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# ADAPTIVE IMPACT ABSORPTION FOR SAFETY ENGINEERING

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**Abstract**. *Adaptive Impact Absorption focuses on active adaptation of energy absorbing structures to actual dynamic loading by using system of sensors detecting and identifying impact in advance and controllable semi-active dissipaters with high ability of adaptation. 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 pneumatic 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 characterized by a high ratio of specific energy absorption. Although the energy absorption capacity of such elements is high 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 focus on semi-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[1-3]. The term ‘semi-active adaptation’ refers to the particular case of semi-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, e.g. repetitive exploitive loads vs. critical emergency impact. Minimisation of an accelerations values 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 (e.g. 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 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 design of semi-active device 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 ADAPTIVE PNEUMATIC LANDING GEAR

Pneumatic absorbers (e.g. protective air bags) are incorporated in some methods of minimizing the contact force between an impacting body and the obstacle during a collision. In classical solutions dedicated to the dissipation of the kinetic energy of the impacting body, no adaptive control of braking force is applied [4,5]. However, in some applications it is necessary to tune the level of the force during the process, in order to minimize its long term destructive influence [6]. The techniques proposed previously, usually incorporated advanced fluids, which are expensive, heavy and difficult to recycle.

### 2.1 The concept of pneumatic landing gear

In order to overcome the above difficulties a new technique of the control of the deceleration process based on adaptive pneumatic absorber was proposed [7,8]. The innovative adaptive impact absorber consists of double-chamber cylinder with a piston and piezoelectric valve in a by-pass configuration. During the process of landing the intensity of the gas flow through the valve is controlled in order to achieve the optimum deceleration level. The piezoelectric actuator is used to ensure sufficiently quick opening and closing of the valve. The advantage of the proposed semi-active approach is the decrease of the peak braking force in comparison to the passive braking of the impacting object. Furthermore, the semi-active control allows to adapt the behaviour of the device to the pre-determined level of the impact energy and therefore to optimize the braking process. Alternative applications for the device are rail cars or precise docking systems.

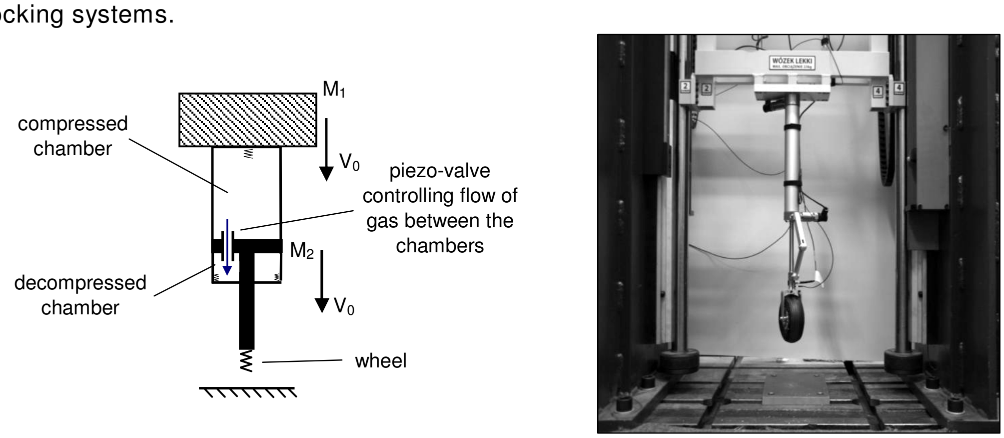



Figure 1: Pneumatic landing gear: a) operating principle, b) experimental stand

## 2.2 Design of the piezoelectric valve

The core element of the Adaptive Impact Absorber (AIA) is a piezo-valve – shown in cross-section view in the two pictures below (Fig. 2). This valve enables the flow of fluid between two sides of the piston inside the cylinder of the absorber. When the gas flow ratio is controlled, the reaction force of the absorber could be adjusted.

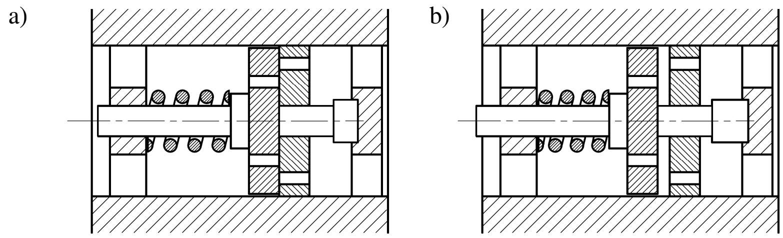



Figure 2: Cross-sectional view through the valve: a) closed, b) opened.

