KU Leuven
Department of Mechanical Engineering
Celestijnenlaan 300 - box 2420
B-3001 Heverlee (Belgium)

Proceedings of

ISMA2018

International Conference on

Noise and Vibration Engineering

USD2018

International Conference on

Uncertainty in Structural Dynamics

17 to 19 September, 2018
Editors: W. Desmet, B. Pluymers, D. Moens, W. Rottiers.

Dynamics and control of adaptive airbags for UAV impact protection

Z. Wolejsza[1], J. Holnicki-Szulc[1], C. Graczykowski[1], K. Hinc[2], R. Faraj[1]
T. Kowalski[2], G. Mikulowski[1], K. Kazmierczak[1], R. Wiszowaty[1], P. Pawlowski[1]
[1] Institute of Fundamental Technological Research Polish Academy of Sciences, Department of Intelligent Technologies, ul. A.Pawińskiego 5b 02-106, Warsaw, Poland
e-mail: **zwol@ippt.pan.pl**

[2] Adaptronica sp. z o.o., ul. Szpitalna 32, 05-092 Łomianki, Poland

Abstract

Small drones with total mass of a few kilograms are becoming more and more popular in many applications increasing the probability of occurrence of emergency situations caused by an equipment failure or a human error. In case of a fall from a high altitude very often it is possible to use parachute rescue systems, which however require relatively long time for deployment and development of braking forces. The touchdown velocity may be large enough to exceed limit accelerations for UAV equipment. The paper presents the concept of deployable airbag systems, in particular with adaptive flow control, which provides a possible solution to the above-mentioned problems. The paper discusses the overall control and adaptation strategy. Simplified methods for mathematical modeling are proposed and formulated for an example on a cylindrical airbag. The conceptual part is concluded with the presentation of the methodology of experimental verification and results of initial tests of the integrated airbag system.

1 Introduction

Small drones with a total mass of a few kilograms are becoming more and more popular in many applications including aerial surveillance and monitoring, filming, laser scanning etc. The popularity of this type of UAV's applications increases the probability of occurrence of emergency situations caused by an equipment failure or a human error. Drones very often operate over densely populated urban areas, therefore it becomes crucial to protect people or objects on the ground. The second objective is the minimisation of shock loads transferred to a fragile and expensive electronic equipment on board of a UAV (e.g. cameras and lenses, lidars).

In case of a fall from a high altitude (approx. above 10-15m) very often it is possible to use parachute rescue systems, which however require relatively long time for deployment and development of braking forces. The vertical velocity close to the touchdown is in this case large enough to excess limit accelerations for UAV equipment, which very often can be estimated as approx. 20g.

These drawbacks can be avoided by application of deployable airbag systems, in particular with adaptive flow control. The problems of dynamics and control for adaptive impact and shock absorption (including the application of inflatable structures pneumatic systems) are research topics for more than 15 years at the Department of Intelligent Technologies of IPPT PAN [1]. The concept is based in general on the application of semi-active or real-time control over mechanical characteristics of a shock absorbing structure in order to provide the optimal level of resistance forces minimizing dangerous accelerations levels.

1.1 Systems of Adaptive Impact Absorption

One of the first adaptive impact absorbing systems were active hydraulic aircraft landing gears developed in the 1970s in NASA Langley Research Center. In these devices, the damping force generated by the absorber was controlled by changes of pressure of the applied fluid. However, such technology required large amount of the energy submitted to the system and had caused technical problems related to ensuring large flow rates and pressure ranges. The above shortcomings were eliminated by applying landing gears based on servo-valves, where the control was performed in a semi-active way.

