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Inflatable Structures with Controlled Release of Pressure for Adaptive Impact Absorption

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ABSTRACT

The paper presents the concept of inflatable structures with controlled release of pressure and its application for adaptive impact absorption. Modelling of adaptive inflatable structure subjected to impact loading is introduced and pressure release strategies providing adjustment to various impact scenarios are developed. The paper describes briefly three impact related applications of inflatable structures. The first one is pneumatic landing gear for small unmanned aerial vehicle which adapts itself for various landing conditions. Another application is smart road barrier which internal chambers are inflated with gas under pressure adjusted to actual impact loading. Finally the paper introduces the concept of 'flow control – based' external airbags which can be used for improving safety of docking operations and helicopter emergency landings.

Keywords: Adaptive Impact Absorption, inflatable structures, pressurized structures, controlled pressure release, adaptive airbags

1. INTRODUCTION

Adaptive Impact Absorption (AIA) focuses on active adaptation of energy of system absorbing structures to actual dynamic loading by means of sensors detecting and identifying impact in advance and controllable dissipaters, so called structural fuses [1,2]. The purpose of adaptive impact absorption is to smooth down the impact effect i.e. to mitigate forces and accelerations arising during impact or to enhance the process of energy dissipation. A semi-active or fully-active controllable dissipative devices used for AIA are usually based on magneto-rheological fluids or piezo actuated valves [3].

Adaptive Inflatable Structures (AIS) are one of the special approaches to adaptive impact absorption. AIS are structures filled with gas which pressure is actively adjusted during the event. Pressure adjustment relies on appropriate initial inflation and controlled release of gas during impact. The form and shape of pneumatic structure depends on its particular application. The inflated structure may be rigid (as cylinder enclosed by piston), it may be a thin-walled steel structure or completely deformable cushion made of fabric. Inflatable structures investigated so far by authors are dedicated for automotive industry (adaptive pressurised road barriers, [4]) and waterborne applications (torus-shaped structures for protecting offshore wind turbines, [5]). Recently conducted research is oriented toward landing gear for lightweight unmanned plane [6] and an external airbags for helicopter emergency landing.

Initial inflation of pneumatic structure is triggered by impact detection system and it is usually executed by pyrotechnical gas generators. Initial gas pressure depends on actual impact scenario i.e. hitting object mass, velocity and impact direction. Additionally, inflatable structure can be divided into several separate air chambers, which allows to adjust level of pressure in different parts of the structure. Controlled release of gas during impact is performed by high speed controllable exhaust valves based on piezo-stacks, piezo-fiber composites, multifolding microstructures [7] or thermically activated membranes [8]. Active pressure release allows to change global compliance of the pneumatic structure in subsequent stages of impact and to prevent excessive accelerations and forces in the system. Moreover, it helps to control dissipation of energy and to avoid hitting object rebound. Utilization of compressed air under appropriate initial pressure and its controlled release causes that considered structure can easily alter its properties and adapt to various impact scenarios.

2. MODEL AND CONTROL PROBLEM FORMULATION

2-1. Full Fluid-Structure Interaction model

Numerical analysis of inflatable structure subjected to impact load requires considering the interaction between its walls and the fluid enclosed inside. Applied external load causes large deformation of the structure and change of the capacity and pressure of the fluid. Pressure exerted by the fluid affects, in turn, the deformation of the solid wall and its internal forces. The most precise method of analysing above fluid-structure interaction problem is to solve coupled system of nonlinear structural mechanics equations (taking into account geometrical and material nonlinearities) for solid domain and compressible viscous Navier-Stokes equations for fluid domain, cf. [9]. Such approach is usually applied for extremely fast processes like airbag deployment or out of position (OOP) airbag-occupant contact, cf.[10].

FSI model of adaptive inflatable structure is composed of almost-closed solid domain Ω_S and fluid domain Ω_F located inside and around the solid, cf. Fig 1a. Boundary of the solid region comprises a small part which is fixed in space and forms an orifice allowing outflow of the fluid. On the rest of the solid boundary Γ_{int} the fluid-solid interface is defined where solid and fluid stresses and velocities are coupled. This part of the boundary deforms under applied external loading and thus changes the geometry of fluid and solid domains. Moreover the model contains an internal void Ω_C at which boundary Γ_C conditions for fluid velocity are imposed. In mathematical model of active inflatable structure location and shape of void Ω_C can be arbitrary changed in time to alter the fluid domain and change the flow distribution. The void domain Ω_C can be understood in engineering manner as flow control device (e.g. valve head).

