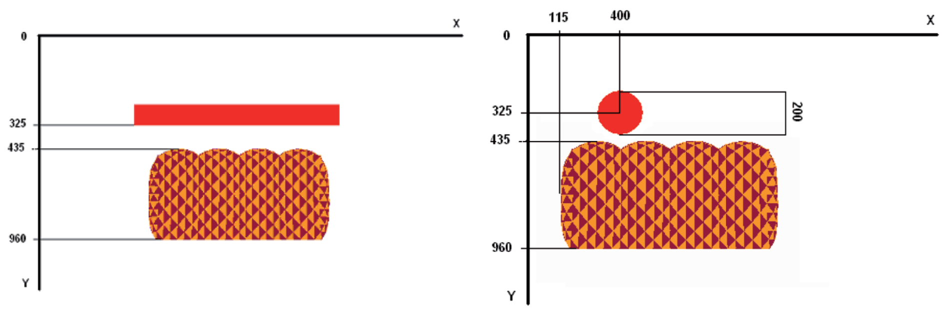

Fig. 7. Airbag model with a flat and cylindrical obstacle at initial position

All collision parameters have been calculated in a reference frame related to the vehicle body. All velocities and displacements are relative to the vehicle. During the simulation, forces arising between the obstacle and the airbag, the instantaneous obstacle velocity, the pressure prevailing in the interior of individual chambers of the airbag, and the airbag shape deformation were recorded.

4.2 Collision with flat obstacle

For the case of a collision with a flat vertical obstacle, we performed a number of numerical simulations to determine the effect of basic parameters on airbag function. The influence of the outflow cross-section of the release valve, the valve opening pressure, and the number and area of the exhaust valves were investigated. For the parameters considered, optimal simulations of a collision with the obstacle at different speeds were carried out. A simulation was conducted for the case of a collision of the vehicle with an obstacle perpendicular to the external airbag.

The considered airbag is relatively slim, and the airbag fabric during the collision loses stability and deforms in an asymmetric way. This phenomenon should be taken into account when designing this type of airbag.

A repulsive force between the obstacle and the nodes forming the airbag shell elements will occur when the distance between them falls below the predifined limit. This force is inversely proportional to the distance between nodes and the obstacle surface. In this way, a contact process is simulated. Due to the orientation of the coordinate system, it will operate along the Y-axis. Along the other axes (X and Z), there may be static or frictional forces acting between the airbag shell elements and the obstacle. These forces will be directly proportional to the force of repulsion.

4.2.1 Effect of release valve opening pressure level

The assumed vehicle mass (small city car) was 200 kg. The collision with the obstacle occurs at 30 km/h. The initial pressure in the chambers of the airbag is 125 kPa (over the ambient pressure). Each airbag chamber is equipped with two release valves opening at different pressures. The surface areas of the valves have values:

– Basic valve area: 0.0015 m^2

– Additional valve area: 0.0005 m^2

As shown below, a series of numerical simulations was used to examine the effect of the pressure at which each valve is opened on the behavior of the airbag. Three cases were tested:

a) 170 kPa – basic valve opening pressure, 220 kPa – additional valve opening pressure

b) 160 kPa – basic valve opening pressure, 200 kPa – additional valve opening pressure

c) 150 kPa – basic valve opening pressure, 180 kPa – additional valve opening pressure

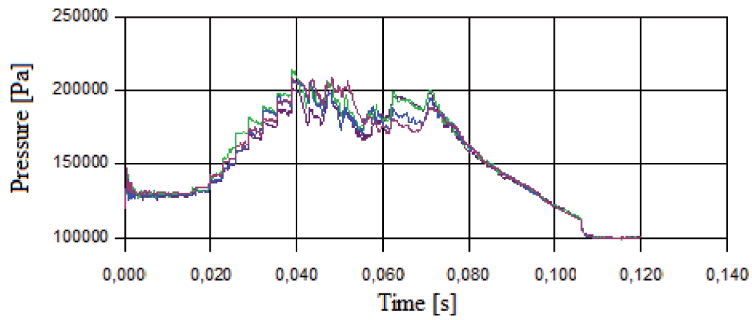

Fig. 8. Variation of the pressure in the airbag chambers for the case a)