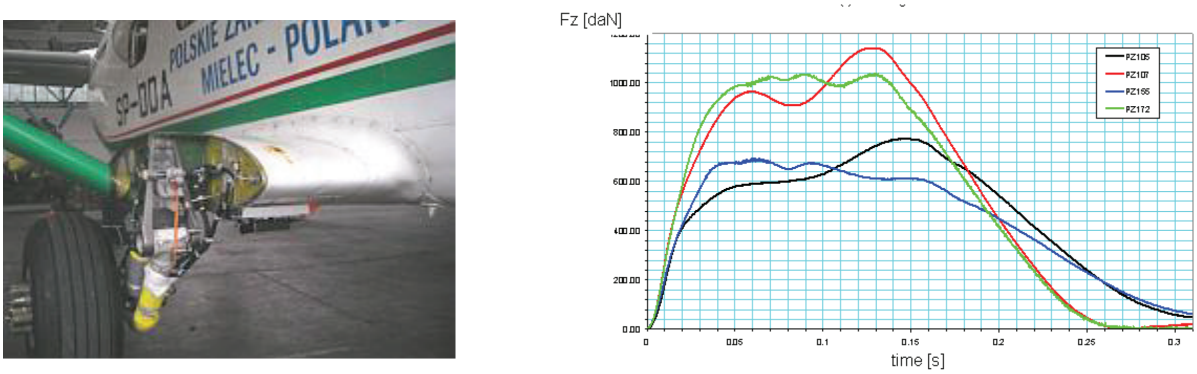

Figure 1: Adaptive aircraft lading gear (FP7 project ADLAND - flight tests, experimental results)

The system of the adaptive impact absorption was successfully implemented for a semi-active aircraft landing gear within the FP6 research project ADLAND [2], [3]. Introduction of the intelligent materials in the design of the adaptive absorbers allowed for substantial shortening of the system response time and it enabled real-time control of the damping force generated by the absorber. Within the project two alternative solutions were tested: the magneto-rheological valve based on the application of the magneto-rheological fluid and the magnetic head and the valve based on piezoelectric actuator controlling flow of the standard hydraulic fluid.

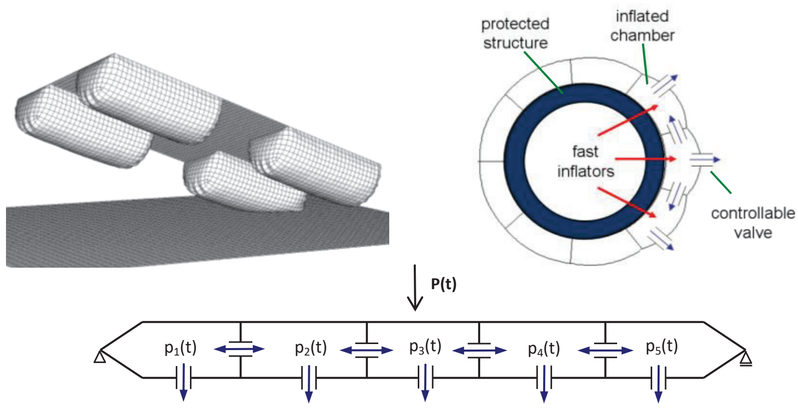

Figure 2: Adaptive Inflatable Structures: a) emergency flow control-based airbags, b) inflatable fenders, c) adaptive inflatable barrier

The airbag system for UAVs proposed and presented in this paper belongs to a wider class of Adaptive Inflatable Structures. The concept is based on application of compressed gas and controlling its pressure as an effective methodology allowing for adaptation of energy absorbing structures (e.g. airbags, fenders, barriers - Fig.2) to actual impact loading [4]. Adaptive Inflatable Structures contain sealed chambers filled with compressed gas and equipped with controllable inflators and discharge valves. Pressure adjustment relies on appropriate initial inflation of particular chambers and control of the gas flow between the chambers and outside the structure during the process of deformation. Appropriate change of the actual value of pressure in different parts of the structure enables adaptation to dynamic loading of various energy, amplitude and location.

The real-time controlled fully pneumatic adaptive landing gear for small UAV was developed and described in [6]. The 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 0,25 s. The control procedure introduction decreased the maximum deceleration level of the drop-weight from 12 m/s^2 to 8 m/s^2.

