Adaptive Impact Absorption – the concept, innovative solutions, applications

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ABSTRACT: Adaptive Impact Absorption focuses on active adaptation of energy absorbing structures by using system of sensors detecting and identifying impact in advance and controllable semi-active dissipaters with high ability of adaptation to actual dynamic loading. The article presents a review of research carried out in the Department of Intelligent Technologies of Institute of Fundamental Technological Research dedicated to applications of systems for adaptive impact absorption. Wide range of presented examples covers aircraft landing gears, adaptive crashworthy structures, wind turbine blade-hub connections and flow control based airbags for maritime and aeronautical applications.

1 INTRODUCTION

Increasing demand for safety becomes a clearly visible trend in contemporary engineering. The widespread research is oriented towards development of systems protecting against heavy dynamic excitation (such as impact or blast) or harsh environmental loading. Examples of such structures are thin-walled tanks with high impact protection, vehicles with high crashworthiness, protective barriers, etc. Typically, suggested solutions focus on the design of passive energy absorbing systems which 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.

Above shortcomings of passive structures can be significantly reduced by application of systems of Adaptive Impact Absorption which focuses on ‘active adaptation’ of energy absorbing structures to actual dynamic loading by using system of sensors detecting and identifying impact in advance and by applying controllable dissipaters (structural fuses) to change structure characteristics in real time, [1-5]. The term ‘active adaptation’ refers to the particular case of actively controlled energy dissipater, where the need for external sources of energy is minimized and the task for actuators is reduced to modify local mechanical properties rather than to apply externally generated forces.

Various strategies of adaptation to the identified impact can be proposed, depending on the particular problem, eg. repetitive exploitive loads vs. critical emergency impact. Minimisation of an acceleration measure in the selected locations for smoothing down the impact reception corresponds to the first case, when reduction of fatigue accumulation is an important issue. On the other hand, maximisation of the impact energy dissipation in the selected time interval for the most effective adaptation to the emergency situation corresponds to the second case. However, other desirable scenarios for AIA can be also proposed in particular situations. For example, the strategy of local structural degradation (eg. due to provoked perforation in impacted location) in order to minimize the damaged zone and preserve the structural integrity can be also an option in critical situations. In general, the AIA system should be designed for random, impact multiloads, what creates new research challenges due to optimal forming of structural geometry and location of controllable devices.

Another challenge of AIA approach is to invent innovative technologies applicable as mentioned controllable dissipative devices. Shock absorbers based on MR fluids or piezo-valves, discussed below, can be successfully used in adaptive landing gears to mitigate repetitive exploitive impacts. Other technology presented in this paper is based on Macro Pyro Systems (MPS) that can be applied for detaching (in real time) selected structural joints in order to improve structural response in emergency situations (eg. in crash of vehicles). The next innovative methodology deals with the concept of 'structural fuses' with elasto-plastic type of overall performance and controllable yield stress level, where the active device itself can be based on various types of actuators, eg. MR fluids or SMAs. Finally, the concept of 'adaptive inflatable structures' utilizes controllable release of pressure as an efficient method of adaptation to impact loading.

The objective of this paper is to present the concept of Adaptive Impact Absorption (AIA) by using several examples from various branches of engineering. The paper presents an overview of research in the AIA field conducted recently in our group and is based on previously published conference contributions. The monograph [1] presents more detailed discussion of the problems under consideration.

2 CONCEPT OF ADAPTIVE LANDING GEAR

An adaptive landing gear (ALG) is a device capable of automatic adaptation to particular landing conditions recognized by a system of dedicated sensors. The ALG is controlled actively in order to mitigate the peak force transferred to the aircraft structure during touch-down (considered as repetitive exploitive impact) and thus to limit the structural fatigue factor. The impacts result in impulsive generation of acceleration levels within the suspension. The objective of the ALG is then to minimize the acceleration peak levels being transferred to the structure [1].

The classical methodology of the conceptual design of shock absorbers assumes tuning of their damping and stiffness properties to one particular magnitude of the impact energy. According to the industry regulations, all landing gears are optimized for the case with the max. aircraft weight and max. sink speed (i.e. max. impact energy), which is purely for the reason of safety. However, the impacts vary significantly between landings. This situation results in non-optimal landing gear behavior for most of the common landings characterized by lower impacts energies. More specifically, this non-optimal behavior results in the generation of very high damping forces and an unwanted reduction in the effective stroke. Consequently, the acceleration being transferred to the protected structures is increased. These unnecessary overloads of the structure significantly influence the fatigue processes. A solution for the mentioned problem is the introduction of the Adaptive Landing Gear, which has the possibility of fitting its characteristics to particular landing sink speeds and weights of the aircraft.

