Smart Technologies for Adaptive Impact Absorption

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Abstract. The article presents a review of recent research carried out in the Department of Intelligent Technologies of Institute of Fundamental Technological Research, dedicated to application of systems for adaptive impact absorption to adaptive aircraft landing gears, novel concept of protective MFM structures, flow-control based airbags, maritime applications of inflatable structures, and development of adaptive wind turbine blade – hub connections.

Introduction

Increasing demand for safety becomes nowadays a clearly visible trend. One of main areas of widespread research is design of systems protecting against heavy dynamic loads such as low and medium velocity impacts or environmental loadings. Commonly applied passive systems are typically designed for a specified load scenario and therefore their performance over a wide range of expected loads is limited. This shortcoming can be significantly reduced by application of systems of Adaptive Imapct Absorption (AIA). The general concept of AIA (e.g. [1], [2]) refers to the application of intelligent technologies, which focus on adaptation of energy absorbing structures to extreme overloading by impact identification and application of controllable dissipaters based on magneto-rheological fluids, piezo- or magnetostrictive- actuated devices.

The article presents a review of recent research carried out in the Department of Intelligent Technologies of Institute of Fundamental Technological Research, dedicated to application of systems for adaptive impact absorption to aircraft landing gears, a novel concept of protective MFM structures, flow-control based airbags, maritime applications of inflatable structures and development of adaptive wind turbine blade – hub connections.

Adaptive Multifolding Structures

The model multifolding structure (MFM c.f.[3]) is composed of truss-like elements arranged into a special pattern, depicted in Fig. 1. The elements are equipped with micro-devices (so-called "micro-fuses") which control the axial force in each element. The stress thresholds, triggering the micro-fuses, are uniformly distributed along horizontal layers but may change in the vertical direction. Therefore, during deformation, layers with the lowest stress values collapse first. The repetitive use of elements (multifolding effect, e.g. element 2 in Fig. 2-left) provides the synergistic effect in the process of energy dissipation. Two selected deformation modes of the most basic MFM system are depicted in Fig. 2.

The initial distribution of the control thresholds plays a crucial role in the adjustment of the stiffness characteristics of the MFM to the impact loading. Different initial distributions of those parameters will result in different folding sequences and therefore will change the capability of energy absorption and the level of acceleration during the impact.

The concept of multifolding was verified experimentally. The tests aimed at implementing models and control strategies applied in the theoretical and numerical studies.

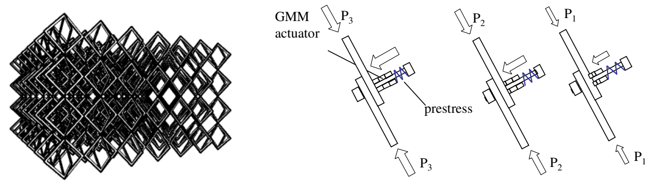


Figure 1. The layout of Multifolding Structure (left); Concept of “structural fuse” (right)

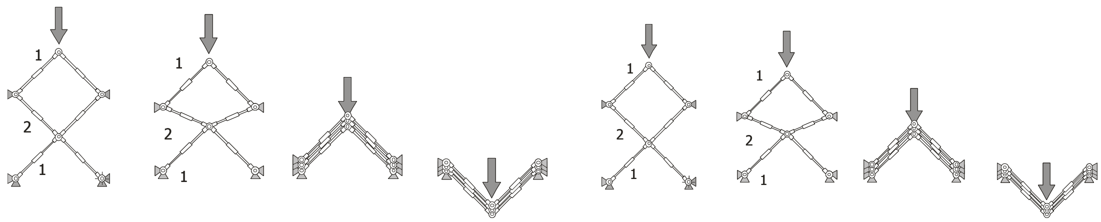


Figure 2. Selected folding patterns of basic MFM structure: mode 2 (left) and mode 1 (right)

The experimental set-up represents the most basic MFM substructure, composed of six controlled elements, which are magnetorheological fluid dampers. Nodes of the structure are guided by slide bearings (providing only one axis of movement) and are equipped with force and displacement sensors. The design of the set-up gives possibility of realising different folding sequences and control algorithms of the MFM structure.