The piezoelectric valves provide very fast response of the system, however with limited the flow rate of the gas. One of the proposed solution to this problem is application of flow-driven high performance valves. Two different devices (membrane valve and a bistable valve) with different working principles are presented in [7], which provide effective, semi-active three stage control sequence “close-open-close”. In the case of membrane valve the rapid destruction of clamping elements results in different deformation modes of two membranes forming the valve, caused by the gas flow. The operating principle is depicted for three stages of operation in Fig.3.

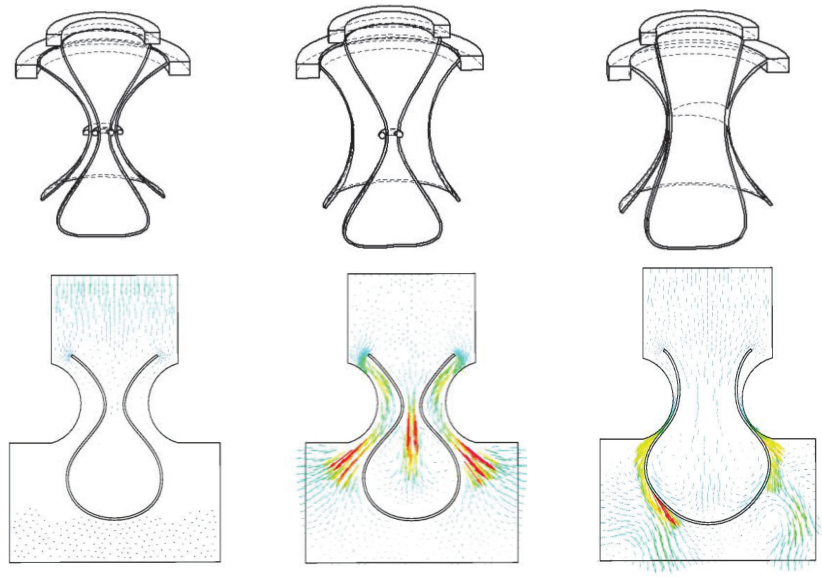

Figure 3: The cross-section of the membrane valve and simulation of the gas flow during subsequent stages of valve operation.

2 Adaptation technique for AD-BAG system

The emergency landing system should be developed as a module which is entirely independent from the autopilot and other onboard subsystems of the UAV lest the accident can result from their failure. In order to provide efficient and reliable operation of the AD-BAG system the influence of following problems and challenges has to be reduced:

- instant detection of the UAV’s failure,
- stabilization of the UAV’s spatial orientation,
- fast inflation of the emergency airbag,
- possibly precise prediction of the impact conditions,
- proper gas release to avoid ‘stiff contact’ or ‘rebound’.

Detection of the UAV's failure can be implemented using inertial sensors and should result in turning off the engines so as stabilization of spatial orientation can be obtained in passive way. The prediction of loading conditions resulting from the contact with the ground or on-ground obstacle [8] can be can implemented in a number of pretty different ways e.g., based on the measurements of AGL (altitude above ground level). The AGL can be measured once and then the impact conditions can be estimated. Nevertheless, such measurement requires the use of radar altimeter or LIDAR, etc., what results in quite complex and expensive solution. On the other hand, the AGL can be estimated using inertial, barometric sensors and GPS. Unfortunately, for reliability of such solution the terrain map should be available for online use of developed system. Other alternatives relates to the velocity estimation techniques. The measurements of velocity relative to the ground and in result the emergency system should update predicted impact condition and sequentially re-adapt in real-time until the contact with obstacle is detected and finally calculated scenario is implemented.

The impact absorption of the system protected by airbags includes gas compression and then its release to ensure dissipation of impact energy. In order to provide more efficient impact mitigation than in case of passive solutions, the airbag should be closed at the beginning of the process so that gas is only compressed. After fast increase of internal pressure the gas release should be activated and finally the release opening should be closed. In case of different impact conditions the moment of gas release and size of airbag opening should be selected carefully. The significant challenge is very short time period between each control action (time periods at the level of single milliseconds). To minimize probability of errors during adaptation to impact conditions, the system characteristics should be adjusted by single control action, similarly as in case of adaptable pneumatic shock-absorber presented in [9]. The more efficient and more robust but simultaneously more complex solutions involve online control of the internal pressure or deceleration of the UAV [10] as well as additional kinematic feedbacks [11].

