

ADAPTIVE INFLATABLE STRUCTURES FOR IMPACT ABSORPTION

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Abstract. *The paper presents the concept of using Adaptive Inflatable Structures (AIS) for efficient impact absorption. Modelling and control of an inflatable structure subjected to impact loading is described. Optimal strategy of pressure release providing adjustment for various impact scenarios is developed. The paper describes briefly three impact related applications of inflatable structures. The first one is an adaptive road barrier with properties adjustable to the mass and velocity of the hitting object. Another application provides safety of the docking operations in rough sea conditions by means of air-filled rubber cushions. Finally the paper presents an external multi-chamber adaptive airbag dedicated for helicopter emergency landings.*

1 INTRODUCTION

Motivation for the undertaken research is to respond to requirements for high impact energy absorption e.g. in the structures exposed to risk of extreme blast, thin wall tanks with high impact protection, vehicles with high crashworthiness, protective barriers, etc. Typically, suggested solutions focus on the design of passive energy absorbing systems. These systems are frequently based on the aluminium or steel honeycomb packages characterised by a high ratio of specific energy absorption. However high is the energy absorption capacity of such elements they still remain highly redundant structural members, which do not carry any load in an actual operation of a given structure. In addition, passive energy absorbers are designed to work effectively in pre-defined impact scenarios only.

In contrast to the standard passive systems Adaptive Impact Absorption (AIA) approach focuses on *active adaptation* of energy absorbing structures (equipped with sensor system detecting and identifying impact in advance and controllable semi-active dissipaters, so called *structural fuses*) with high ability of adaptation to extreme overloading^{1,2}. The following characteristic cases of AIA problems should be distinguished:

- the case of a protective structure (e.g. protective barrier) sustaining impact overloading with minimised maximum accelerations (or forces)
- the case of an adaptive structure sustaining impact overloading with minimum global measure of plastic-like distortions generated in adaptive dissipaters during the impact scenario

The first case corresponds to smoothing down the impact effect (e.g. for reduction of fatigue effect as in adaptive landing gears) coming from service loads, while the second one corresponds to the impact absorption (e.g. from critical environmental loads) with minimal cost of induced distortions. In both cases a semi-active or fully-active solutions can be applied, which depend on constant or time-dependent modifications realised via controllable dissipative devices. These devices are dissipaters (with no need for significant power supply) rather than actuators. Feasible, adaptive dissipative devices under considerations can be based on the following technologies: MR fluids or (hydraulic or pneumatic) piezo-valves³.

Adaptive Inflatable Structures are one of the special issues for AIA technology. AIS are structures filled with gas under appropriately adjusted changeable pressure. The idea of using compressed air and its controlled release makes pressurised structures easily adaptable for various impact forces and scenarios. The inflated structure can be rigid (as cylinder enclosed by piston), it can be a thin-walled structure undergoing plastic behaviour or it can be a completely deformable air-filled cushion.

Particular types of inflatable structures (for instance road barrier) should be permanently inflated with a relatively low pressure for mitigation of weaker impacts. In other types of inflatable structures (as an airbag) the deployment is planned only when the collision occurs. Pressure of the gas must be adjusted according to the velocity, mass and area of contact with the hitting object. Fast reacting pyrotechnic systems based on the concept of micro explosions (similarly as in an airbag in a car) can be used for immediate gas pumping. Pressure of the gas acting outwards increases the stiffness of the pneumatic structure and prevents its huge deformation effected by the hitting object. Compressed air has also beneficial influence on the buckling behaviour of the structure since it may profitably change the distribution of the compressive forces which cause loss of the structure stability. Further improvement of AIS can be achieved by dividing the structure into several packages separated by flexible walls in which the piezo-valves allowing flow of the gas are mounted. This method almost does not demand the use of additional material, but allows to adjust separately the level of initial pressure in different parts of the structure.