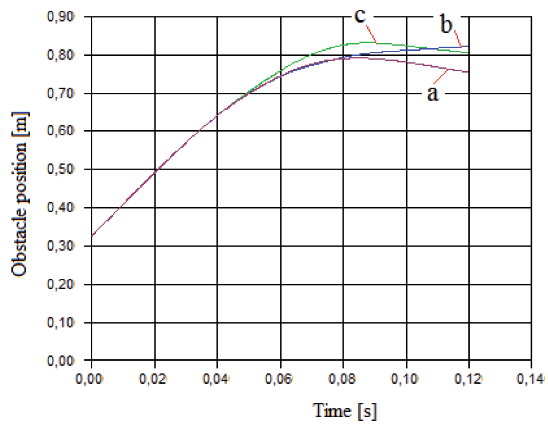

Fig. 9. Position of obstacle as a function of time for three different airbag valve parameters

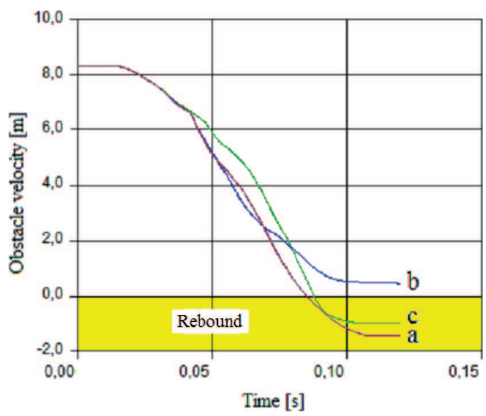

Fig. 10. Time function of obstacle velocity for three different airbag valve parameters

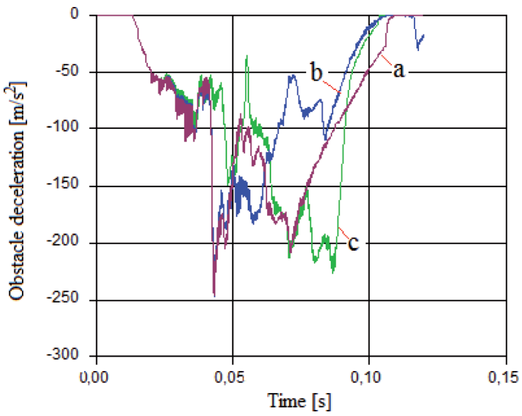

Fig. 11. Obstacle deceleration over time for three different airbag valve parameters

In Fig. 8, variation of the pressure inside individual chambers is depicted for the considered case (a). Pressure values change in all chambers in the same way. Analysing the results presented in Fig. 8-11, one can reach the following conclusions.

For case a), there is no opening of the additional valve. The pressure in the shell does not reach the opening threshold. The additional valve opens only for cases b) and c).

For cases a) and c), the obstacle is rebounded from the airbag. Obstacle deceleration causes the accumulation of energy in the compressed gas in the airbag shell; some of this energy is released, resulting in obstacle rebound. This means that the flow of gas through the open valves it is too small.

For case b), the air escaping from the shell does not absorb all the energy of a collision.

The smallest force acting on an obstacle has been noticed in case c).

4.2.2 Effect of number of valves and valves outflow areas

The assumed vehicle mass was 200 kg. The collision with the obstacle began at 30 km/h. The initial pressure in the chambers of the airbag was 125 kPa (over the ambient pressure).