Figure 2 depicts the piezo-valve schematically in closed (a) and opened (b) position. Two plates with holes are tight when they are aligned. Moving one plate apart from the other one enables the flow of fluid through the valve. To ensure small dimensions and a compact structure of AIA, it is advisable to locate the valve in the piston of the absorber. This results in dimensional constraints of the valve. Short operating time also requires the use of the piezo-stacks for opening and closing the valve. As it is shown in the pictures, the opening of the valve is achieved by elongation of the piezo-stack (marked on the right hand sides of both pictures) and closing is done by the spring connecting one of the plates with housing.

## 2.3 Experimental results

During the laboratory tests, the outcomes of previously conducted numerical computations were verified versus the results of experiments performed with a model of adaptive landing gear (Fig. 3a, Fig. 3b). The experimental program for the presented part of the research was aimed at confirmation of the design assumptions and correctness of the packaging concept. The development of the optimal control strategy for the device was out of the scope of the presented study.

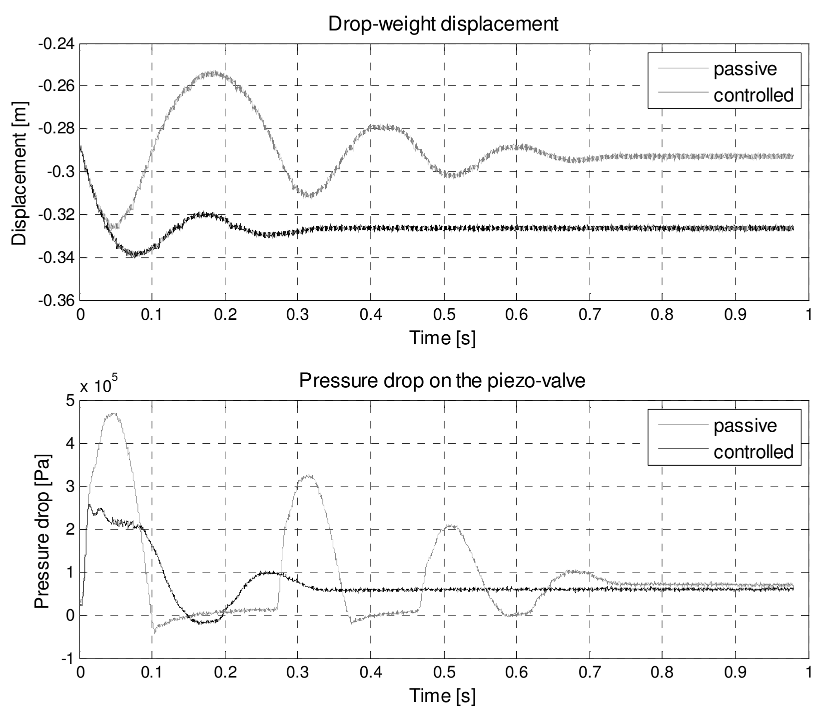



Figure 3a: Comparison of two modes of the absorber operation: passive and active.

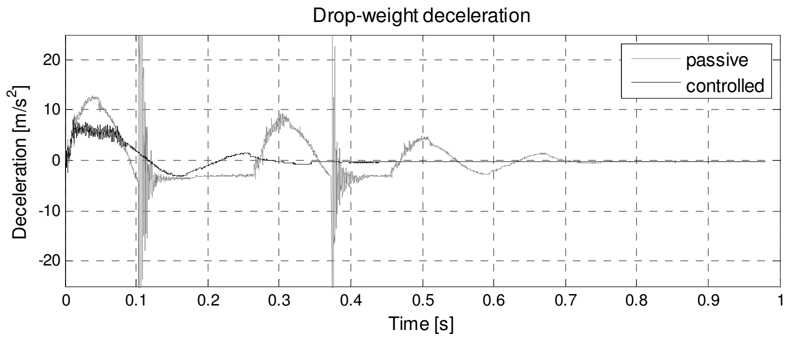



Figure 3b: Comparison of two modes of the absorber operation: passive and active.