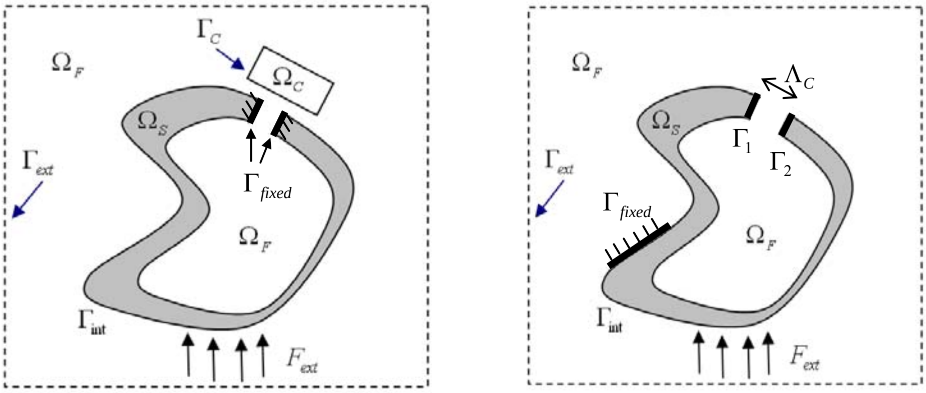

Figure 1: FSI model of Adaptive Inflatable Structure: a) with orifice fixed in space b) with moving orifice

In case when valve can move freely across the fluid domain the approach with void domain

Ω_C can not be easily implemented since void Ω_C would have to track moving orifice. Therefore, separate mathematical treatment is applied, cf. Fig 1b. Constraint Λ_C defining actual distance between two parallel boundaries of the orifice Γ_1 and Γ_2 is introduced and modified during analysis which changes conditions of gas migration. The slight disadvantage of such model is that altering the orifice width introduces additional, not feasible, stress field into the solid domain. Above FSI models can be implemented numerically by using 'partitioned coupling scheme', i.e.:

- solution for the fluid domain can be obtained by CFD code (typically based on Finite Volume Method),
- solution for solid domain can be found by Finite Element Method code,
- finally MpCCI software can be used to obtain equilibrium between two considered domains

2-2. Simplified model based on assumption of uniform pressure

Above model can be significantly simplified by using Uniform Pressure Method (UPM) which assumes that gas is uniformly distributed inside each chamber and chamber walls are subjected to uniform pressure. Such assumption is applicable since the impacting object velocity is much lower than the speed of impulse propagation in gas and pressure becomes constant across the chambers relatively fast. Let us consider the finite element model of pneumatic structure which dynamics is in general described by the nonlinear equation of motion:

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

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

where matrices **M,C,K** indicate mass, damping and stiffness, **q** denotes vector of degrees of freedom and vector $\mathbf{p} = \{p_1(t), p_2(t),..., p_n(t)\}$ indicates pressures in the cavities. The impact can be modelled by the force vector $\mathbf{F}_I$, by initial conditions or by contact defined between the inflatable structure and other object. The **F**(**p**,**q**) vector is always present in the problem, since it provides the coupling with the internal fluid. Each cavity of the inflatable structure is filled with a compressible (pneumatic) fluid, which is described analytically by ideal gas law:

$$\overline{p}(t) = \rho(t) R \overline{T}(t) \qquad (2)$$

Absolute pressure $\overline{p}$ is defined as $\overline{p} = p + p_A$ where p is gauge pressure and p_A is an ambient (atmospheric) pressure. Moreover, the variables $\rho, \overline{T}$ indicate gas density and gas absolute temperature, respectively. The direction of the gas flow depends on the sign of pressure difference between the cavities and the mass flow rate is assumed to be related to pressure difference according to the formula:

$$\Delta p(t) = C_V(t)\dot{m} + C_H(t)\dot{m}|\dot{m}| \qquad (3)$$

where C_V is the viscous resistance coefficient, and C_H is the hydrodynamic resistance coefficient. Both these coefficients depend on the area and shape of the orifice and they can be found experimentally for given type of the valve. The balance of the energy for each gas chamber is given by the first law of thermodynamics for an open system [11]:

$$dQ + dm_{in}\overline{H}_{in} - dm_{out}\overline{H}_{out} = d(m\overline{U}) + dW \qquad (4)$$

where specific gas enthalpy $\overline{H}$, specific gas energy $\overline{U}$ and work done by W gas are defined as in classical thermodynamics and the flow of the heat across the cavity walls described by equation:

$$\dot{Q}(t) = \lambda A(t)(\overline{T}_{ext} - \overline{T}(t)) \tag{5}$$

where λ is the heat conductivity coefficient of the cavity wall and $A(t)$ is the total area of the cavity walls. If the wall of the cavity is perfect insulator ($\lambda = 0$) or when the process is very fast, adiabatic conditions are fulfilled and no heat transfer through the chamber walls occurs.

2-3. Formulation of control problems

The main advantage of *adaptive* inflatable structure over *passive* one is that in adaptive structure gas exhaust can be controlled and adjusted to actual impact scenario. Development of optimal pressure release strategy is the main challenge related to adaptive inflatable structures. The objective of applied control is to protect the impacting (or impacted) object by minimizing its accelerations $a(t)$, internal forces $\sigma(t)$ or rebound velocity V_R.

In full FSI model of adaptive inflatable structure location and shape of void domain Ω_C can be regarded as an external control whereas in simplified (based on uniform pressure assumption) model flow resistance coefficients $C_V(t)$ can be treated as a control variable. Therefore, two possible formulations of control problem read:

$$\begin{array}{l} 1.\ \text{Find}\quad \Gamma_C \in \Gamma_C^{adm} \\ 2.\ \text{Find}\quad C_V \in \left\langle C_V^{\min}, C_V^{\max} \right\rangle \end{array} \quad \text{such that} \begin{cases} \max_t a(t) \\ \max_t \sigma(t) \\ \max V_R \end{cases} \quad \textit{is minimal} \tag{6}$$

where Γ_C^{adm} defines admissible locations of the void domain Ω_C, for example confines its movement to rigid body motions. Coefficients $C_V^{\min}$ and $C_V^{\max}$ define the smallest and the largest admissible valve opening. Let us note that control variables in both defined control problems, Γ_C and C_V, influence introduced numerical model in completely different way. Variable Γ_C defines the shape of fluid domain on which PDEs describing the flow are solved, while C_V is a coefficient in one of the ODEs describing the simplified model. Due to complexity and high computational cost of the FSI approach the simplified method will be applied in numerical examples presented in further sections.

3. ADAPTIVE PNEUMATIC LANDING GEAR

The concept of innovative adaptive landing gear for Unmanned Aerial Vehicle (UAV) is based on double chamber pneumatic cylinder equipped with active piezoelectric valve which controls flow of the gas between the chambers, cf. Fig.2a. Such device can serve as a shock absorber dissipating UAV kinetic energy during landing as well as suspension utilized during taxiing and ground maneouvres. Active adaptation of a pneumatic absorber to actual landing scenario is based on the following steps:

1. identification of kinetic energy of aerial vehicle based on touch down velocity measurement by ultrasound sensors;
2. semi-active or active control of the piezoelectric valve opening providing the lowest possible pneumatic force generated by the absorber during landing

Numerical model of the pneumatic cylinder is based on equations introduced in Sec. 2.2. The typical response of the pneumatic cylinder with constant valve opening is depicted in Fig. 2b.