As shown below, a series of numerical simulations examined the effect of the number of valves and the outflow area of valves on the behavior of the airbag. Three cases were examined:

a) 150 kPa – basic valve opening threshold, 0.0015 m^2 – ouflow area, no additional valve
b) 150 kPa – opening threshold of the primary valve, 0.0015 m^2 – outflow area, 180 kPa – opening threshold of an additional valve, 0.0005 m^2 – outflow area

c) 150 kPa – basic valve opening threshold, 0002 m^2 – outflow area, no additional valve

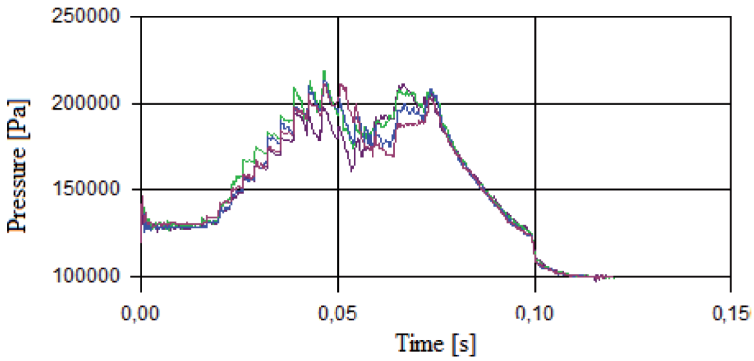

Fig. 12. Dependence of the pressure in the airbag chambers for the case a)

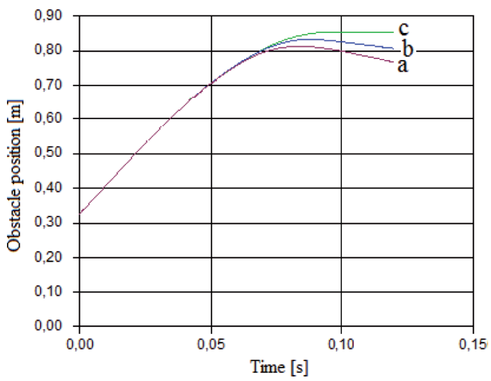

Fig. 13. Position of obstacles as a function of time for three different airbag valve parameters

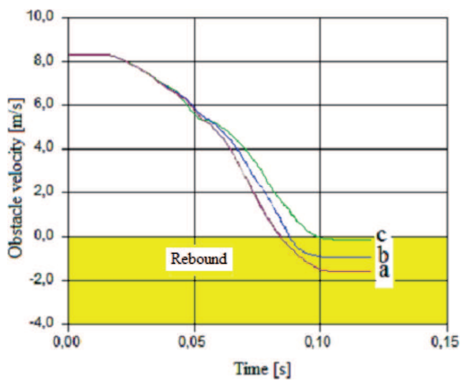

Fig. 14. Obstacle velocity dependence as a function of time for three different airbag valve parameters

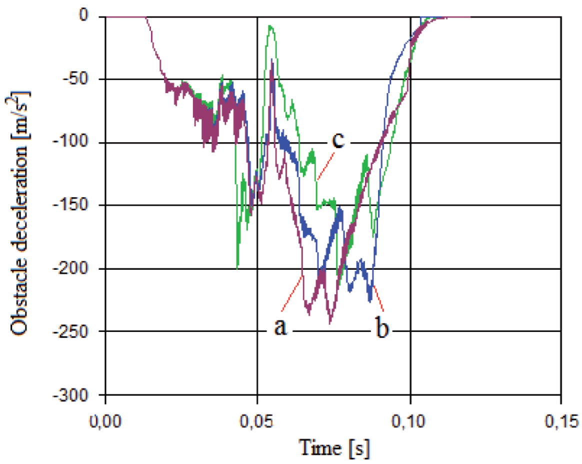

Fig. 15. Obstacle deceleration over time for three different airbag valve parameters

Upon analysing the results presented in Fig. 12-15, one can draw the following conclusions.

For all three cases, rebound of the obstacles from the shell airbag can be observed.