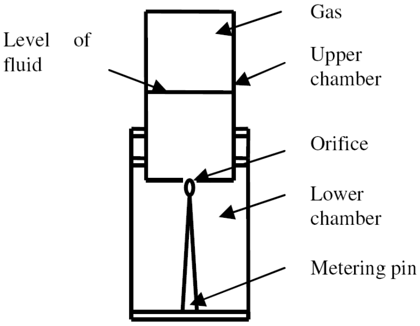

Figure 1. Scheme of an oleo-pneumatic shock strut with metering pin.

This adaptation of the shock absorber in ALG would allow optimal performance to be achieved for a wide range of impact velocities and weights of the structure. The force generated by the LG depends on the difference between the fluid and gas pressures in the lower and upper chamber of the strut [6,7] (Figure 1). This force can be controlled via proper management of the operational media's migration between the chambers. The value of the pressure drop can be modified via control of the gas pressure in the upper chamber, or by regulating the fluid flow resistance across the orifice (using a fast actuated valve or by changing the rheological properties of the fluid in the gap). An interesting ALG concept for improving the energy dissipation of a landing impact was considered by NASA researchers for several decades [8-12]. The statistical benefit from the introduction of an ALG in a small cargo aircraft, considered as reduction of the fatigue factor was estimated at 16 % [13].

In the recent years conceptual research were performed on the adaptive landing gears actuated via magnetorheological fluids, which solved the problem of time delays, cf. ADLAND project [4,14]. The implementation of the MR fluid into the shock absorber gives an unique opportunity to control the pressure drop between the upper and lower chamber. The fluid has a feature of changing its apparent viscosity when it is subjected to an external magnetic field [15]. Having the magnetic force generator incorporated around the hydraulic orifice, one can reach a controllable valve effect by means of control of the local apparent viscosity of the fluid. The time delays of the MR valve's operation depend on the rate of generation of the magnetic excitation [16]. This approach allows to reach even 30% of max load reduction factor in particular cases [17]. Another possibility for control of the medias migration in the shock absorbers is using fast valves actuated by piezo elements. The first experiment dedicated to utilization of this technology were conducted within the ADLAND project [4].

Figure 2. Adaptive Landing Gear during tests in PZL Mielec (Polish Aviation Factory) within the ADLAND project [4].

2.1 *Control system for Adaptive Landing Gear*

The control system for the adaptive landing gear is a challenging task to design. The designer must take into account a series of aspects, which are results of uniqueness of the aircrafts ground operations. The control system design must consider the following important issues.

A class of the problems is related to the duration of the phenomenon. In general, the landing impact lasts between 50 to 200ms, depending on the size of the landing gear and the landing conditions. This short time period makes it difficult to implement the active control strategies effectively as the present actuators are not able to respond fast enough. High response valves currently available on the market offer the best time performance on the level of 10-12ms operational delay in the case of hydraulic valves, directly operated, with electrical position feedback [18]. This circumstance drove the designers to develop a new class of High Performance Valves (HPV) based on piezo-electric actuation [19] or utilization of the fast responsive MR fluid actuator [17,20] whose time delay do not exceed 5 ms.

An important problem is also fast recognition of actual mass of the aircraft. The exact estimation of this parameter's value is crucial for proper operation of the control algorithm. An active method of mass estimation can be realized via introduction of the Real Time Mass Identification system [21], which enables identification of the actual weight loading each landing gear strut. When Real-Time Mass Identification is used with an integrated sink speed measurement, it is possible to assess precisely the energy of the coming impact for each wheel. This configuration would make it possible to establish the optimal strategy for active energy dissipation of the whole structure.

The next problem to be considered for the design of the control system for the Adaptive Landing Gear is calculation of the exact position of the aircraft during landing in relation to the runway. The position is important since the impact energy dissipation process must be significantly different, depending on whether the plane lands on one or both main landing gears. The position of the aeroplane is continuously monitored during flight by gyroscopic sensors but the measurements give the absolute outcome, and it is not possible to calculate the exact position of the aeroplane in relation to the surface of the runway. One method of conducting these measurements is to integrate the height sensors with sink speed sensors on each landing gear. This would enable monitoring of the 6DoF position of the aeroplane, so that the landing gears can adapt more effectively to the coming impact. [19]

