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Mathematical models and numerical methods for the simulation of adaptive inflatable structures for impact absorption

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ABSTRACT

The paper describes various approaches for the mathematical modelling of Adaptive Inflatable Structures (AIS) along with the corresponding numerical methods. The introductory part presents a general idea of adaptive impact absorption (AIA) and the concept of inflatable structures equipped with controllable valves serving for internal pressure control. Application of AIS for adaptive absorption of the impact loading is briefly explained. The paper focuses on diverse methods of modelling of inflatable structures, which are based on interaction between solid walls and fluid enclosed inside. Modelling of the solid walls is based on rigid body dynamics or initial-boundary value problem of solid mechanics. In turn, modelling of the fluid utilizes either classical equilibrium thermodynamics or Navier–Stokes equations. Consequently, four possible combinations of the above approaches are distinguished, precisely analyzed and applied for the modelling of different types of inflatable structures. Each model takes into account controllable valves, which requires introducing additional coupling between parameters defining the valves and selected results of the analysis. Corresponding numerical methods include classical methods of solving ordinary differential equations, finite volume method (FVM) applied for problems with mobile boundaries, finite element method (FEM) applied for problems involving additional ODEs and, finally, FEM coupled with FVM. Proposed numerical methods and software tools are utilized for the simulation of adaptive pneumatic cylinders, adaptive pneumatic fenders and membrane valves.

1. The concept of adaptive inflatable structures

Adaptive impact absorption (AIA) [1–3] is a contemporary scientific and engineering discipline which belongs to a group of 'smart technologies'. It combines classical impact mechanics with elements of control theory (including optimization techniques) and contemporary material sciences concerning functional materials. The essence of AIA is real-time adaptation of energy absorbing structure to actual dynamic loading by changing local mechanical properties of selected elements during impact. In order to execute the adaptation process the structure is equipped with embedded system of sensors, hardware controller and dissipaters with controllable mechanical properties (structural fuses). Consequently, the subsequent stages of adaptation are: (i) impact detection and identification, (ii) development of the optimal control strategy and (iii) its realization with the use of structural fuses. The entire process is conducted in a semi-active way, without supplying large additional energy to the system. Application of the AIA paradigm allows to adjust structure dynamic characteristics to actual impact loading, to mitigate its response in optimal way and, in effect, to accommodate to contemporary strict safety requirements.

Nowadays, the design and practical realization of AIA systems have become possible and justified due to a broad accessibility of functional materials and required electronic devices (sensors, actuators and hardware controllers). Currently developed demonstrators of adaptive impact absorbing structures are based on miscellaneous adaptation techniques such as application of magneto-rheological fluids [4], piezoelectric actuators [5] or detachable pyrotechnic connections [6].

Typical example of AIA system is adaptive landing gear (Fig. 1) where piezoelectric valve adjusts damping characteristics to actual landing conditions in order to reduce the peak of generated grounding force and to minimize airplane deceleration during touchdown [5]. Another example is adaptive truss structure equipped with structural fuses with controllable yield stress levels, whose proper control allows to maximize dissipation of the impact energy and to obtain desired deformation of the structure [7,8] (Fig. 2).

On the other hand, one of the classical technologies applied for protection against impact loadings are pneumatic and inflatable structures, which are utilized as energy absorbers in land and water transport, aeronautics and astronautics. The most common

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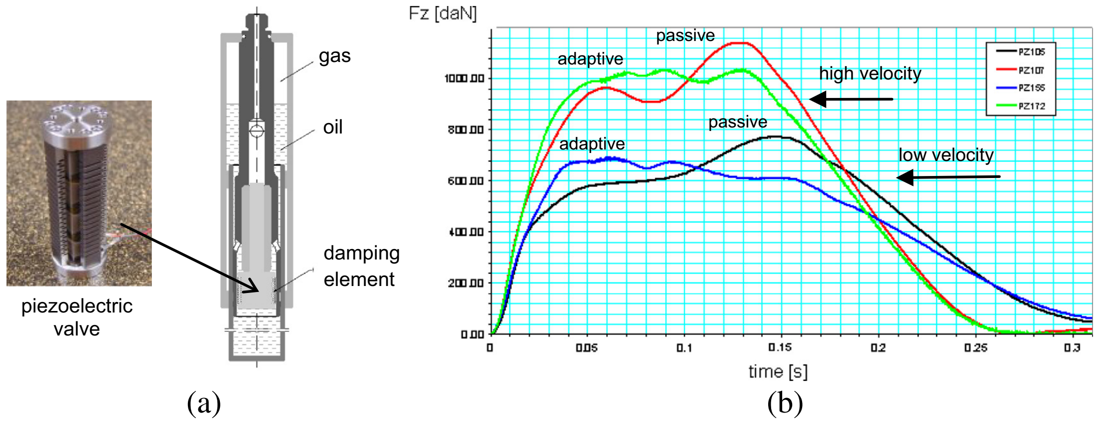

Fig. 1. Adaptive lading gear: (a) design of the absorber and (b) reduction of grounding force obtained during flight tests [5].