At the presented stage of the investigation, the drop-test stand was used with the absorber mounted to the drop-weight of 9 kg at initial height of 0,1 m, which corresponds to the initial velocity 1,4 m/s, where the impact energy was estimated to be equal to 8,3 J. The experimental procedure included two stages. At the first, the absorber operated as a passive pneumatic device with the valve closed during impact. At the second stage the valve's operation was controlled in order to maintain a predefined value of pressure difference between the absorber's chambers and therefore to maintain the reaction force of the absorber on the predetermined level. In both cases the initial gas pressure in the absorber was 450 kPa and the predefined level of expected pressure difference was 210 kPa. The data acquisition setup included: gas pressure sensors inside the absorber's chambers, accelerometer fixed on the drop-weight, displacement sensor indicating position of the drop-weight in reference to the base plate of the stand.

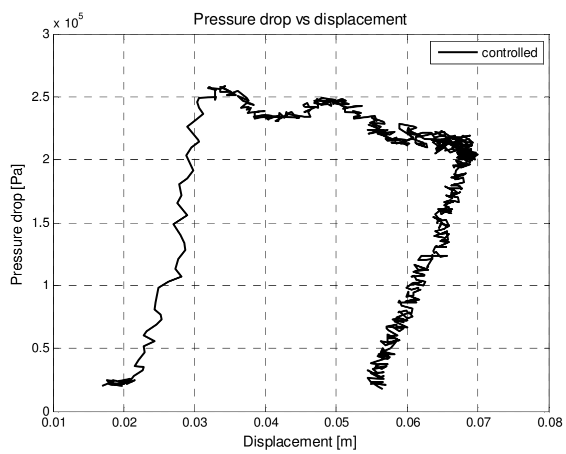



Figure 4: Pressure difference between two sides of the piston during the impact loading in the domain of the piston stroke.

The results of the absorber's operation are presented in Fig. 3. The graphs demonstrate evolution of three parameters (drop-weight displacement, gas pressure difference, drop-weight deceleration) in time domain for two cases: passive and controlled. In the first tested case, when the absorber had almost ideal elastic characteristic (except the friction losses) three bounces of the dropping object are demonstrated at 0,1 s, 0,37 s and 0,58 s time instants. In comparison, introduction of the controlled flow of the gas between the chambers allowed to dissipate the impact energy within the first compression stroke and to mitigate oscillatory movement after 0,35 s. Also the control procedure introduction decreased the maximum deceleration level of the drop-weight from 12 $m/s^2$ to 8 $m/s^2$.

Figure 4 depicts the pressure difference between the absorber's chambers in the domain of the landing gear deflection during the impact loading. The efficiency of the landing gear calculated in accordance to the method proposed by Conway [4] and Currey [5] was 71% in the presented trial.

## 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 [9,10,11] 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 [12]. 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. Detailed numerical study is available in [13].

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 [14] (Fig. 5a).

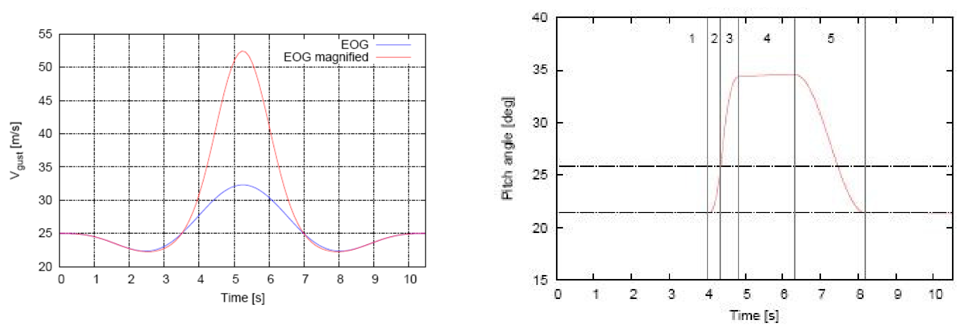



Figure 5: a) Extreme operating gust, b) Pitch angle changes in terms of control phases

The adaptation of the blade – hub connection is summarized on Fig.5b 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 [15].

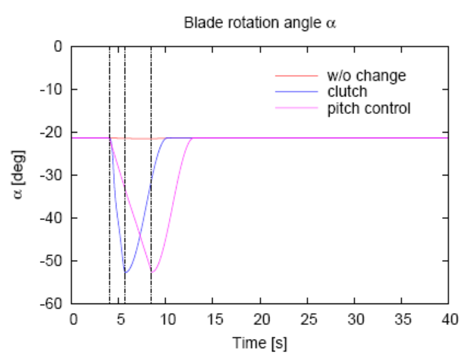
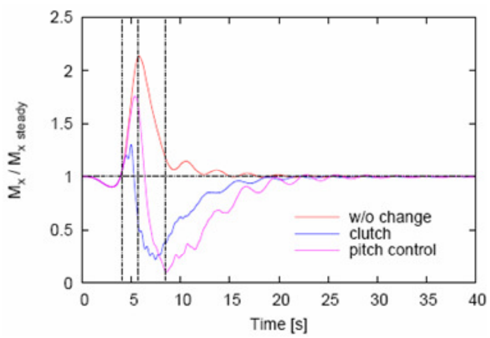



Figure 6: Semi-active vs active device response

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.6.