During the collision with the inflatable structure controlled release of pressure is executed by opening exit piezo-valves. This way the stiffness of the pneumatic structure in the subsequent stages of impact can be controlled. It is possible to stop the penetrating object in

the appropriate way and prevent excessive forces and accelerations in the system. Another purpose of applying a release of pressure is to control the dissipation of the energy.

2 GOVERNING EQUATIONS

Numerical analysis of the pneumatic structure subjected to an impact load requires considering the interaction between its walls and the fluid enclosed inside the chambers. Applied external load causes deformation of the structure and change of the capacity and pressure of the fluid. The pressure exerted by the fluid affects, in turn, the deformation of the structure and its internal forces. The dynamics of the inflatable structure is described by the nonlinear equation of motion, whose general form reads:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{K}(\mathbf{q})\mathbf{q} = \mathbf{F}(\mathbf{p}, \mathbf{q}) + \mathbf{F}_I \quad (1)$$

$$\mathbf{q}(0) = \mathbf{q}_0, \dot{\mathbf{q}}(0) = \mathbf{V}_0$$

Vector $\mathbf{p} = \{p_1(t), p_2(t), \dots, p_n(t)\}$ indicates gauge pressures in the cavities. The impact can be modelled by an r.h.s. force vector \mathbf{F}_I or by initial conditions. In any case, the $\mathbf{F}(\mathbf{p}, \mathbf{q})$ vector is always present in the problem, since it provides the coupling between the fluid and the structure. The interaction with the fluid can be correctly taken into account only by assembling the equilibrium equations in actual configuration so the equation of motion has to be considered in a nonlinear form.

We assume that the structure is filled with a compressible (pneumatic) fluid with no viscosity. The fluid in each cavity is not discretized into finite elements but described analytically by the equation of the state for ideal gas:

$$\bar{p} \cdot V(t) = m(t) \cdot R \cdot (\theta(t) - \theta_z) \quad (2)$$

where absolute pressure \bar{p} is defined as $\bar{p} = p + p_A$ where p_A is ambient pressure and p is gauge pressure, the absolute temperature is defined as $\bar{\theta} = \theta - \theta_z$ where θ is current temperature on the Celsius scale and θ_z is absolute zero temperature. The gas constant R is related to the universal gas constant \bar{R} and molecular weight MW by the formula: $R = \bar{R}/MW$. Moreover, the variables ρ, V, m indicate gas density, volume, and mass, respectively. The initial conditions for the fluid are given by: $\bar{p}(0) = p_0, \theta(0) = \theta_0$. In the case of fluid flow, we also consider conservation of mass given by:

$$m(t) = m_0 + \Delta m(t) \quad (3)$$

The increase of the fluid mass in the cavity $\Delta m(t)$ is described by the following integral:

$$\Delta m(t) = \int_0^t q(\bar{t}) d\bar{t} = \int_0^t q_{in}(\bar{t}) - q_{out}(\bar{t}) d\bar{t} \quad (4)$$

where q_{in} is the mass flow rate into the cavity and q_{out} is the mass flow rate outside the

cavity. The direction of the flow depends on the sign of the pressure difference. The relation defining the mass flow rate depends on the assumed model of the flow. In the simplest case, it is given by the formula:

$$\Delta p(t) = C_V q(t) + C_H q(t)|q(t)| \quad (5)$$

where $\Delta p(t) = p_{out} - p(t)$, C_V is the viscous resistance coefficient, and C_H is the hydrodynamic resistance coefficient. Both these coefficients are dependent on the area of the orifice. In general, the control of the inflatable structure properties is executed by changing the diameter of the orifice thus also by changing the flow resistance coefficients C_V , C_H . Under the assumption of an isothermal process (or arbitrarily given change of temperature) a set of equations (1-5) fully describes the coupling between the fluid and the surrounding structure.