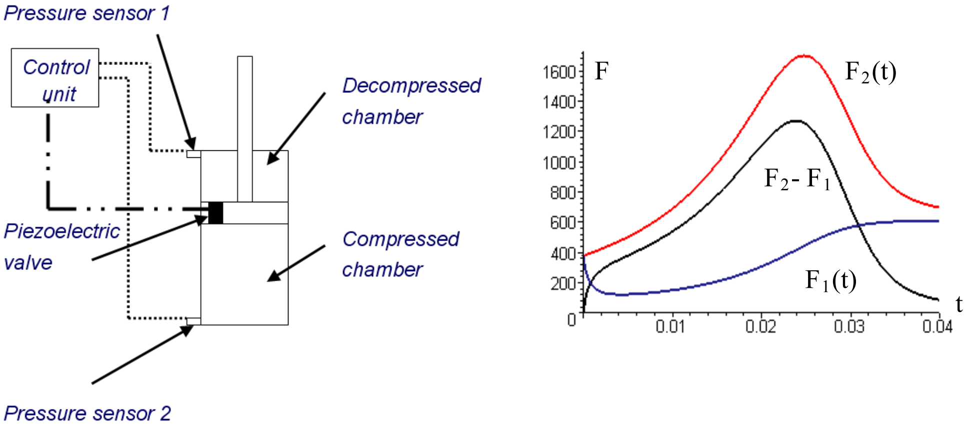

Figure 2 a) Concept of pneumatic absorber, b) Response of a passive system: pneumatic force generated in upper and lower chamber and resultant pneumatic force

Numerical model enables simulation of *adaptive pneumatic landing gear* where gas migration is controlled and adjusted to actual impact scenario. Both in case of semi-active and fully active system the change of valve opening is modelled by the variation of flow resistance coefficient $C_V(t)$ which is treated here as a control variable. In semi-active system initial pressure and constant in time valve opening are adjusted to mass and velocity of the hitting object. For each value of initial pressure the valve opening is chosen in a way that the largest stroke of the pneumatic cylinder is used and the resultant pneumatic force is minimal.

In active system the valve opening is actively changed during the analysis depending on actual response of the system. Active control strategy is composed of two steps: i) initial increase of absorber force caused by compression of lower chamber and decompression of upper chamber while closed valve and ii) maintaining the absorber force on the constant level by controlling gas migration between the chambers. Development of active control strategy for fully active system with no constraints imposed on valve opening is based on the following steps (cf. Fig. 3):

- computation of force level required to stop the hitting object using whole absorber stroke (by integrating equation of motion over displacement and utilizing recognized impacting mass and velocity)
- computation of valve opening required to maintain constant force level (by solving system differential equation with absorber force imposed)

Limitation of maximal valve opening requires different control strategy for minimization of absorber force (cf. Fig. 3):

- full opening of the valve at the beginning of the 'active stage'
- optimization of force level which triggers the valve opening

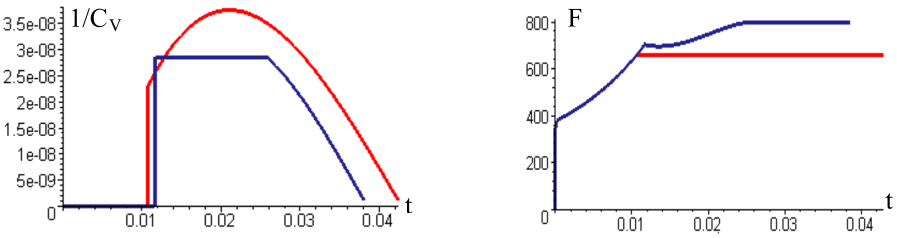

Figure 3 Active control strategy with (blue) and without (red) constraints imposed on valve opening: a) optimal change of flow coefficient (left); b) resulting pressure difference (right)

The presented concepts were implemented in a lab-scale experiment and verified on a drop test stand (cf. Fig. 4a). The pneumatic cylinder was equipped with a piezo-valve (cf. Fig.4b) characterised by response time equal 2 ms. Initial pressure inside cylinde was equal p_0=3atm and the parameters of impact for the drop test were: mass = 27.2kg, drop height = 0.4m. Primarily drop tests were conducted with various valve head position. The change of system characteristic from elastic to dissipative was clearly observed (Fig.5a).