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.7a and Fig.7b respectively. Results are relative to the steady state responses.



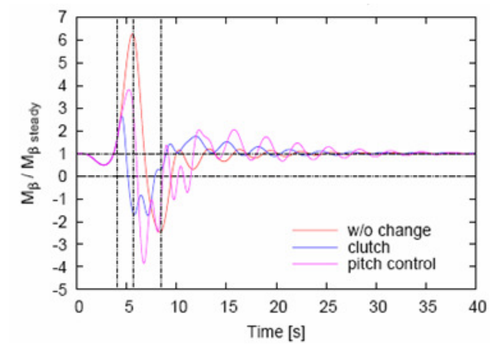
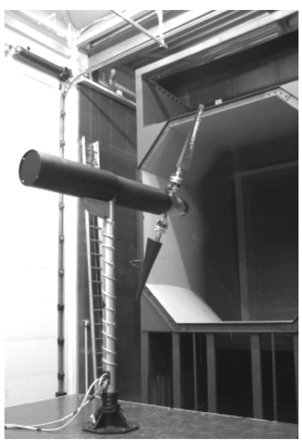
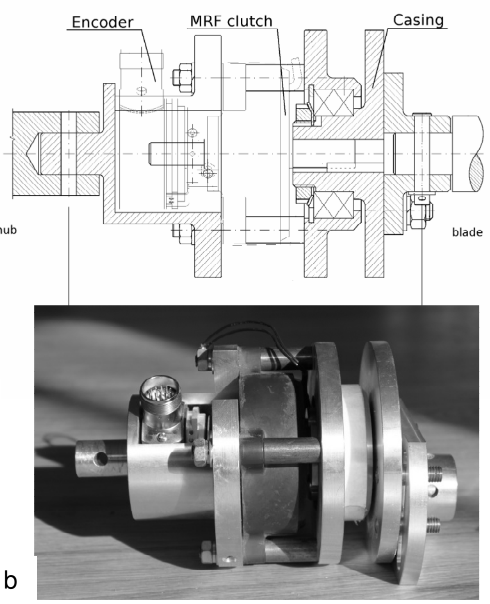




Figure 7: a) Tower bending moment, b) Blade bending moment

Experiments in open jet wind tunnel have been carried out to demonstrate the above load alleviation technique on a two-meter diameter rotor (cf. Figure 8a). Releasing of the torsional connection between blade and hub has been realized by means of an MRF-based clutch inserted between the blade root and the hub. The general view of the adaptive device is depicted in Figure 8b.



a




b

Figure 8. a) Experimental set-up in wind tunnel; b) Adaptive clutch (cross section and general view)

The reaction moments at the blade root, calculated from the strain gauges measurements, change in response to the blade rotation, which is shown in Figure 9, for the rotor speed of 180 RPM. Depending on the rotor speed the average value of out-of-plane bending moment ($M_{flap}$) is decreased 18-29%, as compared with average value before clutch release. Respectively the average values of the in-plane bending moment ($M_{edge}$) are decreased 54-84%.

Conclusions from the carried out numerical simulations and experiments 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) A blade can be drawn towards feather by the torsional moment provided that a certain mechanism releases the torsional connection between blade and hub
d) Blade rotation can be considered as an ‘emergency pitch’, in order to alleviate the wind loading