The balance of the heat transferred to the system ΔQ , increase of the gas internal energy ΔE and the work done by gas ΔW are given by the first law of thermodynamics:

$$\Delta E = \Delta Q - \Delta W \quad (6)$$

For rapid changes of gas state, an adiabatic process, which assumes conservation of the gas energy, should be considered. When this assumption is applied, the temperature change is calculated from the condition that no energy is added to or removed from the cavity except the gas flow between or outside the cavities. An additional equation reads:

$$\frac{d(m\bar{E})}{dt} = q_{in}\bar{H}_{in} - q_{out}\bar{H}_{out} - \dot{W} \quad (7)$$

where specific energy \bar{E} , specific enthalpy \bar{H} and work done by gas W are given by:

$$\bar{E} = \bar{E}_l + \int_{\theta_l}^{\theta} c_v(T) dT \quad (8)$$

$$\bar{H} = \bar{H}_l + \int_{\theta_l}^{\theta} c_p(T) dT$$

$$dW = \bar{p} dV$$

In many practical cases, the heat capacity at constant pressure c_p and heat capacity at constant volume c_v are considered as temperature independent and equal for the air: $c_p = \frac{7}{2} R$, $c_v = \frac{5}{2} R$. Having taken into account the above definitions and assuming that there is no mass exchange in the cavity we obtain:

$$mc_v \cdot d\theta = -\bar{p} \cdot dV \quad (9)$$

$$\text{or } \bar{p} \cdot V^\chi = \text{const.}$$

where χ is an adiabatic exponent $\chi = c_p/c_v$ and for the air it is equal: $\chi = \frac{7}{2} R / \frac{5}{2} R = 1.4$.

3 ADAPTIVE ROAD BARRIER

This section is aimed at developing a strategy for optimal distribution and release of gas in pressurized packages within simple two dimensional frame which could serve as a basis for a protective road barrier design (cf. Fig.1). The structure may be divided into various number of packages and it may have clamped or sliding supports. The frame is loaded on the upper beam by mass applied with initial velocity which is modelling lateral (non-axial) impact. Material and geometrical nonlinearities are taken into account. The material is elasto-plastic with the hardening, large deformations of the frame are considered.

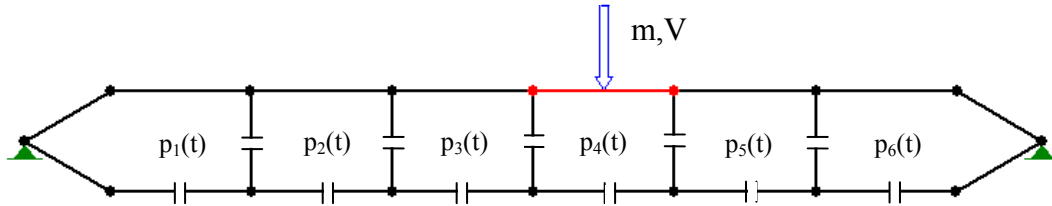


Figure 1: Structure divided into pressurized packages considered in the optimization problem.

Initially we investigate how much we can increase the structure load capacity by filling it with compressed air. Adequate measure of the load capacity is the maximum impact energy which can be applied to the structure. The conditions defining destruction of the structure are based on its deformation shape. Deformation of the structure is admissible if there is no collision between the mass and the lower span and when maximal displacements of the lower span do not exceed a limit value $q_{max} \leq q_{adm}$. Corresponding optimization problem can be understood as searching for the optimum combination of pressure values inside the packages in successive time instances, $\mathbf{p} = \{p_1(t), p_2(t), \dots, p_n(t)\}$, which maximizes the load capacity of the structure.

This approach can be applied for finding the optimal distribution of pressure in three-cell inflatable structure fixed with no sliding (cf. Fig. 2). The loading is executed by object hitting the frame in the middle of the upper span with given initial velocity. Two cases were considered: constant value of pressure and linear decrease of pressure in all packages.