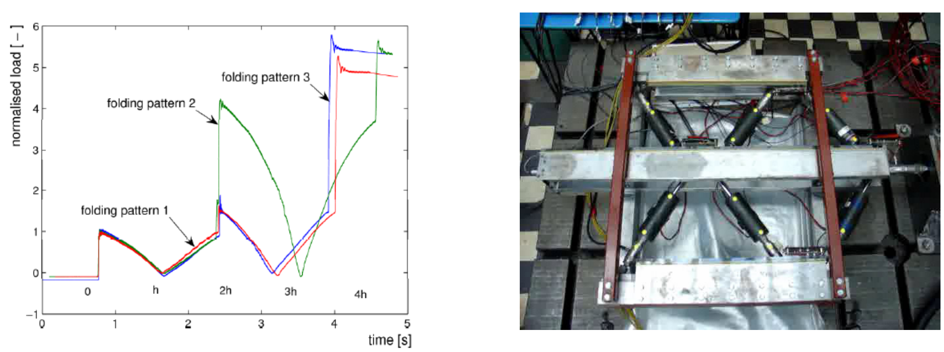


Figure 3. Experimental load curves for different folding patterns of basic MFM structure (left); View of experimental set-up (right)

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; active adjustment of pressure executed by controlled gas release.

The initial velocity and direction of the impacting object can be measured e.g. by ultrasonic velocity sensors. 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].
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
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 or thermically activated membranes. 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 solid wall and its internal forces.

Maritime applications of inflatable structures

Flow control based airbags can be effectively utilized to mitigate open sea collisions, cf. Ref.[4]. 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. 4 a,b. Controllable valves enable flow of the gas from each chamber of the torus structure to environment and between adjacent chambers.

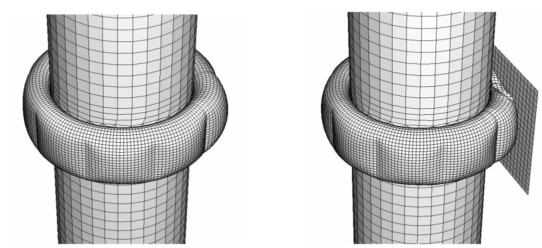


Figure 4: a) inflation of pneumatic structure; b) deformation during collision

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. 5.

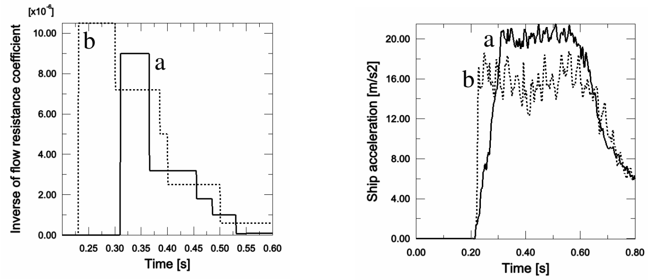


Figure 5: Active acceleration mitigation: a) pressure released during impact (continuous line), b) additional inflation at the beginning of impact (dashed line)

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. 6). 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. 6a) and various landing directions and velocities were analysed (Fig. 6b). 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.

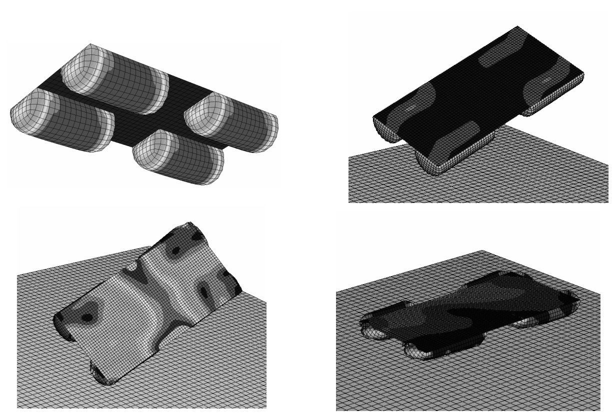


Figure 6: a) Considered model, b)landing scenario; c) non-optimal passive response with rear part rebound d) optimal uniform airbags compression