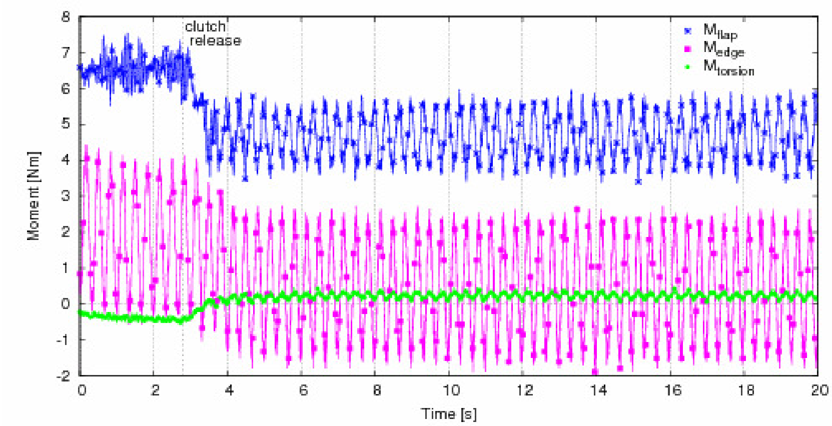



Figure 9. Reaction moments at root; rotor speed 180RPM.

## 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 [16]. 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 10). 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.

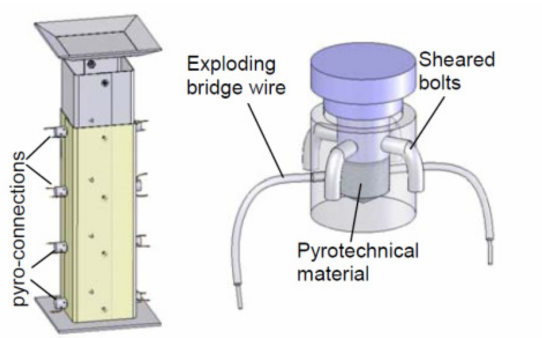



Figure 10: Pyrotechnical adaptive impact energy absorber

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 11a,11b). 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 12.

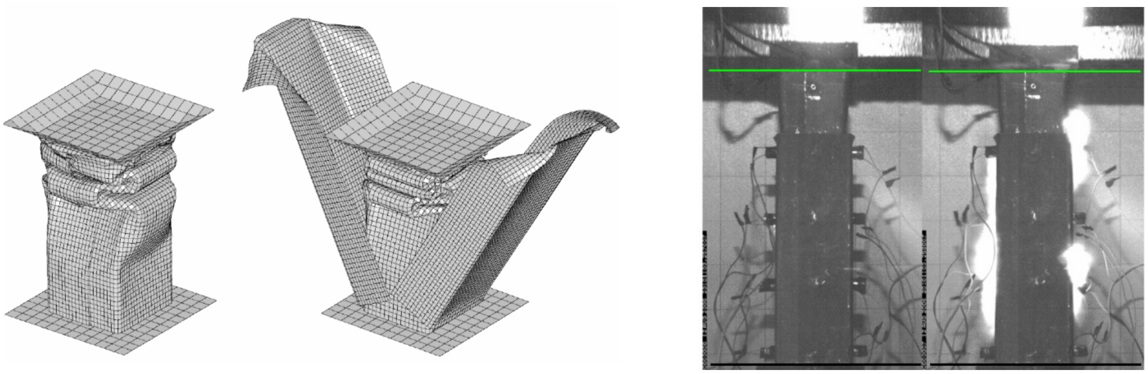


Figure 11: a) Passive (left) and active (right) modes; b) Experimental assessment: absorber before impact (left) and firing sequence (right)

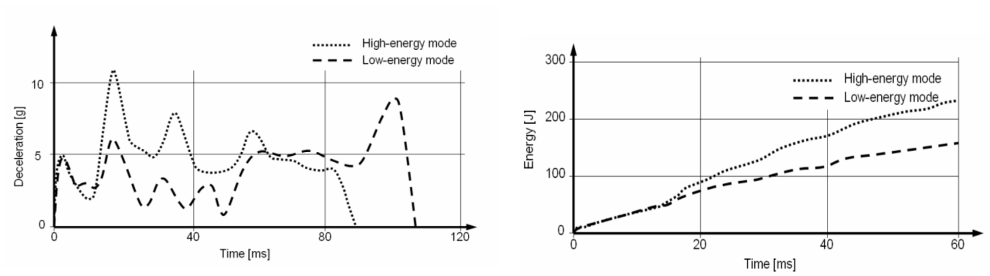



Figure 12: Impacting mass deceleration and dissipated energy versus time curves

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

To demonstrate idea local of structural control [17], a discrete spatial truss-like cantilever structure (Figure 13), 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 Fi(t,p1,p2,..pn) (Figure 14a). 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 Ei during impact

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

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

$$|l_i| < d_{\max}$$

after which its failure occurs.

