ADAPTIVE FLOW CONTROL BASED AIRBAGS FOR WATERBORNE AND AERONAUTICAL APPLICATIONS

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The paper introduces the concept of adaptive flow control based airbags for Adaptive Impact Absorption. On contrary to standard airbag, the considered one is equipped with high performance exhaust valves which control outflow of the gas from the airbag during collision. The proposed system utilizes initial impact detection and identification for development of optimal control strategy of inflation and pressure release. Initially the mathematical modeling of adaptive inflatable structure is described and control problems are formulated. Further two practical applications are proposed: adaptive external airbag designed for emergency landing of a helicopter and adaptive inflatable open sea docking facility. For both problems the corresponding pressure release strategies oriented towards protection of colliding objects are developed and verified.

Keywords: Adaptive Impact Absorption (AIA), Flow Control Based Airbags, Controllable High Performance Valves

Introduction

Airbag systems are commonly used in automotive industry to provide safety of the occupants during collisions since 1980s. Despite many years of development and improvement car airbags remain passive systems where only initial inflation is adjusted to actual impact scenario. After airbag deployment gas is released by fabric leakage only and no precise control of internal pressure is performed. This indicates that airbag behavior is still not optimal and can be significantly improved by introducing controllable gas exhaust. On the other hand, the variety of possible applications of airbags systems outside automotive industry is not yet fully appreciated, which gives strong motivation for undertaken research.

The proposed idea of 'adaptive flow control based airbags' follows more general concept of Adaptive Impact Absorption (Ref.[1,2]) which focuses on active adaptation of energy absorbing structures to extreme overloading by impact identification and application of controllable dissipaters based on magneto-rheological fluids or piezo actuated valves, Ref. [3,4,5]. 'Adaptive flow control based airbags' are deformable inflatable cushions made of rubber or fabric equipped with fast inflators and additionally with controllable high speed and stroke valves. The performance of the adaptive airbags is based on three following stages:

- impact detection and identification;
- appropriate initial inflation;
- active adjustment of pressure executed by controlled gas release.

The initial velocity and direction of the impacting object can be measured by ultrasonic velocity sensor, cf. Ref [3]. Its mass and initial kinetic energy can be recognized during the initial stage of collision by using accelerometers and pressure sensors and by applying one of the impact identification procedures described in Ref.[1].

Identified mass and velocity are utilized for development of optimal control strategy for inflation and pressure release. Controlled gas exhaust can be executed by opening controllable High Performance Valves (HPV) based on multifolding microstructures, Ref.[6] or thermically activated membranes, Ref. [7]. Active pressure release allows to adjust 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 the energy and to avoid hitting object rebound.

1 Model and control problem formulation

1.1 Full Fluid-Structure Interaction model

Numerical analysis of inflatable structure subjected to an 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. Such approach is usually applied for extremely fast processes like airbag deployment, Ref. [8] or out of position (OOP) airbag-dummy collisions, Ref.[9].

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 Γ_{fixed} 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 of zero 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.

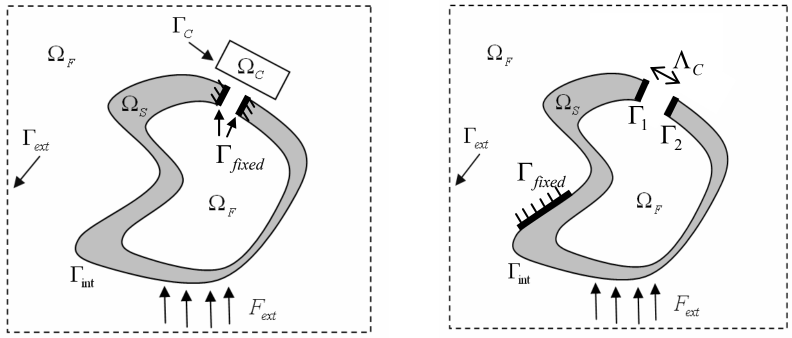

Figure 1: FSI model of Adaptive Inflatable Structure: a) with orifice fixed in space b) with moving orifice

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.

1.2 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:

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

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

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 gauge 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:

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

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:

$$\Delta p(t) = C_V(t)\dot{m} + C_H(t)\dot{m}|\dot{m}| \tag{4}$$

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, Ref.[10]:

$$dQ + dm_{in}\overline{H}_{in} - dm_{out}\overline{H}_{out} = d(m\overline{U}) + dW \tag{5}$$

where specific gas enthalpy, specific gas energy and work done by gas are defined as in classical thermodynamics and the flow of the heat across the cavity walls described by equation:

$$\dot{Q}(t) = \lambda A(t)(\overline{T}_{ext} - \overline{T}(t)) \tag{7}$$

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

1.3 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:

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

where Ω_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, Ω_C and C_V, influences introduced numerical model in completely different way. Variable Ω_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 part of the paper.

2 Inflatable structures for waterborne applications

Flow control based airbags can be effectively utilized to mitigate open sea collisions, cf. Ref.[11]. The inflatable structure that will 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. The dimensions of inflatable structure are limited to 2-3 meters in height and 1m in width due to requirements of fast inflation and pressure release.