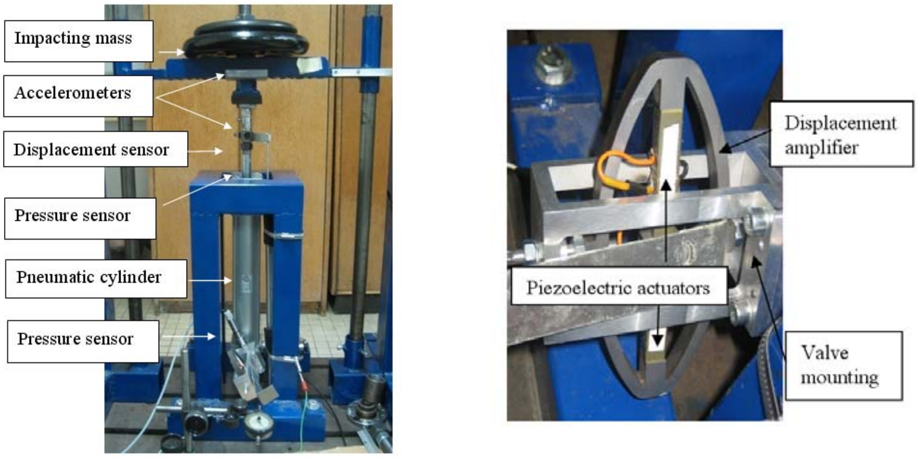

Figure 4 a) Experimental drop testing stand, b) piezoelectric valve

Another test conducted on the lab-scale stand was verification of the system's control strategies under impact loading. The same conditions of impact were established for these tests. Comparison between the results obtained with the semi-active and the active control strategies (Fig. 5b) pronounced reduction of the maximal transferred load value by 30% in the case of the active control strategy.

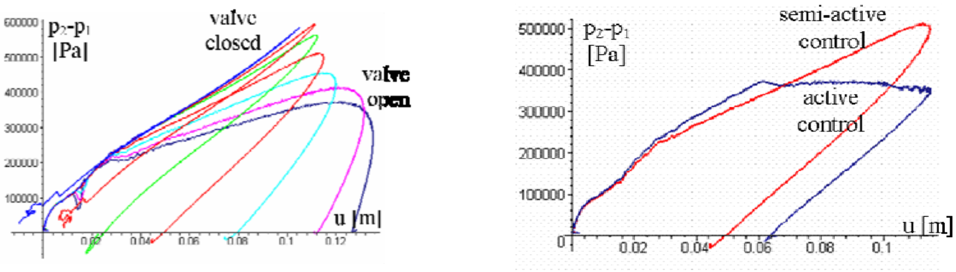

Figure 5 a) Pressure difference obtained for various valve opening,
b) comparison of semi-active and active control strategy

3 ADAPTIVE INFLATABLE ROAD BARRIER

This section is aimed at introducing a concept of inflatable protective road barrier and developing a strategy for optimal distribution of pressure inside its chambers. The structure is divided into several separated cells equipped with flow control devices allowing active pressure adjustment (cf. Fig.6). As a simplified numerical model two dimensional frame structure is applied. The frame is loaded on the upper side by mass applied with initial velocity which is modelling lateral (non-axial) impact. Both material and geometrical nonlinearities are taken into account in numerical simulations. Material is elasto-plastic with the hardening and large deformations of the frame are considered.

The initial problem is estimation of benefit in structure load capacity that can be obtained by using compressed air. Adequate measure of load capacity is maximum mass that can be applied to the structure with established velocity and does not cause its excessive deformation. Deformation of the structure is regarded as admissible if there is no collision between upper and lower span of the frame and when maximal displacements of the lower span do not exceed a limit value $u_{\max} \le u_{adm}$. Corresponding optimization problem is to find the combination of pressure values inside the packages in successive time instances, $\mathbf{p} = \{p_1(t), p_2(t), ..., p_n(t)\}$, which maximizes the load capacity of the structure.

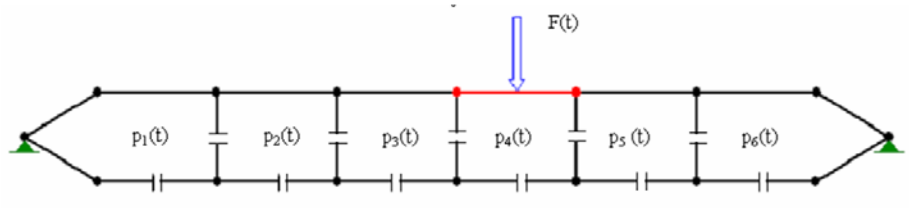

Figure 6: Protective structure divided into pressurized packages

Above approach was applied for finding the optimal distribution of pressure in three-cell inflatable structure fixed with no sliding (cf. Fig. 7). In such case vector **p** has two components p_1 and p_2 which indicate pressures in lateral and middle cell, respectively. Initially, constant value of pressure during impact was considered. The highest increase of load capacity (6.1 times) was obtained for maximal allowable pressure in lateral cells and significantly smaller pressure in middle cell (cf. Table 1).