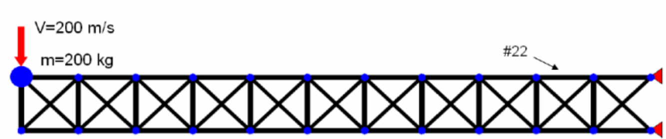



Figure 13. Cantilever model overview

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.

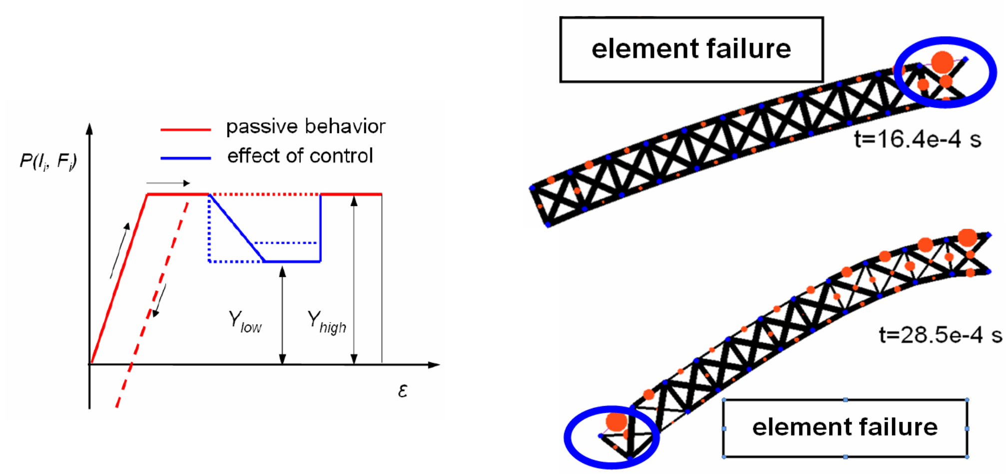



Figure 14: a) Elasto-plastic characteristic of the truss element with modifications due to control function; b) Terminal states (at the failure moment of first element) for the passive structure (left) and self controlled structure (right)

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. 14b. 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 real-time change of pressure during impact executed by controlled gas release. Development of optimal pressure release strategy is one of the main challenges in design of the adaptive airbags. The objective of applied control is to protect the impacting (or impacted) object by minimizing its accelerations, internal forces and rebound velocity. Controlled gas exhaust can be executed by opening controllable High Performance Valves (HPV) based on multifolding microstructures [18] or thermically activated membranes [19]. Real-time 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 analyzing 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 [20] or out of position (OOP) airbag-dummy collisions [21].

The above model can be significantly simplified by using Uniform Pressure Method 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 gas energy and analytical description of flow through the valve [22].

### 5.1 Maritime applications of adaptive airbags

Flow control based airbags can be effectively utilized to mitigate open sea collisions [23]. 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, Fig. 15. Controllable valves enable flow of the gas from each chamber of the torus structure to environment and between adjacent chambers.

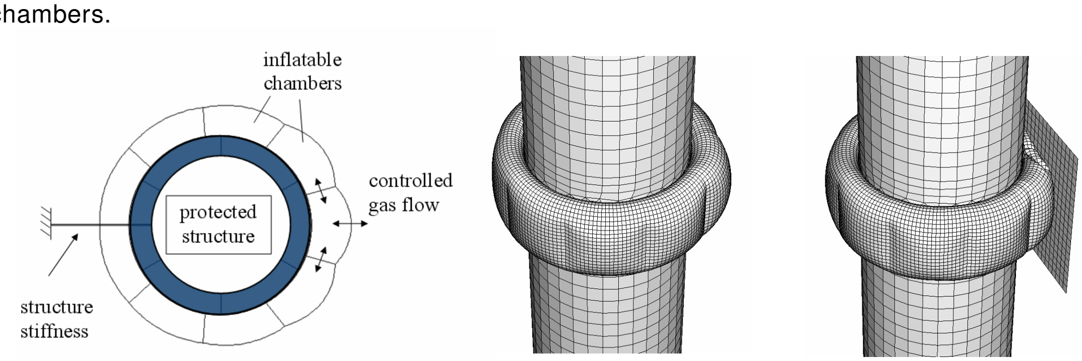



Figure 15: Inflatable structure protecting wind turbine tower: a) simplified 2D model, b) initial inflation before collision, c) deformation during impact

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 the simplest strategy of deceleration mitigation the valve installed in compressed chamber is opened just after ship impact and valve opening is not changed during the entire impact process, see Figure 16, curve 1. By contrast, in real-time control strategies the valve opening is proportionally adjusted on several time intervals which allows to maintain ship deceleration on almost constant level (Fig. 16, curve 2 and 3).