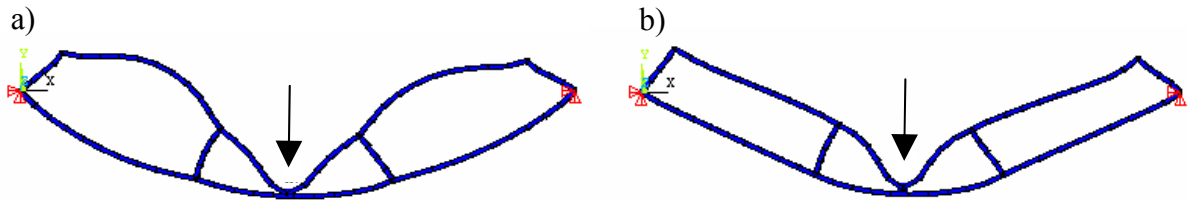


Figure 2: Deformation of the optimally pressurized structure loaded by maximal mass:
a) constant pressure; b) linear release of pressure

In the second case the time when pressure approaches zero is assumed to be equal to the time when the velocity of hitting object drops to zero t_{stop} . In both cases vector \mathbf{p} has two constant components p_1 and p_2 which indicate pressures in lateral and middle cell, respectively. In optimal solution the load capacity is increased 9,01 times. Detailed results for both cases are presented in Table 1 and corresponding deformation of the structure is presented in Fig. 2.

$\mathbf{p}_1(0)$ [kN/m]	$\mathbf{p}_2(0)$ [kN/m]	$\mathbf{p}_1(t_{stop})$ [kN/m]	$\mathbf{p}_2(t_{stop})$ [kN/m]	q_{max} [m]	t_{stop} [s]	\mathbf{m} [kg]
0	0	0	0	0,04	0,152	7596
1600	1147	1600	1147	0,18	0,213	46374
400	3925	0	0	0,18	0,265	68489

Table 1. Comparison of structure load capacity for different values of pressure (central impact)

The second purpose of applying structure inflation is to smooth down the impact by changing structure stiffness during the collision. The goal is to control the displacement, velocity and acceleration of the hitting object. The most beneficial scenario is linear descent of the velocity and constant value of acceleration during the whole process. Hence, optimal displacement trajectory is a second order curve. It must be situated above initial displacement curve since by inflation we can not decrease initial structure stiffness. By applying these strategy we control both maximal accelerations and maximal penetration of the hitting object. The introduced problem can be solved for several numbers of packages in the structure, however pressurizing the one to which the impact is applied is the most efficient method to achieve assumed response of the structure.

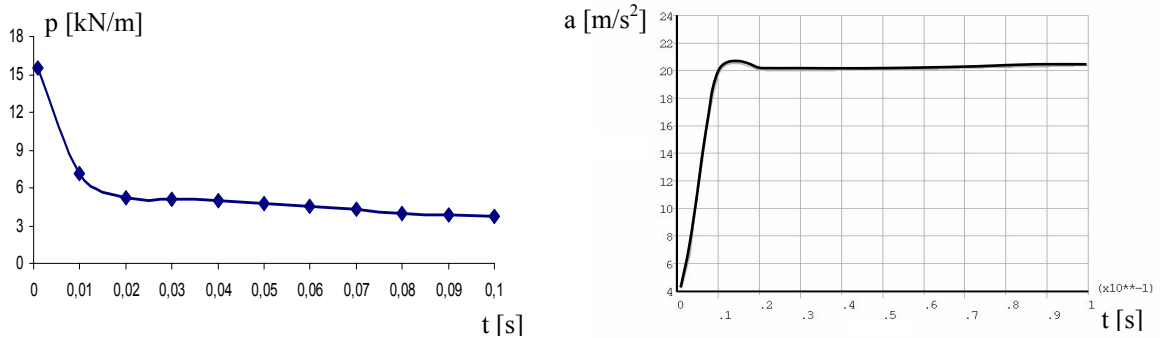


Figure 3: Results of the optimization: a) change of pressure in time; b) resulting acceleration of the hitted joint

The structure considered here consists of only one package and has a sliding support which results in much lower values of optimal pressure than in the previous case. Pressure in every time step is adjusted to fit the displacement of the mass to the assumed curve. The

resulting change of pressure is shown in Fig 3a. High value of pressure is necessary at the beginning of the impact and then the curve of pressure is gradually declining.