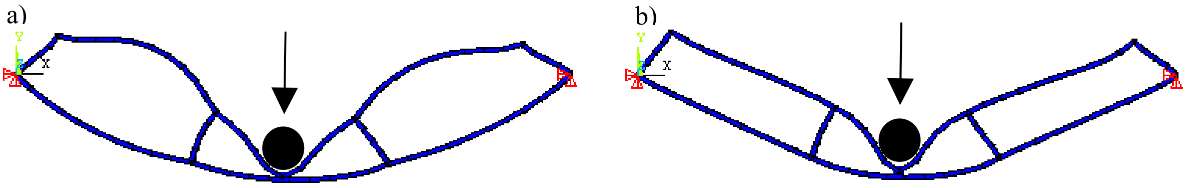

Figure 7: Deformation of the optimally pressurized structure loaded by maximal mass: a) constant pressure; b) linear decrease of pressure

In the second example linear decrease of pressure was assumed. Gas was fully released at time t_{stop} when the velocity of hitting object was decreased to zero. In optimal solution middle chamber is almost tenfold more inflated than the lateral chambers. The load capacity is increased 9,02 times in comparison to generic barrier. Detailed results are presented in Table 1 and corresponding deformation of the structure is depicted in Fig.7.

$\mathbf{p}_1(0)$ [kN/m]	$\mathbf{p}_2(0)$ [kN/m]	$\mathbf{p}_1(t_{stop})$ [kN/m]	$\mathbf{p}_2(t_{stop})$ [kN/m]	$u_{\max}$ [m]	t_{stop} [s]	**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

The second strong advantage of using compressed air and its controlled release is the possibility of smoothing down the impact effect by changing structure stiffness during collision. The acceleration of the hitting object can be controlled in order to reduce its maximal value or, by contrast, it can be maintained at a high level to confine hitting object displacement and resulting protective structure penetration. The introduced problem can be solved by using several pressurized packages in the structure, however inflating the chamber to which the impact is applied is sufficient to control hitting object kinematics.

The structure considered in numerical example consists of only one package and had a sliding support which results in much lower values of optimal pressure than in the previous case. Control goal is to obtain constant, preliminary assumed, impacting mass acceleration. Reasonable precision of solution (cf. Fig. 8b) is obtained by adjusting pressure in ten uniformly distributed time instants. It is achieved by applying high value of pressure at the beginning of the impact and its gradual decline in the following period.

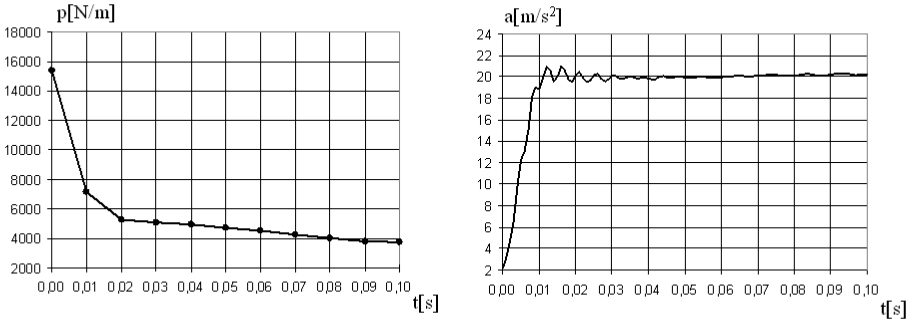

Figure 8: Results of the optimization: a) change of pressure in time; b) resulting acceleration

4 FLOW CONTROL BASED EXTERNAL AIRBAGS

Flow control based external airbags are another type of adaptive inflatable structures. On contrary to standard airbags they are equipped with controllable exhaust valves improving significantly their efficiency.

External airbags can be effectively utilized to mitigate open sea collisions, cf. [5]. The inflatable structure that is proposed to be used for protecting offshore wind turbine against impacts of small ships is torus-shaped and surrounds the tower at the water level. The walls of the pneumatic structure can be made of rubber reinforced by steel rods or any other material which provides high durability and allows large deformations during ship impact. To obtain better adaptation to various impact scenarios, the inflatable structure is divided into several separate air chambers located around the tower, cf. Fig.9 a,b. Controllable valves enable flow of the gas from each chamber of the torus structure to environment and between adjacent chambers.