The general scheme of emergency system operation is shown in Fig. 4. The generic sequence of actions performed by the system is valid for all of impact prediction techniques discussed above.

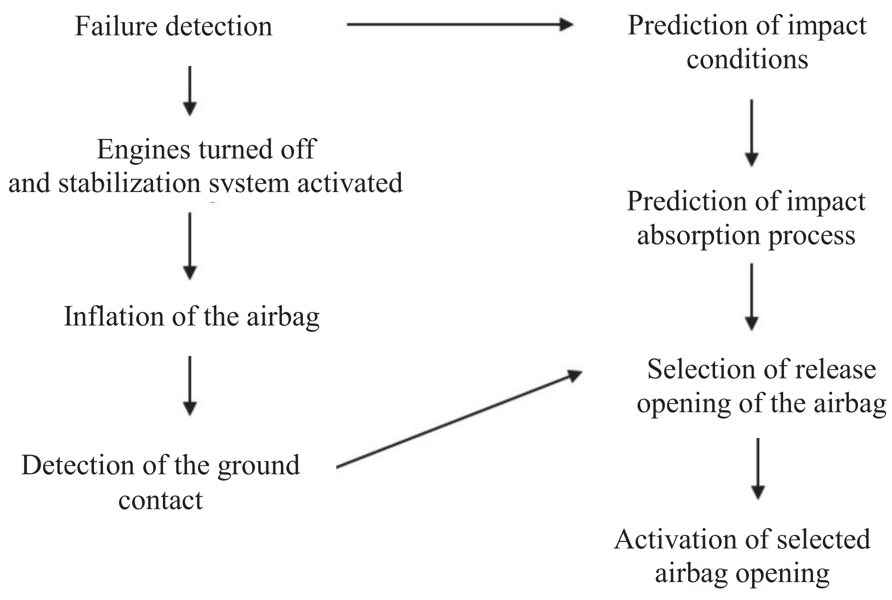

Figure 4: The general scheme of emergency system operation

3 Mathematical models of the process of emergency landing with adaptive airbag

In this section, we consider falling object with attached adaptive airbag made of thin fabric and equipped with a controllable valve, which enables the outflow of gas to the environment. The object approaches the ground with certain initial velocity. When impact with the ground occurs the airbag is compressed and considerably deformed, which causes an increase of internal pressure of the gas. Simultaneously pressure is reduced by leakage of gas through the airbag fabric and its controlled outflow through the valve. The objective of the adaptive airbag is to dissipate the entire impact energy and to optimally mitigate the impact process by reduction of generated forces and corresponding deceleration of the impacting object.

In order to simplify the modeling process, it is assumed that airbag inflation and its full deployment is accomplished before contact with the ground. Therefore, the process of airbag inflation and the case of impact with airbag being not fully deployed is not considered. Moreover, it is assumed that impact velocity is relatively low and it does not cause significant wave propagation effects in a given volume of gas. Accordingly, the thermodynamic processes arising in the system are modelled with the use of Uniform Pressure Method (UPM), which assumes that gas pressure, temperature, and density are uniformly distributed in the entire airbag. The UPM method utilizes the balance of mass and energy of the gas, the equation of gas state as well as the definitions of gas leakage and outflow, which are expressed either as ordinary differential or algebraic equations. In the considered problem, the UPM-based modelling is conceded as a sufficiently precise tool for the preliminary simulation of the response of adaptive airbag.

In general, two approaches to the modelling of the process of emergency landing with adaptive airbag can be proposed:

- Extended Uniform Pressure Method (E-UPM), in which the falling object is modeled as one degree-of-freedom system, its movement is described by single equation of motion, the thermodynamic processes arising in the gas are modeled with the use of UPM, while deformability of the airbag is taken into account by introducing additional terms and coefficients into the governing equations;
- the combination of Finite Element Method and Uniform Pressure Method (FEM-UPM), in which the falling object and the airbag are modeled by classical approaches of continuum mechanics, their motion and deformation are described by partial differential equations and solved by FEM, the thermodynamic processes arising in gas are modeled with the use of UPM and, moreover, appropriate coupling conditions between gas and airbag fabric are applied.