The detailed description of various optimization problems related to inflation of structure presented in (Fig. 2) can be found in paper ⁴.

4 PROTECTION OF OFFSHORE STRUCTURES

Inflatable structures can be effectively used to provide safety of docking operations in open sea, for instance docking to offshore wind turbines. Pressurized structure that will be used for the purpose of protecting the wind turbine is torus-shaped and surrounds the tower, as illustrated in Fig. 4. The AIS is located on the water level and it is partially submerged. The AIS is 2m in height and the thickness can vary from 0.5 to 1m. The walls of the pneumatic structure are made of rubber reinforced by steel rods which provide high durability and allow large deformations during ship impact. To achieve better adaptation for various impact scenarios, the inflatable structure can be divided into several separate air chambers located around the tower, as shown in Figs. 4 and 5.

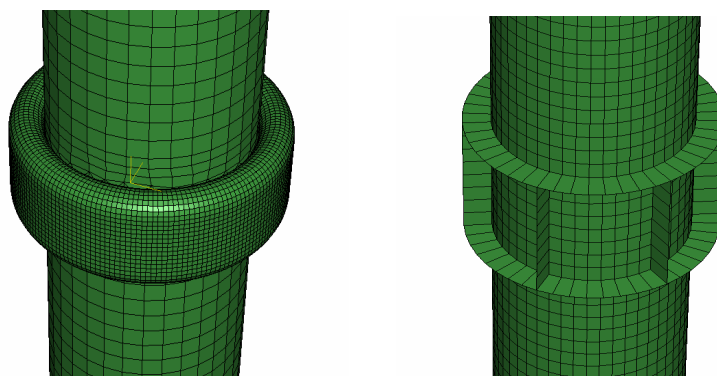


Figure 4. Adaptive Inflatable Structure surrounding the wind generator tower

The inflatable torus helps avoid direct collision between the ship and the tower and potential excessive forces and accelerations. The adaptation is achieved by adjusting the internal pressure and varying its level between the chambers according to the velocity, the mass and the area of contact with the ship. During collision, when the contact of a colliding object with the inflatable structure occurs, a controlled release of pressure is executed. For this purpose, the AIS is equipped with controlled piezoelectric valves located in its outer walls and internal divisions which allow the flow of gas between the cells and outside the structure.

The main goal that inflatable structure should fulfil is to dissipate the initial energy of the ship. Since after a collision most of the energy is accumulated as the kinetic energy of the ship, the loss of ship velocity is a good measure of dissipation. By minimizing the final ship velocity we avoid bouncing of the ship from the wind turbine.

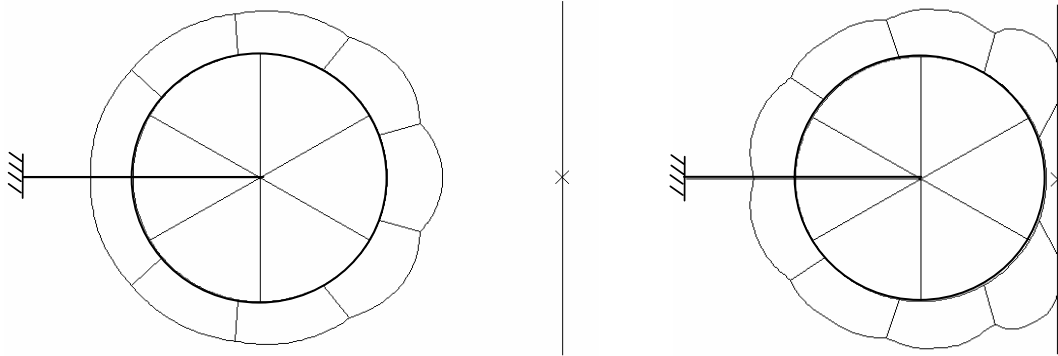


Figure 5. Simplified model of collision between ship and inflatable structure.