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. 7a). Three pressure adjustment strategies were applied (Fig. 7): i) optimisation of initial pressure only (continuous line), ii) optimisation of initial pressure and constant valve opening (dashed line):, iii) continuous control of valve opening to maintain precomputed optimal pressure pressure level (dotted line):

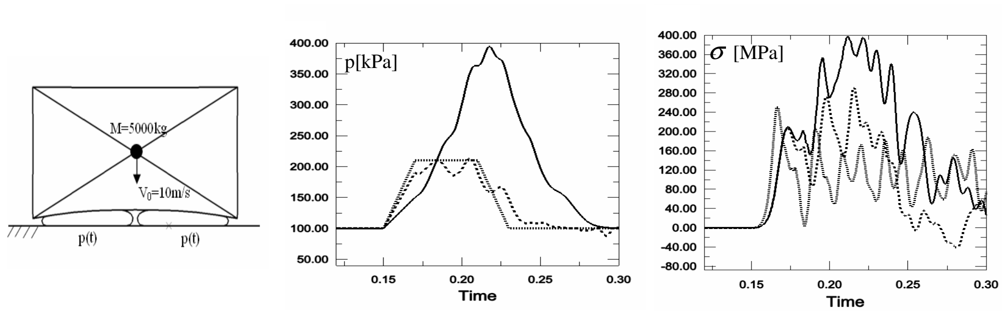


Figure 7: Active stress minimisation: a) considered model , b) applied pressure variation , c) resulting stresses at lower beam of the model

Adaptive pneumatic landing gear for Unmanned Air Vehicle (UAV) application

Landing gears are considered by the aeronautic designers as indispensable components of the aircraft. However, they are also aware that undercarriage disturb the aerodynamics and limit significantly the payload of the aircraft due to its own weight. Considering only these two mentioned constraints, it can be concluded that the optimal landing strut should have the minimal possible weight and the minimal possible volume.

The presented problems in design of the landing gears might be omitted via utilization of the concept of pneumatic adaptive impact absorber. Primarily, a design of gas shock absorbers for landing gars will let reduce the effective weight of the structure. Secondarily, the introduction of the smart technology allows execution of the gas migration management in the shock absorber and therefore to adapt the characteristics of the absorber to the actually recognized energy of the landing impact.

The idea of introducing active systems with capability of controlling the behaviour of landing gear struts was considered since the 1970s. Most of the concepts were based on the idea of influencing the shock absorber performance by regulating the internal fluid pressure over time. The initial concepts developed e.g. in NASA Langley Research Center, were followed by first experimental works in the 1980s, which indicated that utilised hydraulic control systems were not fast enough to perform an efficient control procedure during impact phase of the landing. More promising semi-active concept, which was based on real-time control of a piezo-valve adapted to landing gear, was the result of the research project ADLAND (FP6 2002 Aero1 - 502793).

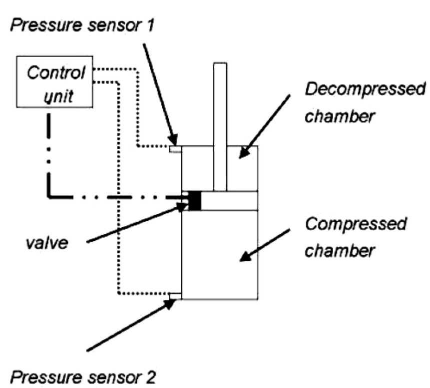


Figure 8: Concept of adaptive pneumatic absorber

The proposed solution for adaptive landing gear is based on double chamber pneumatic cylinder equipped with active piezoelectric or magnetostrictive valve which controls flow of the gas between cylinder chambers, cf. Fig. 8. Proposed device can serve as a shock absorber dissipating UAV