The following problem that must be considered in the design of active landing gears is the spring-back force that occurs during touchdown. Spring-back forces come from the acceleration of the wheels after contact with the runway surface. The circumferential velocity of the wheels must be equalised with the horizontal velocity of the aircraft. The horizontal component of the load vector acting on the landing gear causes bending of the strut. The deflected strut springs back rapidly and increases seal friction within telescopic oleo-pneumatic landing gears. This phenomenon introduces significant friction damping, which acts parallel to the oleo damping generated by the orifice. The influence of friction damping is very difficult to predict since it varies with each landing and is dependent on the horizontal speed of the aeroplane, the sink speed of the aeroplane, runway adhesion, temperature and the exact 6DoF position of the aeroplane. Prediction of the exact value of friction is a very complex task and the result can be estimated with a significant error. In the case of a control system for which the damping force would be treated as an input, the safest and most convenient solution is to use a sensor that measures the total force generated by the landing strut, and to modify it with the adaptive component. Control systems used in such a routine were analysed and tested in the laboratory [20], but the measurement of the total axial force in the strut is a challenging problem due to technological limitations in real applications.

According to the presented discussion, the preliminary requirements for the active landing gear control system can be summed up as follows. In connection with the fact that the impact process duration does not exceed 50ms in the most severe cases, the control system must have the capability of recognizing the impact energy before touchdown in order to adapt the system before the process starts. The second requirement is that the system (actuator + sensors + control hardware) must have the capability to update its state within 4 ms in order to keep the control system performance efficient. The third established requirement for the control system refers to the feedback signal on which the control is based. The signal must describe the total reaction of the landing gear during the process.

Summary

The system of Adaptive Landing Gear is currently developed for ultra-light aircraft as the idea of increasing of the safety factor for amateur pilots. The system can also be very useful for owners of rental fleets since their customers are often inexperienced pilots. The ALG should also be considered as the first step on the way of development of the fully automatic, semi-active landing system.

3 ADAPTIVE WIND TURBINE

In order to meet the EU goal for the wind energy production for year 2020 it is expected that the rate of the market growth will be increasing, and considering that one big wind turbine is more efficient that many small ones, it is expected that also the size of wind turbines has to be increasing. There are, however technological barriers on the way to up-scaling, such as the weight limit, tip speed limit or the blade loading. Classical control mechanisms may be adapted for load reduction control strategies, as described in Ref. [22], [23], [24], even though their main task is to maximize the energy capture.

In particular the blade root bending due to extreme wind gusts causes the blade root bending stress to be a design limiting factor. Two possibilities to overcome this barrier are new composite materials development on one hand and new adaptive solutions on the other. The latter is the subject of presented work.

A semi-active adaptation technique was proposed basing on the following observation. Since the aerodynamic torsional moment forces a blade to turn to feather, it can be expected that, once the torsional connection of a blade is freed, it could increase the blade pitch angle thus reducing the blade loads caused by a gust. Consequently the root bending and resulting stresses could be also mitigated.

For the purpose of assessing the effectiveness of the proposed solution a simple wind turbine numerical model has been built. The turbine chosen for simulations was similar to one analyzed by Lindenburg [25]. The model consists of aerodynamic, structural an adaptation modules. All degrees of freedom that influence the aerodynamic forces are included in the model. Control procedures can be applied to any degree of freedom.

The adaptation process is activated upon the detection of an extreme wind gust. Wind gusts implemented in simulations take the form according to the international standard [26] (Fig. 3).

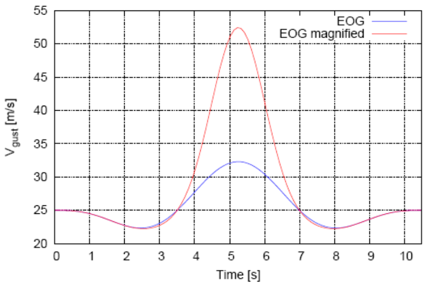

Figure 3: Extreme operating gust

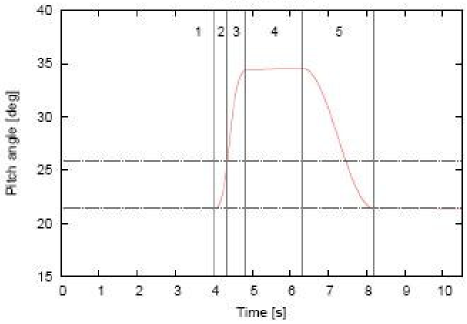

Figure 4: Braking force generated with an MR damper

The adaptation of the blade – hub connection is summarized on Fig.4 in terms of the pitch angle changes. After the gust detection (1) the blade is unclutched and rotates freely about its axis (2) until the braking process (3) is activated. The blade rotation is then slowed down and stopped with a braking system. Once the gust is gone, the initial pitch angle is restored with the regular pitch control mechanism (4) and (5). Classical pitch control mechanisms are described f.e. in [27].