During impact the kinetic energy of the ship is changed into gas energy, the energy of the tower and the strain energy of the strongly deformed AIS walls. The dissipation can be obtained in two manners: by removing compressed gas from the pressurized structure to the environment and by releasing stresses in the AIS walls. The first method is executed by opening the valves in the wall of the pressurized structure. The whole gas energy is dissipated when its pressure equals atmospheric pressure, since it has no capability of expansion. The second method is performed by changing the stiffness of front AIS partitions (short elements between the chambers). This helps to reduce significantly high strain energy accumulated in the tensioned outer AIS wall and transfer it into strain and kinetic energy of other parts of the AIS.

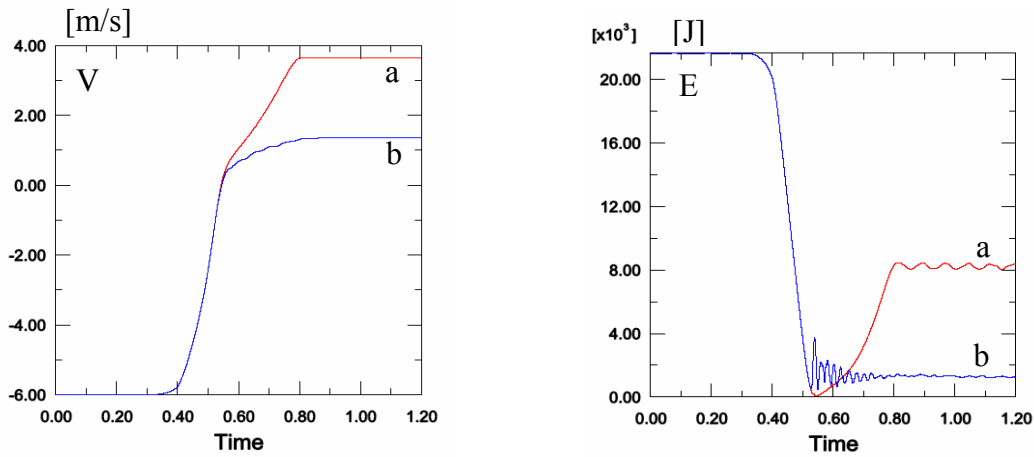


Figure 6. Change of ship velocity and system kinetic energy: a) dissipation by pressure release, b) dissipation by pressure release and change of partitions stiffness.

In the numerical analysis, we considered the impact of a 60-ton ship moving at a velocity of 6m/s. The final kinetic energy of the ship was compared in the two following cases. In the first one, dissipation was executed by pressure release and ship energy was reduced by 41%. In the second example considered, the dissipation was due to both methods mentioned above. The velocity of the ship was decreased to 1.32 m/s, which means an energy reduction of 78%.

The following purpose of the pressure adjustment was to decrease ship accelerations during impact. The impact considered was the same as in the previous example (a 60-ton ship, velocity 6m/s). In the reference case, the value of pressure during the whole analysed period was 0.24 MPa which provides stopping the ship just before hitting the tower wall. In this case, the whole AIS between the ship and the tower is crushed and maximal ship acceleration is equal to 35 m/s².

The optimal situation is stopping the ship just before hitting the tower wall by using constant decelerating force. Corresponding pressure is not constant in time due to various area of contact between the ship and inflatable structure and the forces coming from rubber deformation. The appropriate pressure change can be calculated directly by considering the actual state of the system and comparing it with the optimal case with constant accelerations. The contact area between pressurized structure and the ship has to be estimated by using the geometry of the structure and expressed in terms of ship distance from the tower wall.