The largest part of the impact energy was absorbded in case c) (lowest speed obstacle after rebound). The largest instantaneous force acting on an obstacle arises in case a).

4.2.3 Effect of vehicle speed during a collision

The assumed vehicle mass was 200 kg. The initial pressure in the chambers of the airbag was 125 kPa (over the ambient pressure). Each airbag chamber was equipped with two exhaust valves.

– Basic valve outflow area: 0.0015 m^2

– Additional valve outflow area: 0.0005 m^2

Valve opening pressure threshold is:

– Opening the primary valve: 150 kPa

– Opening an additional valve: 180 kPa

As shown below, a series of numerical simulations of vehicle collisions has been studied for three different speeds:

a) 45 km/h

b) 30 km/h

c) 15 km/h

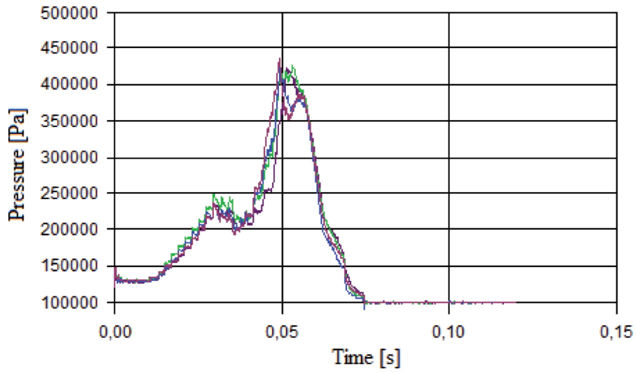

Fig. 16. Variation of the pressure in airbag chambers for the case a)

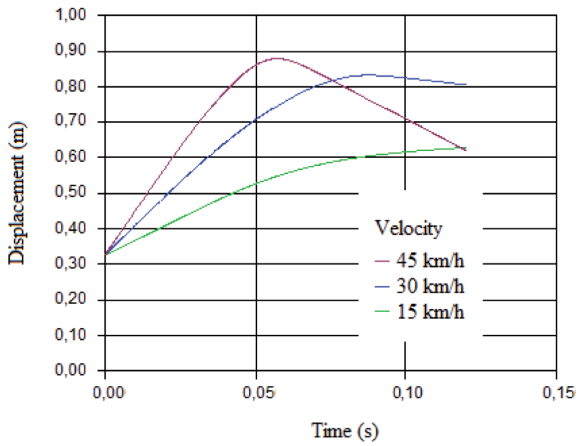

Fig. 17. Position of obstacle as a function of time for the three obstacle speeds