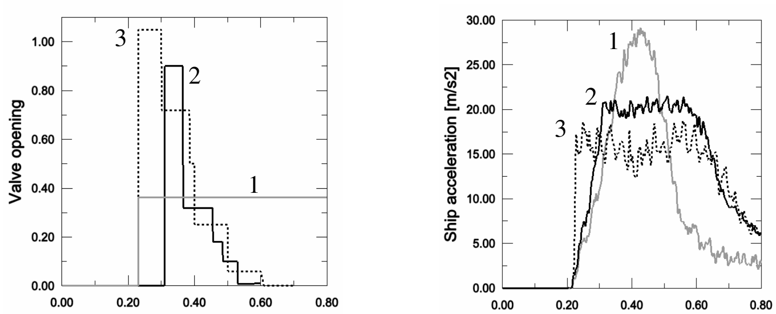



Figure 16: Strategies of acceleration mitigation: 1) constant valve opening , 2) pressure only released during impact, 3) additional inflation at the beginning of impact

When only release of pressure is feasible (i.e. there is no fast inflator in the system) the valve has to remain closed until deceleration achieves the value required to stop the ship before reaching the tower wall, cf. Figure 16, curve 2. Finally, the lowest value of deceleration is obtained by applying additional inflation at the beginning of impact which helps to avoid adverse initial stage of gradual increase of deceleration and to maintain its constant level during the whole process, cf. Figure 16, curve 3.

### 5.2 Adaptive airbags for 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. 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.

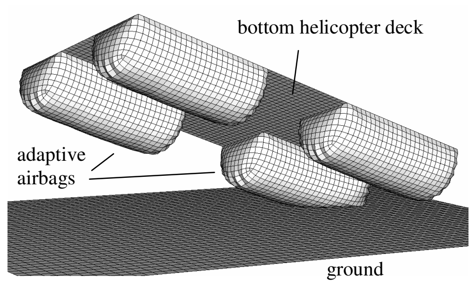



Figure 17: Numerical simulation of emergency landing with adaptive airbags

Initially the problem of helicopter stabilization during landing was considered. For this purpose three dimensional model composed of stiff plate and four airbags was developed (Figure 17) and various landing directions and velocities were analyzed. 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, Fig. 18a.

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 optimization problem was formulated as global measure of acceleration defined as the total of linear and angular acceleration taken with appropriate weight coefficients. It was found that constant in time valves opening of various size and time of activation for each valve provides almost constant level of acceleration, Fig. 18b,c.

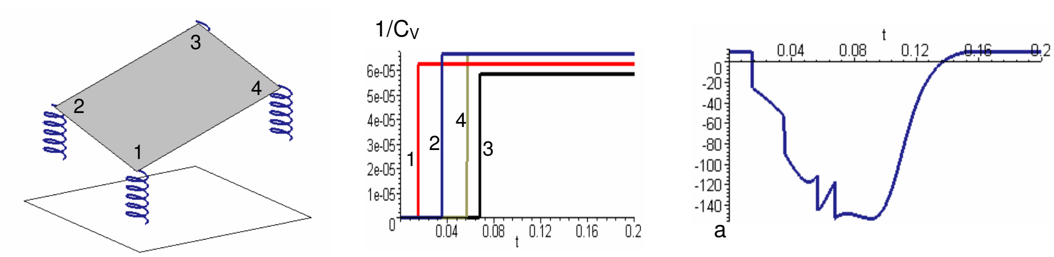



Figure 18: a) Simplified model of emergency landing, b) applied valve opening (represented by inverse of flow coefficient), c) resulting linear acceleration of the center of the mass

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 19.

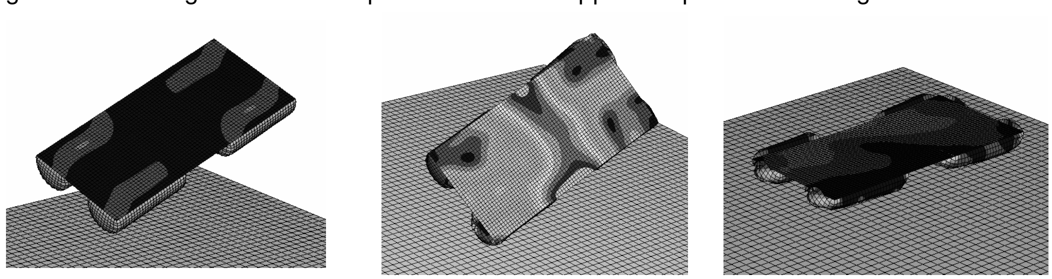


Figure 19: a) Considered landing scenario, b) non-optimal passive response with rear part rebound, c) optimal uniform airbags compression obtained by semi-active pressure control