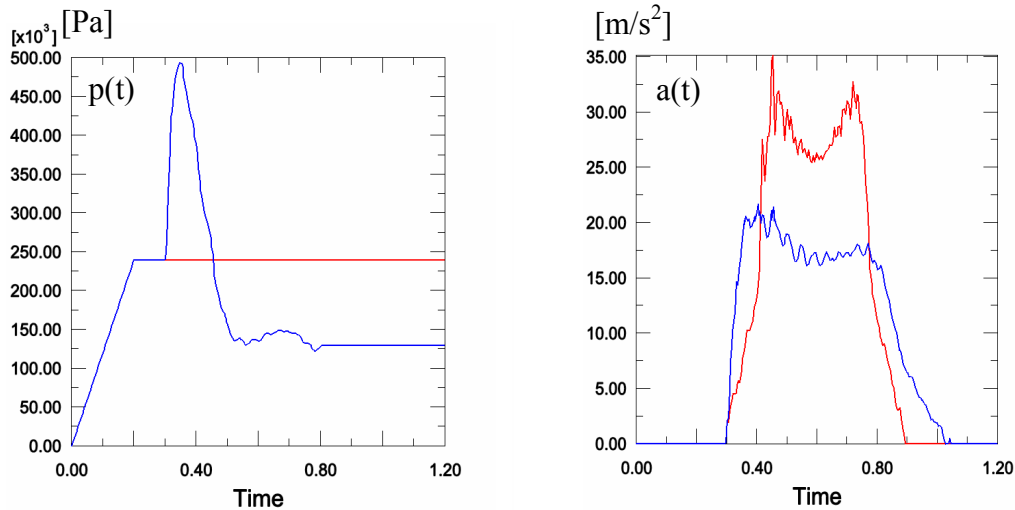


Figure 7. Pressure change and corresponding ship accelerations: initial pressure adjustment (red line) and full adaptation procedure (blue line).

The results achieved by applying this subroutine are presented in Fig. 7. The red line concerns the case without adaptation. Maximal acceleration is quite low during the initial stage of impact but increases significantly to the level of 35m/s due to high forces coming from rubber deformation. The blue curve is obtained as a result of the described control procedure. Pressure increases strongly at the initial stage of impact, which helps to achieve the desired level of acceleration. It can be observed that the maximum value of acceleration was decreased by about 37%.

The detailed results related to the application of inflatable structures in maritime events are presented in paper ⁵.

5 FLOW CONTROL BASED EMERGENCY AIRBAG

The last application considered is an adaptive external airbag for helicopter. The system is designed for extremely severe, emergency landing. It consists of a multi-chamber air filled cushions attached to the helicopter undercarriage (cf. Fig. 8). Deployment of these cushions is executed just before touchdown by means of pyrotechnic system. Distribution of pressure is adjusted to landing direction and velocity which are identified by ultrasonic velocity sensor and pressure sensor inside the airbag. Release of pressure is due to fabric leakage and additional piezoelectric based controllable high speed and stroke valves.