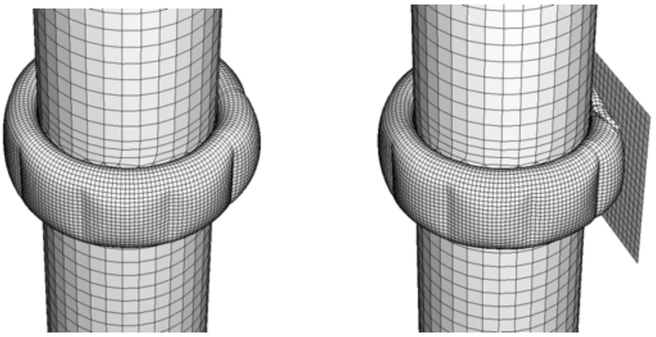

Figure 9: a) Inflation of pneumatic structure; b) deformation during collision

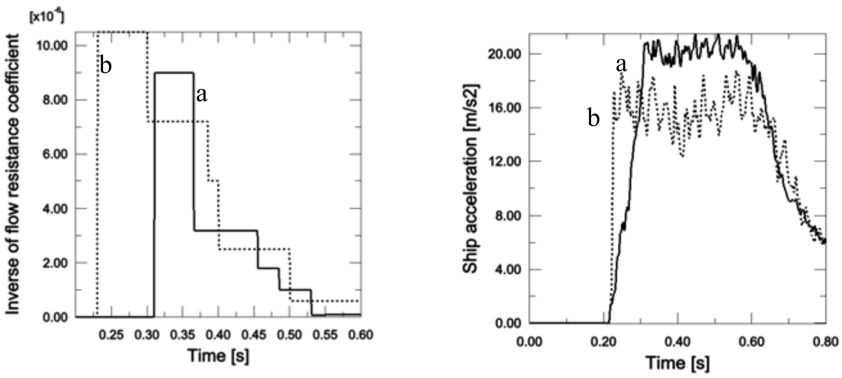

Figure 10: Active acceleration mitigation: a) control of valve opening during impact (continuous line), b) additional adjustment of initial pressure (dashed line)

The purpose of applying pneumatic structure is to mitigate the response of both the ship and the wind turbine tower. In particular, the inflatable structure helps to minimize ship deceleration, avoid ship rebound, decrease stresses arising at the location of the collision and mitigate tower vibrations. In case of active acceleration minimisation an additional improvement can be obtained by adjusting value of initial pressure which helps to avoid preliminary stage of pressure increase, cf. Fig.10.

4-2. Adaptive airbags for helicopter emergency landing

Another applications of the proposed concept are adaptive external airbags for helicopter emergency landing. The system consists of four cylindrical cushions attached at outer side of helicopter undercarriage (cf. Fig. 11). The airbags are deployed and inflated just before touchdown by pyrotechnic inflators. During collision with the ground pressure is released by fabric leakage and by additional controllable high speed and stroke valves.

Initially the problem of helicopter stabilisation during landing was considered. For this purpose three dimensional model composed of stiff plate and four airbags was developed (Fig. 11a) and various landing directions and velocities were analysed (Fig. 11b). The control problem was to find initial airbags pressures and optimal (but fixed during landing) openings of each airbag valve for which landing scenario runs possibly smoothly i.e. the direct contact of the stiff plate and ground does not occur, the falling object does not bounce or rotate strongly and finally global measure of plate acceleration is minimised. The heuristic algorithm covering whole range of landing conditions and corresponding pressure release strategies is currently under development.