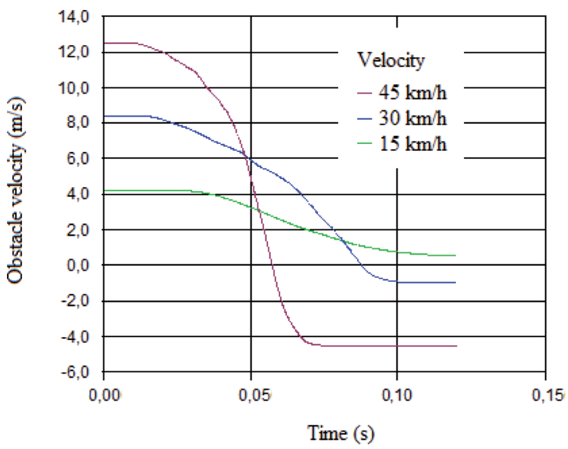

Fig. 18. Instantanous obstacle velocity for three different initial velocities

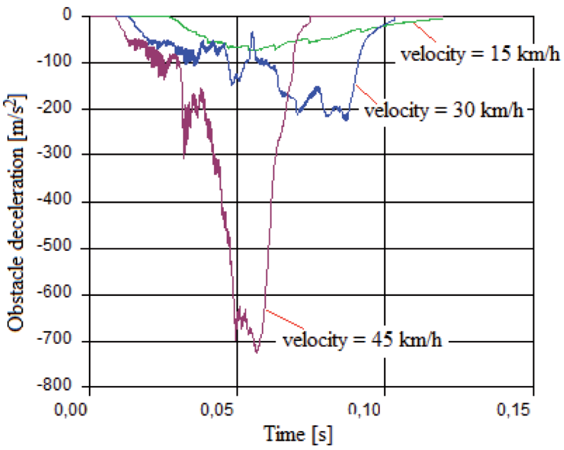

Fig. 19. Obstacle deceleration during the collision for three different initial velocities

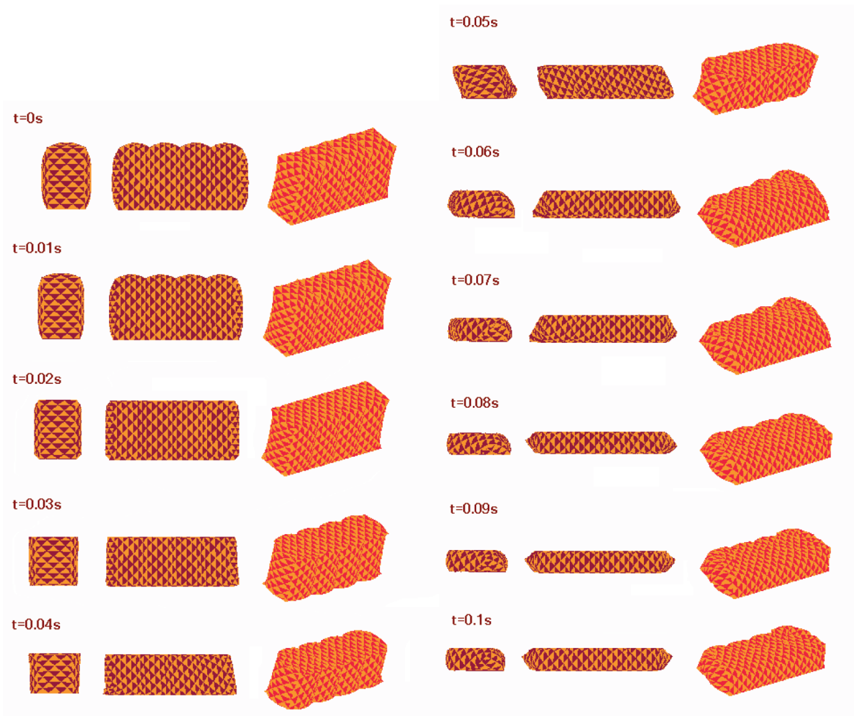

Fig. 20. Phases of the airbag deformation during a collision with a flat obstacle.The initial pressure – 125 kPa; mass – 200 kg; basic valve opening pressure threshold – 150 kPa, outflow area 0.0015 m^2, additional valve threshold pressure180 kPa, outflow area: 0.0005 m^2; vehicle speed – 30 km/h

Upon analysing the results presented in Fig. 16-19, one can make the following conclusions.

For case a), the airbag is not able to absorb all the impact energy; the shell collapses completely so that the obstacle is rebounded from the surface to which the airbag is attached.

In case b), the obstacle is rebounded from a shell filled with compressed gas. In case c), the gas escapes from the shell before it can fully absorb the impact energy.

In Fig. 20, a set of instantaneous airbag shell shapes is presented. There is visible destabilisation of the airbag shell at time t=0.05 s.

4.3. Collision with cylindrical obstacle

For the case of a collision with a vertical circular column with a diameter of 200 mm, only one example of the simulation is shown (Fig. 21-25). Simulation parameters are:
vehicle mass – 200 kg
– initial speed – 45 km/h (12.5 m/s)
– initial pressure – 155 kPa
– valve outflow surface – 0002 m^2
valve opening pressure threshold – 205 kPa
no additional valve

Similarly as in the case of a flat wall, the forces acting between the airbag fabric and the obstacle appear when the distance between these elements falls below the set limit. These forces are inversely proportional to that distance.