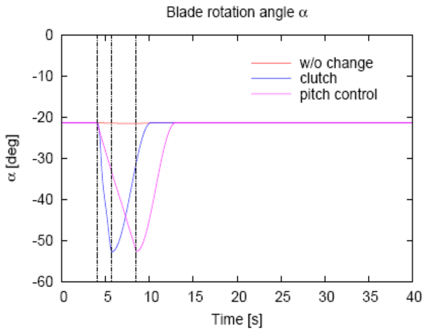

Figure 5: Semi-active vs active device response

The adaptation process described above was compared with a pitching mechanism working with the speed of 6 deg/s. It is observed that the unclutching process (semi-active), with the average rate of ca. 26 deg/s, is faster than the pitching mechanism (active solution), cf Fig.5

The more sudden the gust, the faster the semi-active solution as compared to the pitching mechanism. Fast reaction time creates a possibility to effectively reduce the internal forces resulting from an extreme gust load. This, in turn, could be crucial in the up-scalling process as the blade root bending is an important design criterion. An example answer, i.e. tower and blade bending are depicted on Fig.6 and Fig.7 respectively. Results are shown relative to the steady state response.

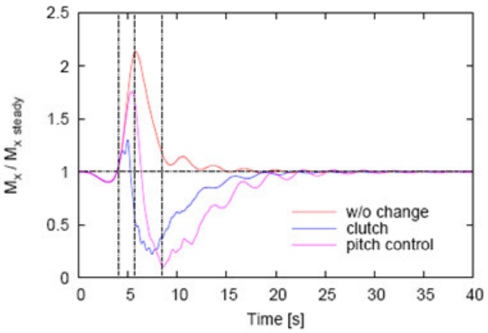

Figure 6: Tower bending moment

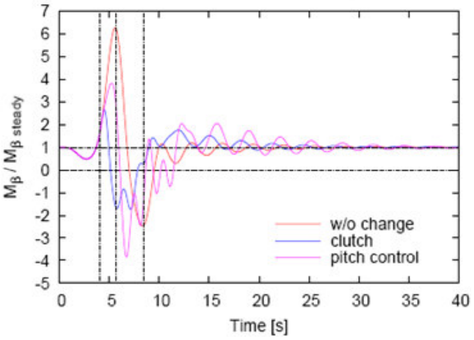

Figure 7: Blade bending moment

Parameters that influence the response are the time instant of unclutching, duration of the free rotation phase, the braking force control and the time delay before initial pitch restoring. Parametric studies have been made for the influence of above variables on the out-of-plane bending moment and results are shown on Figures 8 and 9.

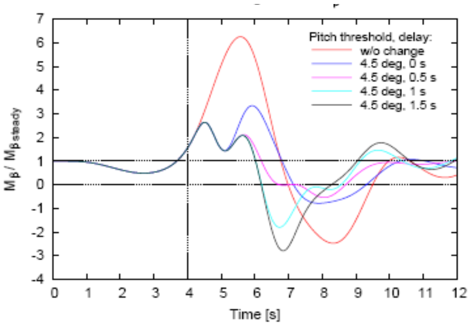

Figure 8: Various free rotation phase duration instants (phase 2 on Figure 4)

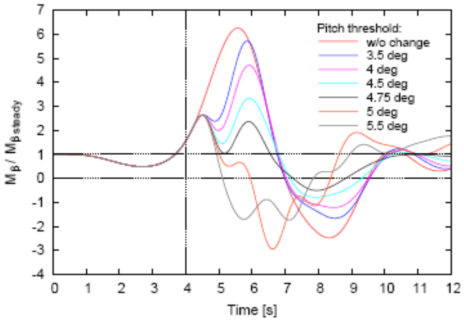

Figure 9: Various initial pitch angle restoring (beginning of phase 5 on Figure 4)

While in the reference case the bending moment range of change is eight-fold its steady state value, the proposed solution can reduce the range of change to three-fold the steady state value.

In the reference case the phase shift between the maximum wind speed and the bending moment peak is about 0.3s, which gives an adventage of the direct sensing (wind speed, wind pressure) over the response sensors (stress, strain) (cf Fig. 10).