The main advantage of the E-UPM approach is elimination of complex simulation of airbag deformation occurring during landing, which requires precise modelling of airbag fabric and time-dependent conditions of contact with the ground. Instead, the simplified approach effectively utilises the analogy between the response of compressed adaptive airbag and the response of compressed single-chamber pneumatic cylinder equipped with controllable valve. The additional physical phenomena which have to be considered during modelling of the adaptive airbag are the following:

- the area of contact between the airbag and the ground significantly changes during the process (in typical impact scenario it rises);
- the volume of the airbag changes nonlinearly in terms of airbag compression;
- when airbag fabric is not completely air-tight then additional outflow of gas and reduction of pressure are caused by fabric leakage;

- when airbag fabric is characterized by non-negligible bending stiffness its deformation during airbag compression causes generation of additional reaction forces.

The E-UPM approach effectively utilizes analytical description of airbag deformation in terms of actual airbag compression and, in case of highly extensible fabric, in terms of internal pressure. The assumption of extensible fabric significantly simplifies the analysis. For given initial shape of the airbag the fundamental geometrical relations can be used to express actual area of contact with the ground A_C and actual volume V in terms of actual stroke of the airbag s and to obtain functions $A_C(s)$ and $V(s)$. Alternatively, the above dependencies can be obtained from the numerical simulation conducted by using FEM-UPM approach or from the experiment. As a result, the contact force between the airbag and the ground can be expressed as a function of its actual stroke and internal pressure of gas: $F_C(s,p) = A_C(s)(p - p_{ext})$.

In addition, the possible structural forces arising as a result of deformation of fabric of considerable bending stiffness are introduced into the E-UPM model by additional visco-elastic forces $F_A(s,\dot{s})$, which enter the equation of motion of the landing object. Eventually, the influence of gas leakage through the airbag fabric is taken into account by introducing the additional terms in the equations governing balance of mass of gas inside the airbag and thermodynamic balance of gas energy.

3.1 The example of cylindrical airbag

The illustrative example of landing with the use of horizontally located cylindrical airbag made of inextensible material is presented in Fig. 5. The process consists of the stage before contact with the ground (A), the stage of gradual compression of the lower part of the airbag (B), and the stage of uniform compression of the entire airbag (C). The second and third stage differ by the relation between the area of contact with the ground A_C and the area when pressure of gas acts directly on the horizontal falling object A_p.

Determination of actual airbag shape effectively utilizes the assumption of weightless fabric, which allows to conclude that the lateral parts of airbag cross-section remain circular. Therefore, the analysis for the second stage of the process includes four unknowns: horizontal coordinate of the point of contact with the ground, the coordinates of the point being the centre of the circle defining lateral parts of airbag cross-section and radius of this circle. In turn, four governing equations include: the equations of circle for both points of contact, the condition that airbag is tangent to the ground at the point of contact and condition of constant length of the airbag perimeter. During the third stage of the process the analysis is significantly simplified due to the fact that the point of contact of the airbag with the ground and with the falling object have the same horizontal coordinate. The detailed derivation of the shape of airbag surface is left to the reader.