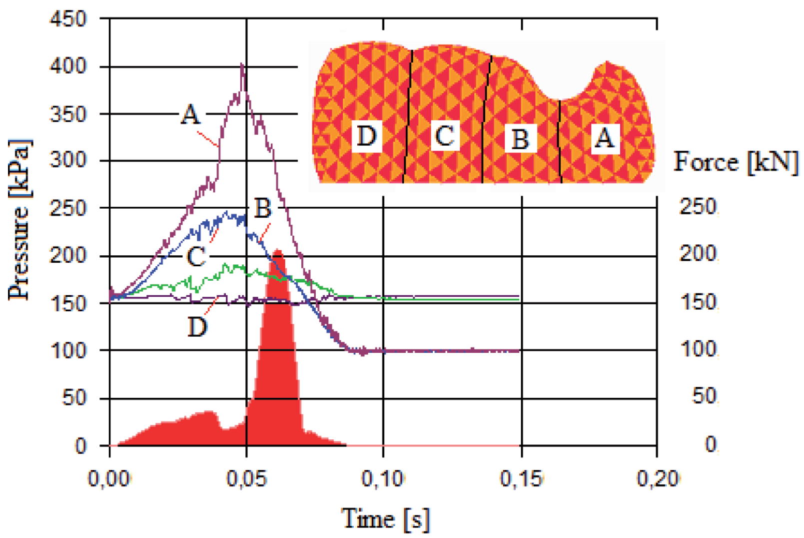

Fig. 21. Variation of pressure in the airbag chambers and the instantaneous force acting on the obstacle during colision with the cylindrical obstacle

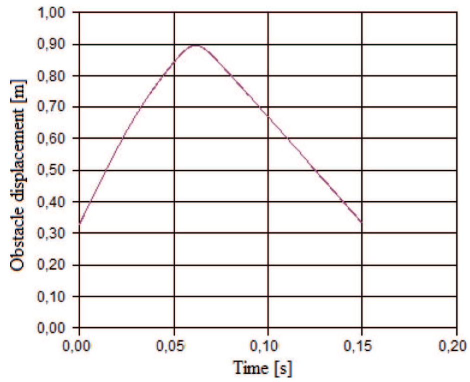

Fig. 22. Obstacle displacement versus time during collision with cylindrical obstacle

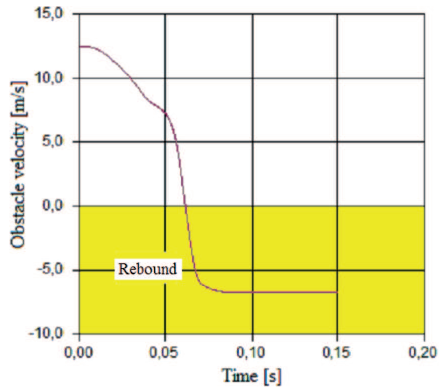

Fig. 23. Obstacle velocity versus time during collision with cylindrical obstacle

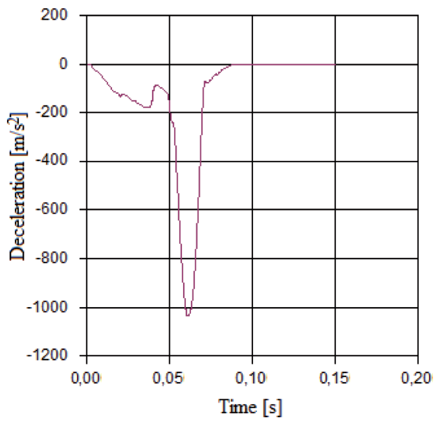

Fig. 24. Obstacle velocity versus time during collision with cylindrical obstacle

Pressure traces representing the pressure in an individual chamber (Fig. 21) are quite different from those observed in previous cases. Only two chambers are practically engaded in the protection process. During a collision with a small object, only neighbouring airbag chambers are deformed enough to initiate the opening of the relase valves. The valves open in only two adjacent chambers of the airbag. In other chambers, the pressure increases but does not reach the valve opening threshold. The obstacle is rebounded from the surface to which the airbag is attached. The shell is unable to absorb all the energy of the collision.