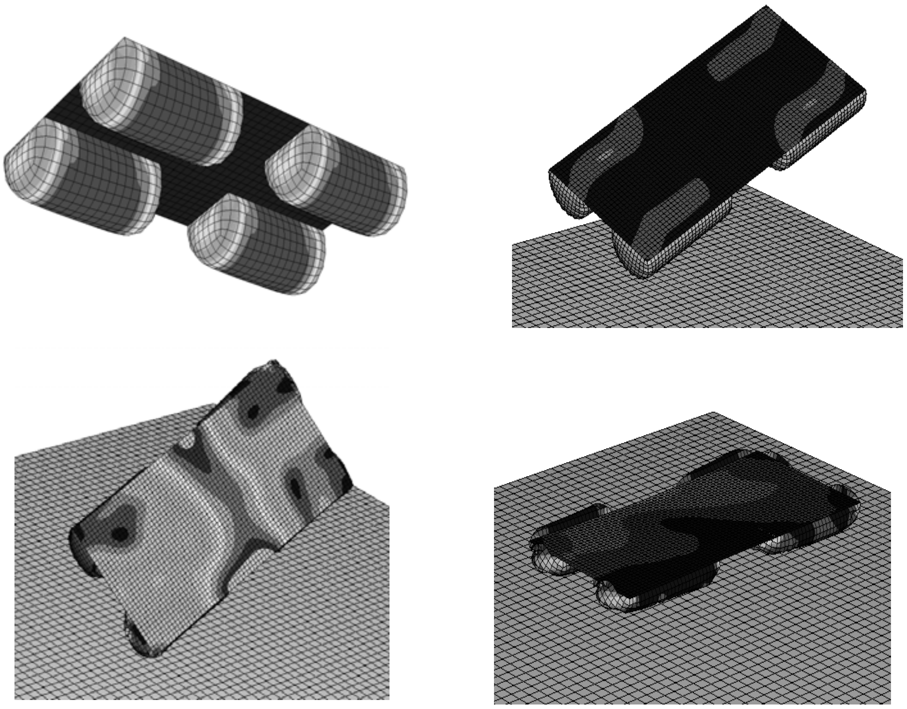

Figure 11 a) Considered model, b)landing scenario; c) non-optimal passive response with rear part rebound d) optimal uniform airbags compression

Another control problem was oriented towards minimization of stresses arising in helicopter undercarriage during landing. In numerical example the simplified two dimensional model of falling object composed of deformable beams and point mass was used (Fig. 12a). Three pressure adjustment strategies were applied (Fig 12): i) optimisation of initial pressure only (continuous line): $\sigma^{\max} = 397MPa$, ii) optimisation of initial pressure and constant valve opening (dashed line):

$\sigma^{\max} = 293MPa$, iii) continuous control of valve opening to maintain precomputed optimal pressure level (dotted line): $\sigma^{\max} = 262MPa$

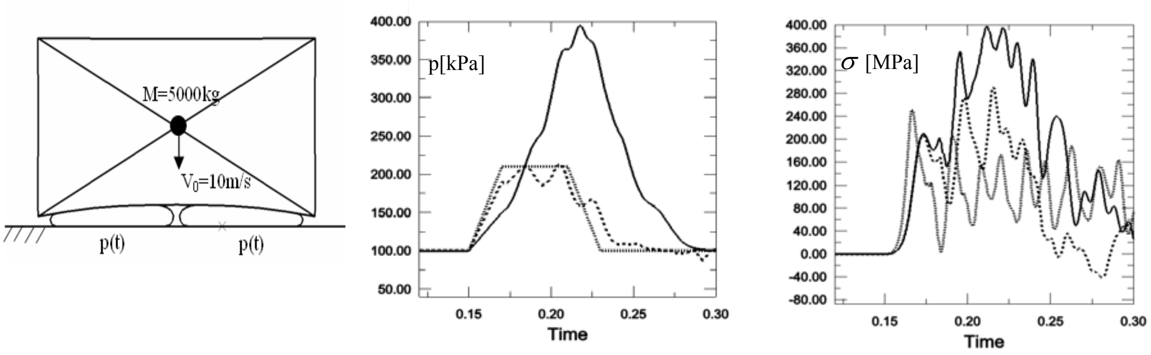

Figure 12: Active stress minimisation: a) considered model , b) applied pressure variation , c) resulting stresses at lower beam of the model

CONCLUSIONS

The concept of inflatable structures with controlled release of pressure was introduced together with precise and simplified mathematical model. Control strategies for mitigation of dynamic response of colliding objects were developed. Numerical simulations of adaptive pneumatic systems show significant reduction of arising accelerations and forces and hence clearly indicate the superiority of adaptive paradigm. In further stages of research full FSI model of adaptive inflatable structures will implemented and control strategies for such model will be developed. The models will be verified against each other and against laboratory tests**.**

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