To obtain better adaptation to various impact scenarios, the inflatable structure is divided into several separate air chambers located around the tower, cf. Fig.2a,b. Controllable valves enable flow of the gas from each chamber of the torus structure to environment and between adjacent chambers.

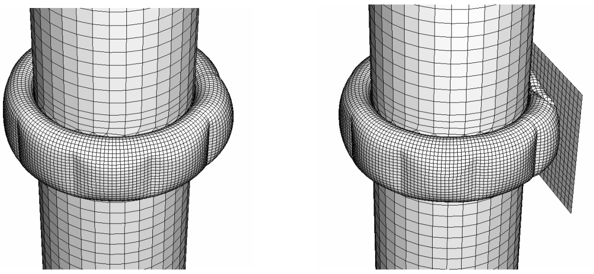

Figure 2: a) inflation of pneumatic structure; b) deformation during collision

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 appropriate chamber valve opening (represented by flow coefficient) is proportionally adjusted on several time intervals and ship acceleration is maintained on desired almost constant, possibly low level, cf. Fig. 3.

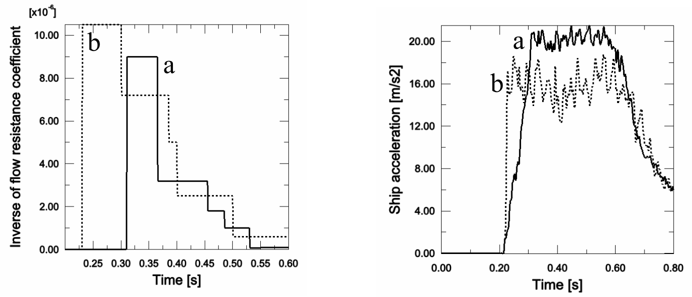

Figure 3: Active acceleration mitigation: a) pressure released during impact (continuous line), b) additional inflation at the beginning of impact (dashed line)

3 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. 4). 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. 4a) and various landing directions and velocities were analysed (Fig 4b). 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.

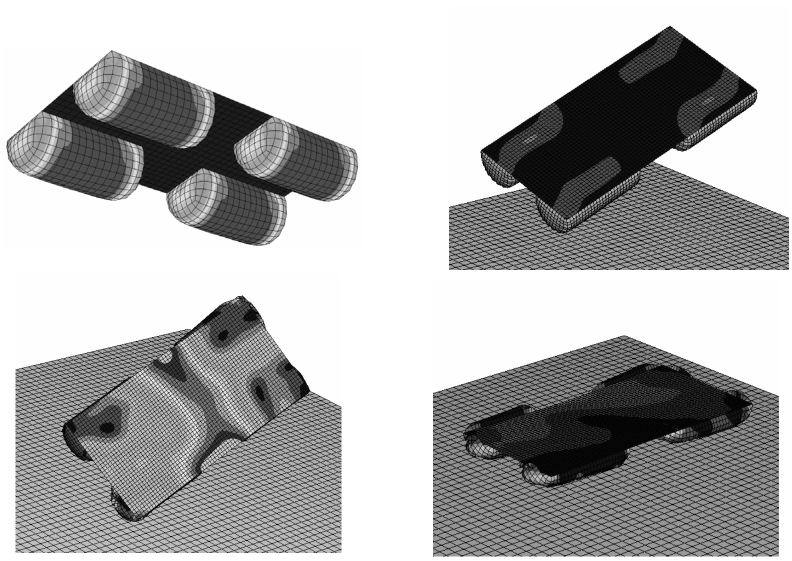

Figure 4: a) Considered model, b)landing scenario; c) non-optimal passive response with rear part rebound d) optimal uniform airbags compression

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. 5a). Three pressure adjustment strategies were applied (Fig 5): 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 pressure level (dotted line): $\sigma^{\max} = 262MPa$

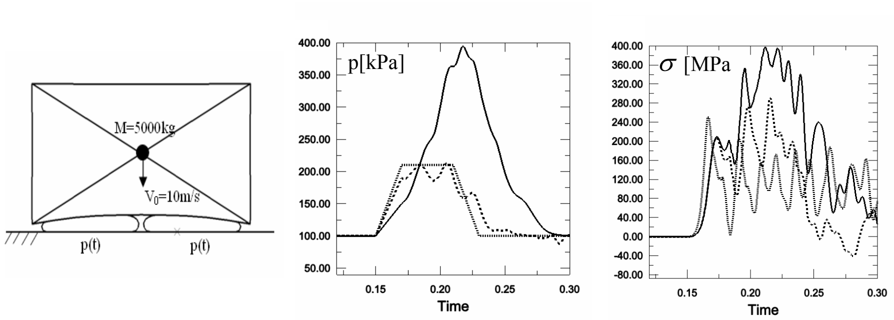

Figure 5: Active stress minimisation: a) considered model , b) applied pressure variation , c) resulting stresses at lower beam of the model

σ [MPa]

Conclusion

The concept of adaptive flow control based airbags was introduced together with precise and simplified mathematical model. Control strategy for mitigation of dynamic response of colliding objects was developed. Numerical simulations of adaptive pneumatic systems shows significant reduction of arising acceleration and force and hence clearly indicate the superiority of adaptive paradigm. In further stages of research full FSI model of adaptive flow-control based airbags will introduced 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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