kinetic energy during landing and as suspension for taxiing and ground maneouvres. Active adaptation of the pneumatic absorber to actual landing scenario comprises the two following steps:
initial identification of aerial vehicle kinetic energy based on ultrasound measurement of touchdown velocity; active control of the piezoelectric valve opening providing constant pneumatic force generated by the absorber and uniform energy dissipation during landing process.
Active control strategy is executed by control system where UAV mass and touchdown velocity are introduced as known input parameters. Actual level of pneumatic force is used as a reference signal for closed-loop feedback system.
The proposed adaptive device was modeled numerically in order to assess system effectiveness and optimal geometry, range of pressures and valve parameters to be applied in final design of UAV absorber.
The presented hardware concepts were implemented in a lab-scale experiment and verified on a drop test stand (cf. Fig 9a). The pneumatic cylinder was equipped with an adaptive valve characterised by response time equal 2 ms .

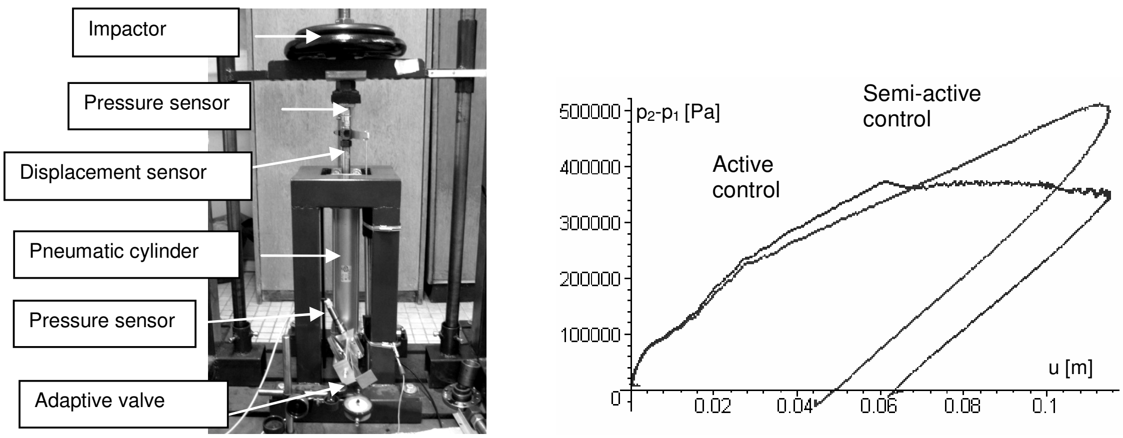


Figure 9: a) Experimental stand. b)Comparison of the pressure difference in the cylinder's chambers for semi-active and active control modes.

Successive tests conducted on the lab-scale stand were verification of the system's control strategies under impact loading. Two control strategies (semi-active and active) under the same conditions of impact were established. Comparison between the results obtained with the semi-active and the active control strategies (Fig. 9b) pronounced reduction of the maximal transferred load value by 30% in the case of the active control strategy.

Adaptive wind turbine blade – hub connection

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 root bending moment. 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 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 of the blade – hub connection is summarized in terms of the pitch angle changes. After the gust detection the blade is unclutched and rotates freely about its axis until the braking process 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.