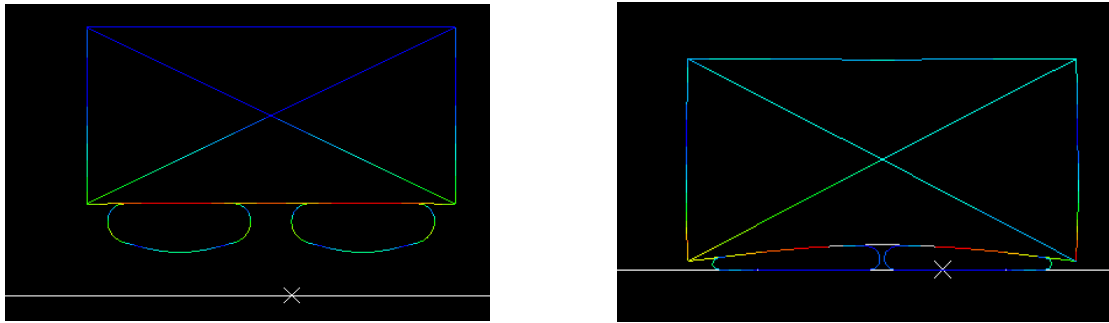


Figure 8. Simplified simulation of landing with adaptive airbag applied

In numerical example the considered helicopter is modeled by deformable beams and point masses. The total mass of the model equals 5000kg (mass of a typical civil helicopter). The velocity of emergency landing is equal to 10m/s which is equivalent to free falling from 5,1m. Estimated dimensions of the airbag are $4m^2 \times 0.5m$. Constant pressure in the airbags necessary to avoid direct collision with ground equals 1.25 atm overpressure (2.25 atm total pressure).

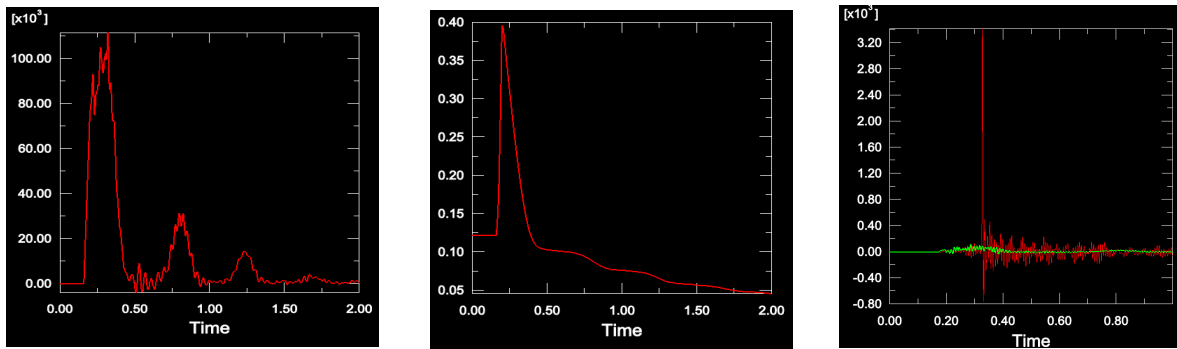


Figure 9. Applied control strategy: a) change of pressure inside the airbag, b) mass of the gas inside airbag
c) reduction of accelerations obtained as a result of applied control strategy

Control strategy is oriented towards: minimization of accelerations acting on passengers, alleviation of forces acting on the helicopter and stresses arising in undercarriage and

stabilization of helicopter during touchdown. To fulfil objectives mentioned, the whole stroke of the airbag is used during the landing, the total force acting on helicopter is kept on constant level and significant release of pressure is applied when helicopter velocity drops to zero. The subsequent peaks on pressure plot (Fig 9a) are related to the rebounds of the falling object. In applied control strategy the amount of the gas inside the airbag has to increase strongly at the beginning of the process (inflation of the airbag) and then the gas is gradually removed.

Conducted simulations prove that both proposed devices efficiently decrease arising accelerations and forces and hence increase the safety of emergency landing. More details concerning aeronautical applications of inflatable structures are described in reference⁶.

6 CONCLUSIONS

Adaptive Inflatable Structures are based on a concept of pressurized packages and controlled pressure outlets. Pressurized structure can be easily adapted to different loading conditions by adjusting the initial value of pressure and controlling its release during the impact. Inflatable structures can be effectively utilised in road, maritime and aeronautical applications. Conducted simulations indicate that pressurized structure efficiently protect both impacting and impacted object. A controlled release of pressure helps to dissipate a major part of the impact energy and avoid bouncing of the hitting object. By applying precise control of valve flow, we can minimize forces and accelerations can be minimized during the impact.

AIS equipped with sensors able to detect and identify (in real time) the impact load can serve as an on-line adaptive impact absorbing system controlling injection and release of pressure in structural sections. The optimal control strategies have to be pre-computed and stored in memory of hardware controllers to make the process feasible.

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