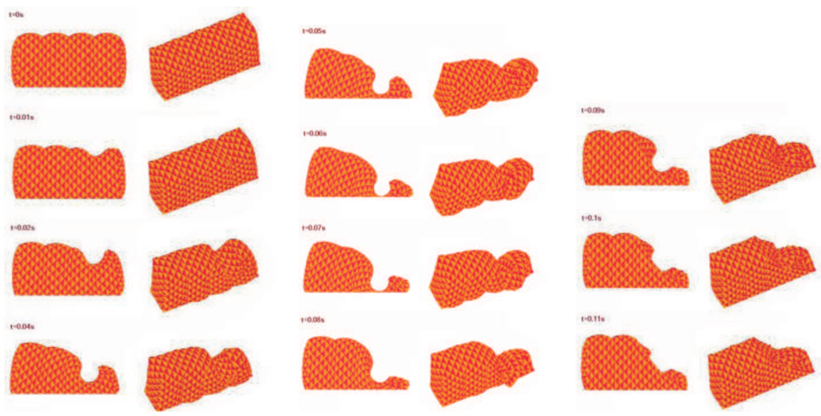

Fig. 25. Phases of the four-chamber airbag deformation during collision with a cylindrical obstacle. The initial pressure – 155 kPa; mass – 200 kg; basic valve opening pressure threshold – 205 kPa, outflow area 0.002 m^2, vehicle speed – 45 km/h

In Fig. 25, a set of instantaneous airbag shell shapes is presented. Also in this case, there is a visible destabilization of the airbag shell at the time instant $t = 0.05$ s.

5. Conclusions

Upon analyzing the results of the calculations, we can conclude that an airbag of the assumed structure has the potential to protect the vehicle under various collision conditions. The developed numerical code can be used for simulation of collision with moving objects with a multi-chamber airbag. The use of only two control valves does not seem to be an optimal solution. The main problem is with the predefinition of the valve opening pressures and valve cross-sectional area. At low-speed collisions, opening the greater valve first will vent the gas from the airbag shell before it has time to absorb the impact energy. At high speeds, the pressure may rise dangerously – it imposes high demands on the strength coating that has not ruptured under the influence of large stresses. The average impact velocity and late valve opening causes a rapid pressure increase in the airbag shell, which is then followed by rapidly exhausting the air from the airbag without absorbing the total impact energy. With an earlier valve opening, pressure grows more slowly, and thus the gas outflow velocity is smaller, and the airbag has a longer time to absorb impact energy. The suggested solutions, which should be further examined, consist of a combination of several valves (three to five) with smaller opening areas that open gradually with increasing pressure in the shell. Another possibility is a valve that has an opening process controlled by an external system. Such system can be based on the so-called ”Adaptive Impact Absorption” technique investigated and presented in [6, 7].

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REFERENCES

[1] Altamore P.F., Steenbrink A.C.: Fluid/structure computational methods in restraint system design, Computational Fluid and Solid Mechanics 2001 Elsevier Science Ltd. K.J. Bathe (Editor).

[2] Bass C.R., Crandall J.R., Bolton J.R., Pilkey W.D., Khaewpong N., Sun E.: Deployment of Air Bags into the Thorax of an Out-of-Position Dummy, SAE 1999-01-0764.