Conclusions from the carried out numerical simulations are as follows:

a) The proposed semi-active solution could effectively mitigate the internal forces caused by extreme wind gusts, in particular the blade root bending moment
b) The proposed semi-active solution is faster than the pitching mechanism
c) The direct sensing of the wind load could provide enough time advance for the adaptation process activation

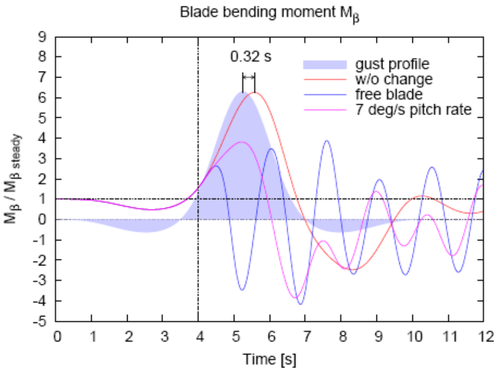

Figure 10: Phase shift between the gust and bending moment maxima

Numerical simulations indicate that there could be a potential in the proposed, novel approach to the wind gust load alleviation. The present research is focused on the elaboration of a lab scale actuator device which will be capable of carrying out the control strategy described above. A wind tunnel experiment is planned in which a wind turbine rotating model will be equipped with '*smart blades*' – blades with controllable connection to the hub.

4 AN OVERVIEW OF ADAPTIVE CRASHWORTHY STRUCTURES

Adaptive crashworthy structures are becoming a new direction in the region of heavy impact problems, where suitable modification of structural properties can severely improve behavior of a system subjected to a unforeseen catastrophic event.

4.1 *The adaptive thin walled energy absorber*

The idea of control of the impact absorber's crushing resistance force, uses the concept of structural connections uncoupled by gas pressure generated by deflagration of the pyrotechnic material [28]. Due to the fact that technology for the controllable increase of the energy absorbing capability is usually more complex than method for its reduction from the initial value, in the presented concept the crushing stiffness is decreased by controlled disconnection of the additional structural members from the main absorber's profile (Figure 11). In the example a rectangular cross-section was used due to its similarity to typical structural parts of a passenger cars. An additional members were designed as two C-shaped profiles connected to the structure by eight detachable pyroconnections.

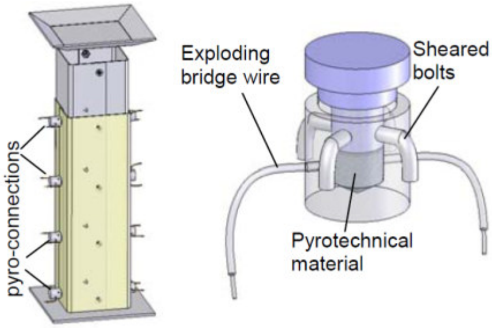

Figure 11. Pyrotechnical adaptive impact energy absorber

The initiation process in the experiment was controlled by the electrical control circuit, which was optically separated from the controller. The silicon-controlled rectifiers (SCR) were used for fast response switching of the initiating current. When the control system basing on the sensors decides to reduce the crushing stiffness a initialization signal triggers the pyrotechnical system. A battery of capacitors, pre-charged to the initial voltage, is being rapidly discharged through the fuse wire, which vaporize in time shorter than 250 microseconds. Fuse of the exploding bridge wire type (EBW), thermally ignite the pyrotechnical material (black powder), filling the deflagration chamber. Rapidly growing pressure acts on the pyroconnection's piston, breaking the sheared pin what release mutual kinematics of the absorber's members (Figures 12,13). When the members become separated from the main absorber body the average crushing force is decreased. Impacting mass deceleration and energy absorption vs. time characteristics are shown on the Figure 14.

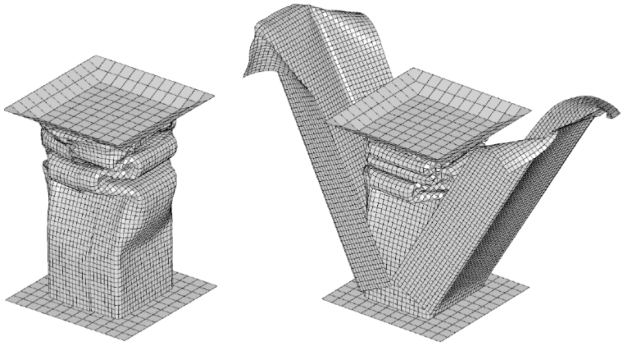

Figure 12. Passive (left) and active (right) modes

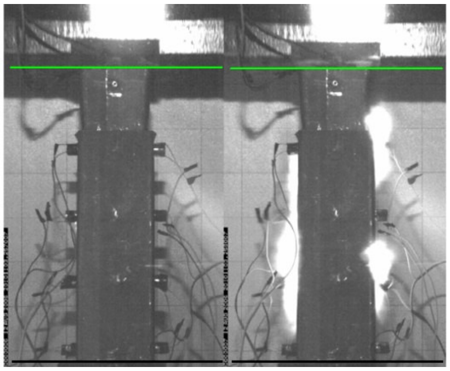

Figure 13. Experimental assessment: absorber before impact (left) and firing sequence (right)