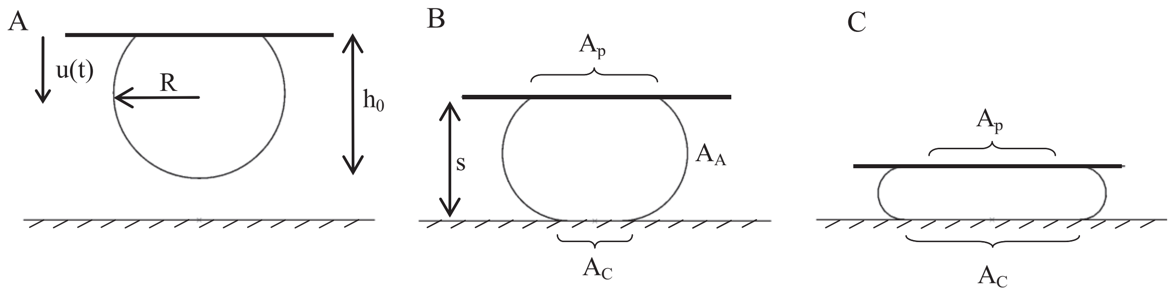

Figure 5: Three stages of the process of landing with adaptive airbag

Next, the area of contact with the ground $A_C(s)$, the lateral area of the airbag $A_A(s)$ and volume of airbag $V(s)$ can be found by calculating appropriate integrals over airbag surface. Let us note that assumption of weightless airbag fabric allows to determine total force acting on the horizontal falling object, which in both the second and the third stage of the process equals to the contact force between the airbag and the ground $F_C(s,p) = A_C(s)(p - p_{ext})$. The proof is fundamental and it is also left to the reader.

Eventually, the proposed analytical model of airbag-assisted emergency landing consists of three ordinary differential equations which describe motion of the falling mass, balance of mass of the gas and thermodynamic balance of gas energy. Two latter equations take into account definition of gas outflow through the valve q_v (which depends on actual area of the valve A_v) and definition of outflow caused by fabric leakage. The system of equations is complemented by equation of gas state and proper initial conditions. The complete model of emergency landing takes the form:

$$M\frac{d^2u}{dt^2} - Mg + A_C(s)(p - p_{ext}) + F_A(s,\dot{s}) = 0 \tag{1}$$

$$\frac{dm}{dt} = -q_V(p,T,p_{ext},A_V) - CA_A(s)\sqrt{\frac{2(p-p_A)p}{RT}} \tag{2}$$

$$\left[q_V(p,T,p_{ext},A_V) + CA_A(s)\sqrt{\frac{2(p-p_A)p}{RT}}\right]c_p\mathrm{T} + \frac{d(mc_V\mathrm{T})}{dt} + p\frac{dV}{dt} = 0 \tag{3}$$

$$f(p,V,m,T) = 0 \tag{4}$$

$$\text{IC:}\quad u(0) = 0,\ \dot{u}(0) = v_0,\ p(0) = p_0,\ m(0) = m_0 \tag{5}$$

The above system of equations can be solved with the use of arbitrary numerical method. The verification of the E-UPM model against more precise FEM-UPM model was conducted for problem of compression of cylindrical airbag discussed in the above example. The comparison conducted for kinematic, static and thermodynamic quantities had revealed satisfactory correspondence of both applied methods [12]-[13].

The proposed E-UPM approach is based exclusively on physical principles and geometrical considerations and, moreover, does not require linearization or neglecting of the selected terms. Therefore, it is expected to be more precise than known from the literature analytical models based on alternate stiffness and damping terms, which model response of the airbag in approximate way. The proposed model seems to be sufficient for basic assessment of the effectiveness of emergency landing systems based on adaptive airbags.

4 Experimental verification

The integrated ADBAG airbag and control systems have been verified experimentally in a laboratory conditions. The objective of the experiments is to demonstrate operability of the system in an emergency situation and ability to protect a falling object against a ground impact.

4.1 Configuration of the stand

The testing setup has been configured to conduct drop tests of the assembled AD-BAG mockup. The available drop heights are up to 25 m performed on a guided truck. The testing object is a mockup of 1.5 kg weight, protected by an airbag of 50 dm3 volume. The airbag is automatically activated and filled with a compressed gas during the test. Synchronized measurements are configured to acquire the following magnitudes: interface force under the airbag, kinematics of the falling object: displacement, velocity, acceleration via digital image analysis method.