[3] Fasanella E.L.: 2009, Multiterrain Earth Landing System Applicable for Manned Space Capsules, Journal of Aerospace Engineering, vol. 22:3 (201).

[4] Franz U., Konig C., Rust W., Wolf A.: Simulation der Airbaggenfaltung fur Out-of-Position-Situationen des Fahrers und des Beifahrers fur den Golf A4.

[5] French H., Burley E., Hill T.H., Rossey M., Schulz K.: Simulation Method for Dynamic Out-of-Position Crash Tests, SAE 1999-01-0638.

[6] Graczykowski C., Holnicki-Szulc J.: Protecting offshore wind turbines against ship impacts by means of Adaptive Inflatable Structures, Shock and Vibration, vol. 16, no. 4, pp. 335-353, IOS Press, Netherlands, 2009.

[7] Graczykowski C., Holnicki-Szulc J.: Optimization of dynamic properties of adaptive pressurized structures subjected to impact loads, Proceeding of the 2nd ECCOMAS Thematic Conference on Smart Materials and Structures, 18-21 July 2005, Lisbon, Portugal.

[8] Jackson K.E., Boitnott R.L., Fasanella E.L., Jones L.E., Lyle K.H.: A History of Full-Scale Aircraft and Rotorcraft Crash Testing and Simulation at NASA Langley Research Center, Proceedings of the 4th Triennial Internatonal Aircraft and Cabin Safety Research Conference, Lisbon, Portugal, 2004.

[9] LS-Dyna Theoretical Manual.

[10] MADYMO Theory Manual.

[11] Malczyk A., Franke D., Adomeit H-D.: Dual-Stage Inflators and OoP Occupants – A Performance Study, SAE 982325.

[12] Nusholtz G.S., Wu J., Wang D., Wylie E.B.: Energy and Entropy in Airbag Deployment: The Effect on an Out-of-Position Occupant, SAE 1999-01-1071.

[13] Rotorcraft External Airbag Protection System (REAPS), Defense Update, International on Line Defence Magazine, Issue 3, 2005.

[14] Sheng J., Mu W., Chen C., Bayley G.: The Investigation of the Effects of Air Bag System Parameters on Out-of-Position Occupant Response.

[15] Siebertz K., Funke M., Dickeson A., O'Connor C., Khan A., Pant R., Devu S.: Beurteilung des Insassenschutzes mit Out-of-Position-Modellen, Occupant Protection Assesment from Out-of-Position Models, VDI Berichte.
[16] Steenbrink A.C., Fairlie G.E.: Detaillierte Simulation eines Airbag Aufblasvorganges durch gekoppelte CFD/FE Methoden Detailed Simulation of the Airbag Inflation Process Using a Coupled CFD/FE Method, VDI BERICHTE NR. 1559, 2000.
[17] Sturt R., Shah B.: Recent Developments in Occupant Protection Analysis with LS-DYNA, Japan LS-DYNA Users Conference Tokyo, November 1998.
[18] Tudruj S., Piechna J.: "New model of the simulation of the airbag operation in the case of the out-of-position occupant-the comparison with existing models," The Archive of Mechanical Engineering, Vol. L, No 2, 2003.

Numeryczna analiza możliwości zastosowania zewnętrznej poduszki powietrznej do ochrony małego pojazdu miejskiego podczas kolizji

Streszczenie

Praca zawiera opis trójwymiarowego modelu zewnętrznej poduszki powietrznej ulokowanej na zderzaku małego samochodu miejskiego. Poduszka ta ma za zadanie chronienie zarówno pojazdu podczas zderzenia z przeszkodą jak i przechodnia podczas zderzenia z pojazdem. W pracy przedstawiono rezultaty obliczeń numerycznych zderzenia z płaską przeszkodą i przeszkodą w formie walca o średnicy 200 mm. W pracy zaprezentowano fizyczny model poduszki, wraz z modelem matematycznym i schematem obliczeniowym.