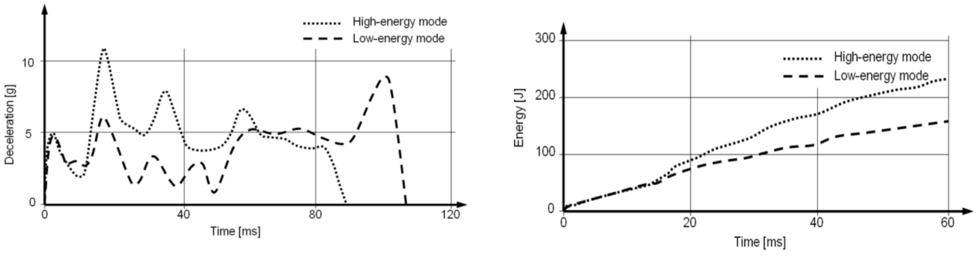

Figure 14.Impacting mass deceleration and dissipated energy versus time curves

4.2 *Example of local heuristic control of truss-like cantilever structure under impact*

To demonstrate idea local of structural control [29], a discrete spatial truss-like cantilever structure (Figure 15), consisting of mass-less structural members, transferring axial forces to two affiliated lumped mass nodal points, was used. The element axial force-displacement characteristics is a combination of elastic-perfectly plastic or elastic-frictional constitutive law with modifications governed by the control function $F_i(t,p_1,p_2,..p_n)$ (Figure 16). The structure is subjected to impact modeled as initial velocity and lumped mass with one of the nodes, becoming the only source of energy in the system. The objective of the control algorithm will be the maximization of maximal internal energy E_i during impact

$$\max \sum_i \int P_i(l_i, F_i)dl_i = E_i \,, \qquad (1)$$

with the constraint defined as the maximal allowed elongation of each element

$$|l_i| < d_{\max} \qquad (2)$$

after which its failure occurs.

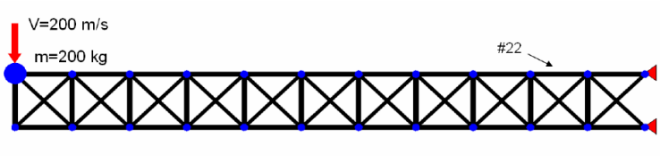

Figure 15. Cantilever model overview

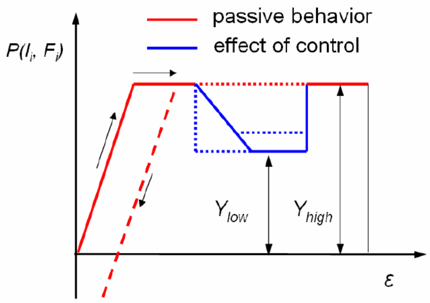

Figure 16. Elasto-plastic characteristic of the truss element with modifications due to control function

The control algorithm, is aimed at preventing of destruction of the single structural element (the master element) by reducing yield stress levels of the neighboring ones (slave elements), which influence to the plastic deformation of controlled element were heuristically assessed as the greatest.

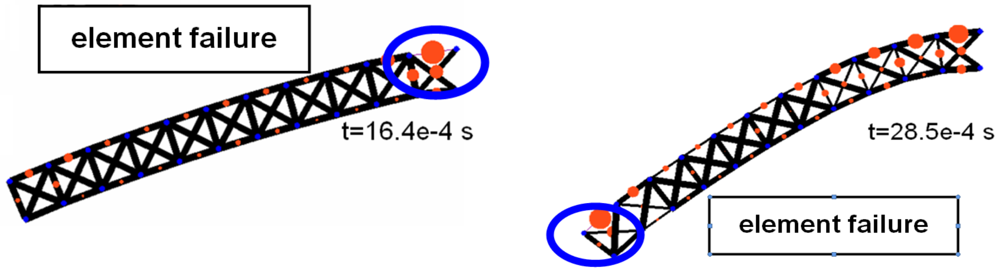

Figure 17. Terminal states (at the failure moment of first element) for the passive structure (left) and self controlled structure (right)

Simulation results display enhancement of energy absorbing capability. Upon assumed limit element's elongation condition it is increased 85% comparing to the passive case without any control. Decelerations of impacted node and example element force histories are shown in Fig. 17. Element thickness is proportional to its current yield stress level, while circular marker's fields at the element's centers are proportional to the amount of dissipated energy for each one.