## 6 CONCLUSIONS

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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## REFERENCES

[1] J.Holnicki-Szulc ed., *Smart technologies for safety engineering*, Wiley (2008)
[2] J.Holnicki-Szulc, C.Graczykowski, G.Mikulowski, A.Mróz, P.Pawłowski*, Smart Technologies for Adaptive Impact Absorption*, Solid State Phenomena, vol. 154, pp.187-194, 2009
[3] J.Holnicki-Szulc, P.Pawlowski, M.Wiklo*, High-performance impact absorbing materials - the concept, design tools and applications*, Smart Materials and Structures, vol.12, 3 (2003)
[4] H.G.Conway, *Landing gear design*, Chapman & Hall Ltd., London (1958)
[5] N.Currey, *Aircraft Landing Gear Design – Principles and practices*, AIAA (1988)
[6] G.Mikułowski, J. Holnicki-Szulc, *Adaptive landing gear concept - feedback control validation*, Smart Materials and Structures, 16, pp 2146-2158 (2007)
[7] G.Mikułowski, P.Pawłowski, C.Graczykowski, R.Wiszowaty, J.Holnicki-Szulc, *On a pneumatic adaptive landing gear system for a small aerial vehicle,* Proceedings of the IV Eccomas thematic conference on Smart structures and materials, 13-15 July, Porto (2009)
[8] R.Wiszowaty, J.Biczyk, C.Graczykowski, G.Mikułowski, *Method of impact energy dissipation by the use of the pneumatic impact absorber with a piezo-valve*, Proceedings of the 5th ECCOMAS Thematic Conference on Smart Structures and Materials, Saarbrucken, (2011)
[9] E.A.Bossanyi. *Wind Turbine Control for Load Reduction,* Wind Energy; 6:229–244 (2003)
[10] T.J.Larsen et al. *Active Load Reduction Using Individual Pitch, Based on Local Blade Flow Measurements*, Wind Energy 8:67–80 (2007)
[11] E.A.Bossanyi, *Individual Blade Pitch Control for Load Reduction*, Wind Energy; 6:119–128 (2003)
[12] C.Lindenburg. *Aeroelastic modelling of the LMH64-5 blade,* DOWEC-083\ECN-C-03-020, ECN, Petten, (2002\2003)
[13] J.Grzędziński, A.Mróz, *Gust load reduction concept in wind turbines*, Wind Energy; 13: 267-274, (2010)
[14] IEC, *Wind turbines - Part 1: Design requirements.* IEC 61400-1, Third Edition (2005)
[15] T.Burton, D.Sharpe, N.Jenkins, E.Bossanyi, *Wind energy handbook*. John Wiley: NY, (2006).
[16] M.Ostrowski, P.Griskevicius, J.Holnicki-Szulc, *Adaptive Crashworthiness of Front-End Structure of Motor Vehicles*, SAE Congress, Cobo Center-Detroit, USA, April 16-19, 2007
[17] M.Ostrowski, J.Holnicki-Szulc, *Adaptive Impact Absorption Controlled via Pyrotechnic Devices*, 4th European Conference on Structural Control, Sankt-Petersburg, Russia, 2008
[18] Patent Pending, *Multifolding-based valve for inflatable structure*
[19] European Patent Pending EPO9461509,3, *Drivable valve to be used in gas bags in particular and method for restricting the flow of the fluid*
[20] H.J.Bungartz, M.Schafer, *Fluid-Structure Interaction, Modelling, Simulation, Optimization*, Springer (2006)
[21] I.Yeh, L.Chai, N.Saha, *Application of ALE to airbag deployment simulation*, International Journal of Vehicle Safety Vol. 1, No.4 pp. 348 (2006)
[22] G.J.Van Wylen, R.E.Sonntag, *Fundamentals of Classical Thermodynamics*, John Wiley & Sons (1978)
[23] C.Graczykowski, J.Holnicki-Szulc, *Protecting offshore wind turbines against ship impacts by means of adaptive inflatable structures*, Shock and Vibration, vol. 16, no.4, pp. 335-353, (2009)