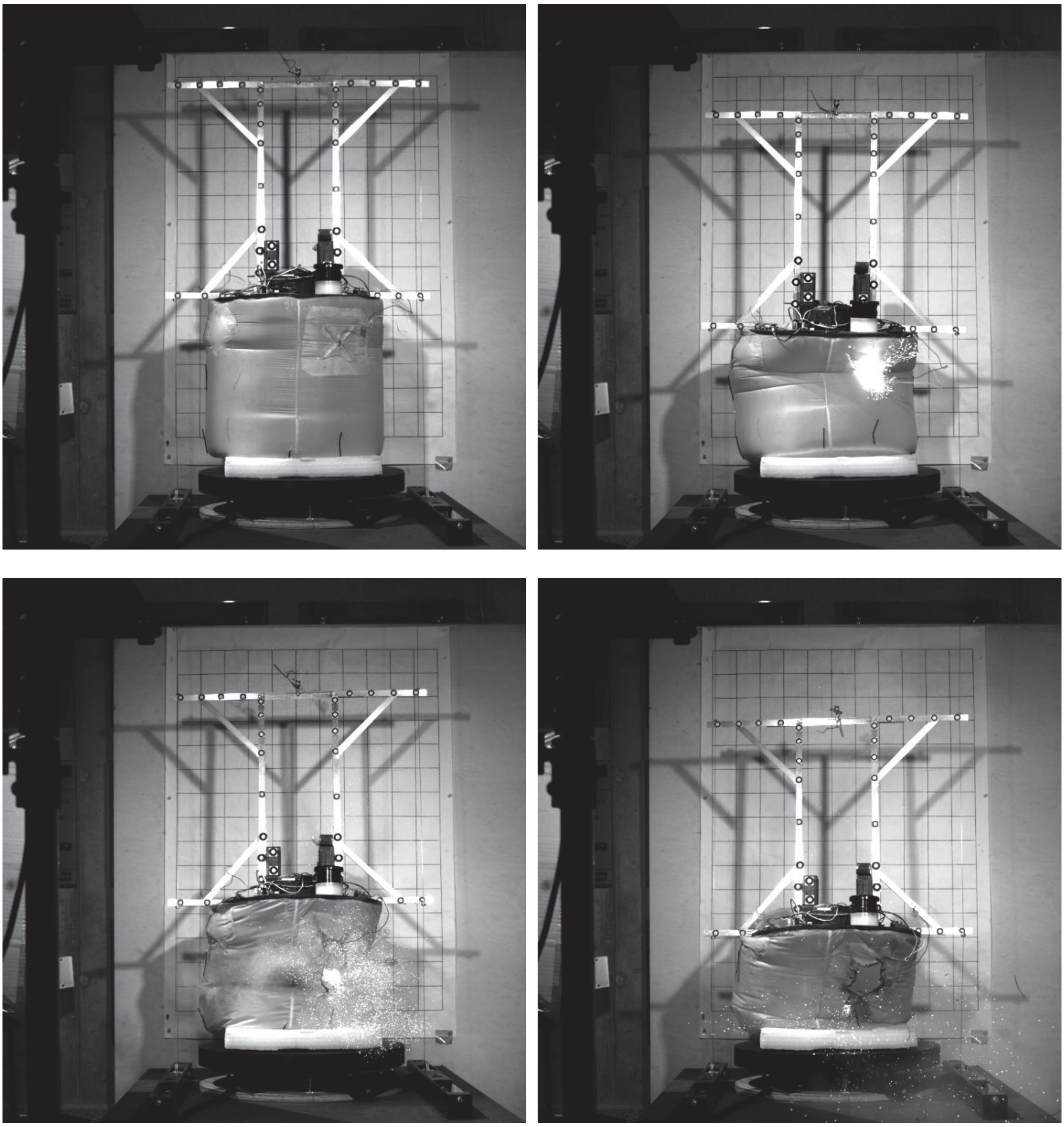

Figure 6: A sequence of the airbag initialization and operation

The interface force is measured with a measuring plate based on three piezoelectric sensors with measuring range 10 kN. The data acquisition is performed with a SCADAS Mobile system and the image recording is conducted with a Phantom 611 fast digital camera. The data acquisition procedure is synchronised with a digital signal provided by a dedicated controller based on a FPGA processor.