5 ADAPTIVE FLOW CONTROL BASED AIRBAGS

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.

'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 and active change of pressure during impact executed by controlled gas release.

Impact identification concerns two main impact parameters: hitting object velocity and its mass. The initial velocity and direction of the impacting object can be measured directly e.g. by ultrasonic velocity sensors located in several points of the structure. Impacting object mass and its 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 proposed in Ref. [21].

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, internal forces or rebound velocity. Controlled gas exhaust can be executed by opening controllable High Performance Valves (HPV) based on multifolding microstructures [30] or thermically activated membranes [31]. 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.

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 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 for solid domain and Navier-Stokes equations for fluid domain. Such approach is usually applied for extremely fast processes like airbag deployment, Ref. [32] or out of position (OOP) airbag-dummy collisions, Ref.[33].

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. Mentioned method effectively utilizes equation of gas state, thermodynamical balance of internal energy and description of flow through controllable valve [34].

5.1 *Maritime applications of inflatable structures*

Flow control based airbags can be effectively utilized to mitigate open sea collisions, cf. Ref.[35]. The inflatable structure that will be used for protecting offshore wind turbine against impacts of small service boats 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 around 1m in width due to requirements of fast inflation and pressure release. Moreover, value of initial pressure is restricted to 3 atm because of high stresses arising in rubber walls after inflation.

To obtain better adaptation to various impact scenarios, the inflatable structure is divided into several separate air chambers located around the tower, cf. Fig. 18a, b. Controllable valves enable flow of the gas from each chamber of the torus structure to environment and between adjacent chambers.

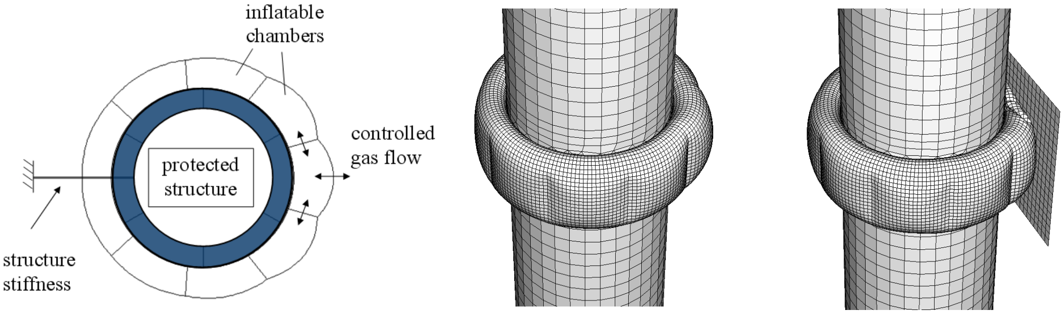

Figure 18: Inflatable structure protecting wind turbine tower: a) simplified 2d model b) initial inflation before collision, c) deformation during impact

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 semi-active acceleration mitigation valve connected to appropriate chamber is opened just after ship impact and valve opening is not changed during the whole impact period, cf. Figure 19, curve 1. In active control strategy valve opening is proportionally adjusted on several time intervals and ship acceleration is maintained on almost constant level required to stop the ship before the tower wall. When only release of pressure is feasible (i.e. there is no fast inflator in the system) the valve has to remain closed until ship acceleration achieves desired level, cf. Figure 19, curve 2. Finally, the lowest value of acceleration is obtained by applying additional inflation at the beginning of impact which helps to avoid disadvantageous initial stage of gradual acceleration increase, cf. Figure 19, curve 3.

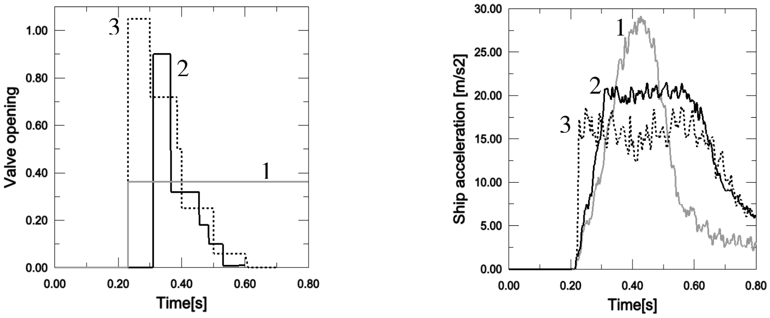

Figure 19: Strategies of acceleration mitigation: 1) constant valve opening (grey line), 2) pressure only released during impact (black line), 3) additional inflation at the beginning of impact (dashed line)

5.2 *Adaptive airbags for helicopter emergency landing*

Another applications of the proposed concept are adaptive external airbags for helicopter emergency landing [36]. The system consists of four cylindrical cushions attached at outer side of helicopter undercarriage. 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.