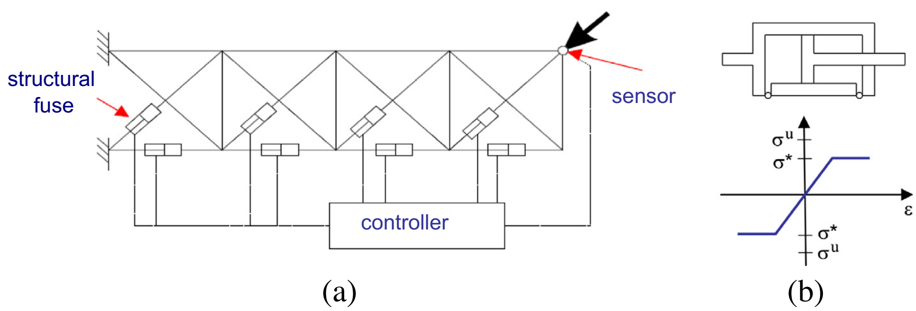

Fig. 2. Adaptive truss structure: (a) general scheme of the system and (b) structural fuses with controllable yield stress levels [7,8].

application in this group are classical airbag systems used in passenger cars to provide safety of the occupants during collisions. The other, less known examples are air fences at speedway tracks, protective suits for motorcyclists, pneumatic fenders used in ports and external airbags for space landers (Fig. 3). Unfortunately, the design of most classical pneumatic structures enables only adjustment of initial inflation or initial pressure level. During the impact process they remain passive systems where change of internal pressure is by no means controlled. This indicates that the process of energy dissipation is not optimal and it can be significantly improved by introducing discharge valves precisely controlling actual rate of gas outflow.

Adaptive Inflatable Structures (AIS, [9]) are innovative pneumatic structures which operate according to the principle of adaptive impact absorption. They are constructed as deformable structures containing sealed chambers filled with compressed gas and additionally equipped with fast inflators and controllable discharge valves. The concept utilizes controlled transfer and release of gas as an effective technique allowing for real-time adaptation of the energy absorbing structure to actual dynamic loading.

The process of adaptation is performed in several stages. The first stage is impact detection and identification, which is executed with the use of ultrasonic sensors or dedicated impact sensors (cf. 'Impactometer' concept [10]). Recognized impact scenario is utilized by a hardware controller to develop optimal strategy of internal pressure control. At the beginning of impact each chamber of AIS is inflated to appropriate initial pressure in order to provide optimal initial stiffness of the structure. During impact the valves manage the flow of the gas between the chambers and its outflow to environment, which allows for precise control of gas pressure in particular parts of the structure during subsequent stages of the process. As a result, dynamic characteristics of the structure can be instantaneously modified and adjusted to actual level of loading. The entire procedure enables significant improvement of the process of energy dissipation and mitigation of dynamic response of both protected structure and impacting object. Hitting object can be stopped by using the whole admissible

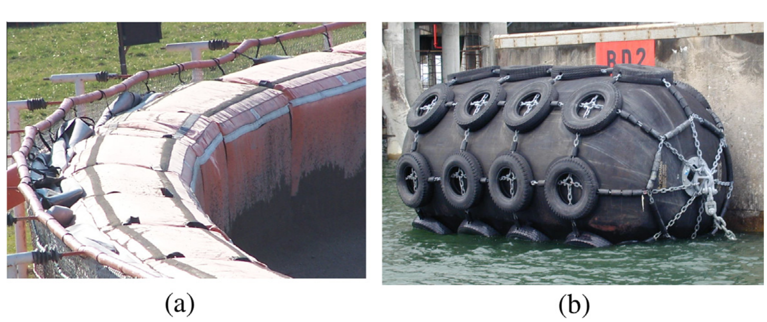

Fig. 3. Passive inflatable structures: (a) air fences at speedway tracks (source: Wikipedia) and (b) pneumatic fender (source: Elha Supply & Engineering, Ltd).

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