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. 10

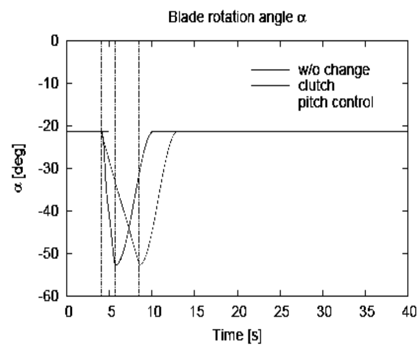
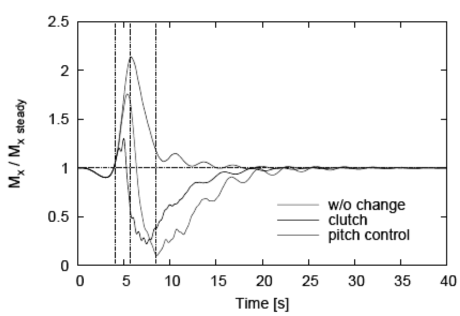


Figure 10: Semi-active vs active device response

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. 11 and Fig. 12 respectively. Results are shown relative to the steady state response.



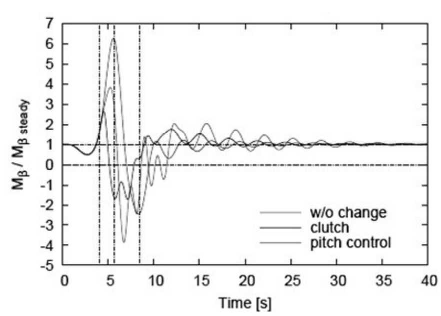


Figure 11: Tower bending moment **Figure 12**: Blade bending moment

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 Figs. 13 and 14.

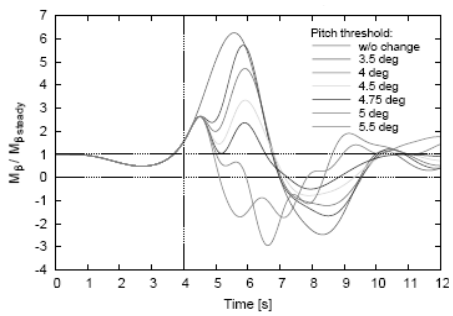


Figure 13: Various free rotation phase duration

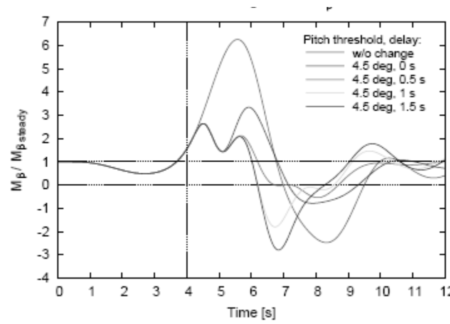


Figure 14: Various initial pitch angle restoring instants

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.

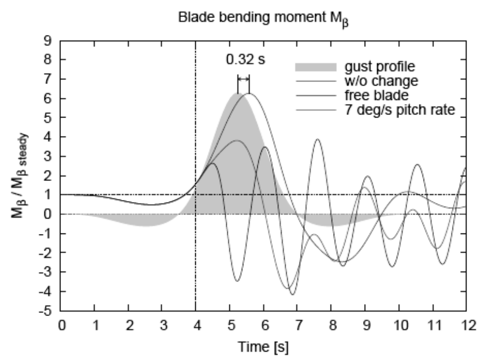


Figure 15: Phase shift between the gust and bending moment maxima

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. 15).
Conclusions from the carried out numerical simulations show that the proposed semi-active solution could effectively mitigate the internal forces caused by extreme wind gusts, in particular the blade root bending moment and provides response faster than the pitching mechanism.

Acknowledgement

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References

[1] Holnicki-Szulc, J. (Ed.), *Smart Technologies for Safety Engineering*, J.Wiley, 2008

[2] J. Holnicki-Szulc, A. Mackiewicz, P. Kolakowski. *Design of Adaptive Structures for Improved Load Capacity*. AIAA Journal vol.36, No.3, 1998.

[3] Holnicki-Szulc J., Pawlowski P., Wiklo M., *High-performance impact absorbing materials - the concept, design tools and applications*, Smart Materials and Structures, vol.12, number 3, 2003

[4] Graczykowski C., Holnicki J., *Protecting offshore wind turbines against ship impacts by means of adaptive inflatable structures*, Shock and Vibration, IOS Press, in print