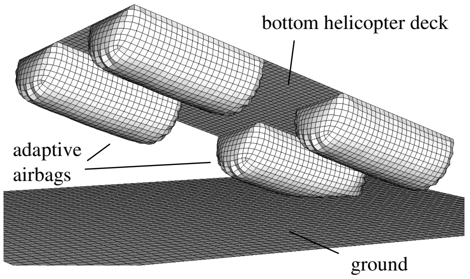

Figure 20: Numerical simulation of emergency landing with adaptive airbags

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 (Figure 20) and various landing directions and velocities were analysed. However, the above model is quite heavy numerically due to large material and geometrical nonlinearities and extensive and changeable contact conditions. Therefore, simplified model comprising stiff plate and adaptive pneumatic cylinders with assumed leakage and controllable pressure outlet was also developed, cf. Figure 21a.

The control problem was to find initial pressure inside cylinders and optimal (but fixed during landing) opening of each valve for which landing scenario runs possibly smoothly i.e. the direct contact of the stiff plate and ground does not occur and the falling object does not bounce or rotate strongly. The objective function in optimisation problem was formulated as global measure of acceleration defined as the total of linear and angular acceleration taken with appropriate weigh coefficients. It was found that constant in time valves opening characterised by various intensity and time of activation for each valve provides almost constant level of acceleration, cf. Fig. 21.

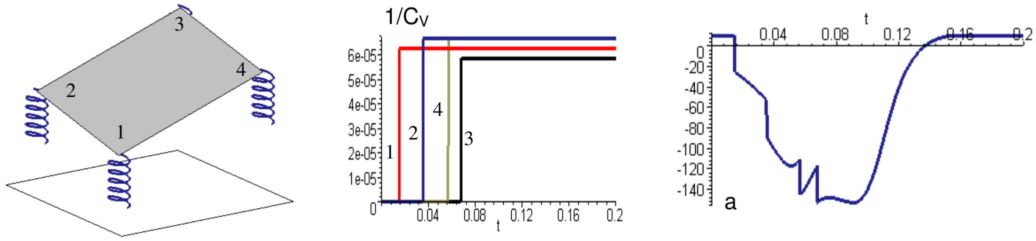

Figure 21: a) Simplified model of emergency landing, b) applied valve opening (represented by inverse of flow coefficient), c) resulting linear acceleration of the center of the mass

As a next step, obtained control strategy was accommodated to the system containing airbags instead of adaptive pneumatic cylinders. Both initial area of the airbags and their deformation during landing was taken into account. Comparison of adverse landing scenario with passive airbags and advantageous one with pressure control applied is presented in Figure 22.

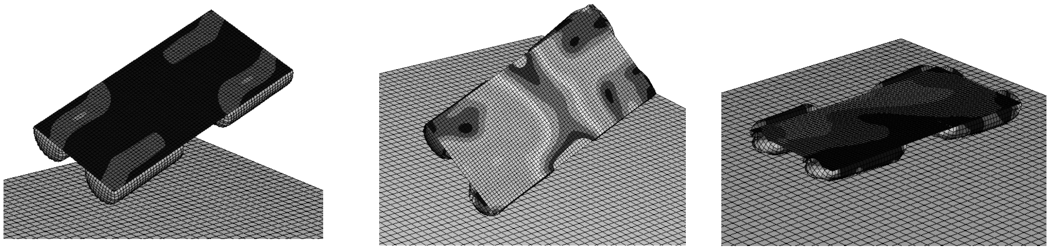

Figure 22: a) Considered landing scenario; b) non-optimal passive response with rear part rebound c) optimal uniform airbags compression obtained by semi-active pressure control

6 CONCLUSIONS

Adaptive Impact Absorption seems to be promising technique both for mitigation of repetitive, exploitative loads and for protection against heavy unexpected or environmental loading. Both experimental and numerical results presented in the article prove that the benefits of using adaptive impact absorbing structures instead of passive ones are significant. The main still challenging problems to be solved to improve the proposed methodology of AIA are the following:

- to develop technologies for structural fuses with short response-time
- to improve and test techniques of on-line impact load identification
- to develop control algorithms for optimal structural adaptation
- to apply integrated AIA systems to well-chosen demonstrative case studies.

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