4.2 Testing procedure

The first step is lifting the object to a predefined height e.g. 5 m. Afterwards, the drop is conducted and the electronic unit is activated, which is programmed to carry out the following steps:

1. recognition of a free fall phenomenon which equates an emergency situation;
2. activation of the airbag and pressurizing it with air;
3. recognition of a touchdown moment,
4. initialization of adaptive system of the air release in order to match the airbag response and the actual the impact energy.

4.3 Tests results

An exemplary sequence of the airbag operation is depicted in Fig. 6. The upper left photo represents a state of the airbag after contact with the touchdown surface but before initialization of the release valve. The following photos (upper right and lower left) depict the process of the valve opening. The photo placed in the lower right corner shows the outflow valve completely open.

As a whole, the system operability is demonstrated and the ability of the system to adapt to the recognized impact condition is available.

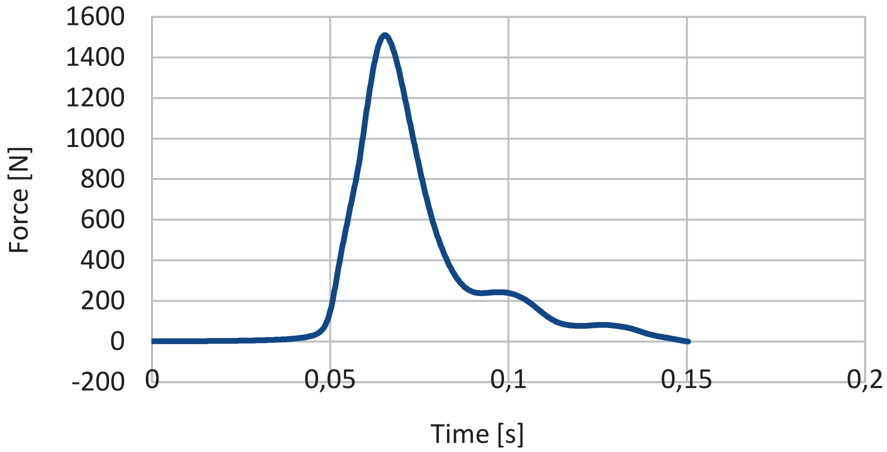

Figure 7: Interface force of the airbag in time domain

A time history of the force measured on the interface between the airbag textile and the touchdown surface is ploted in Fig. 7. The maximum force recorded during tests does not exceed 1,5 kN. The second force peak at time instant 0,1 s represents the influence of the adaptive valve in the airbag. The conducted investigation confirmed functionality of the system and its readiness for the following development phase – tuning the control parameters.

Acknowledgments

The article was prepared with the support of the project: "Adaptive airbags for unmanned aerial vehicles emergency landing (ADBAG)" co-financed from the European Regional Development Fund within the Operational Programme Smart Growth 2014-2020, Measure 1.2. Sectoral R&D Programs. Contract No .: POIR.01.02.00-00-0083 / 16. The period of the project implementation: 01.01.2017-30.06.2019.

References

[1] J. Holnicki-Szulc, C. Graczykowski, G. Mikulowski, A. Mroz, P. Pawlowski, R. Wiszowaty, Adaptive impact absorption - the concept and potential applications, International Journal of Protective Structures, Vol. 6, Issue: 2 (2015), pp. 357-377.

[2] G. Mikulowski, P. Pawlowski, Z. Wolejsza, Adaptive landing gear (in polish: Podwozie lotnicze z adaptacyjnym systemem absorpcji energii), Journal of Aeronautica Integra, vol. 2, no. 1, (2007)

[3] G. Mikulowski, R. LeLetty, Advanced Landing Gears for Improved Impact Absorption, in proceedings of 11th International Conference on New Actuators/5th International Exhibition on Smart Actuators and Drive Systems, Bremen, Germany, (2008), June 27-30.

[4] C. Graczykowski, J. Holnicki-Szulc, Crashworthiness of inflatable thin-walled structures for impact absorption, Mathematical Problems in Engineering, Vol. 2015, (2015), pp. 830471-1-22

[5] Graczykowski, J. Holnicki-Szulc, Protecting offshore wind turbines against ship impacts by means of Adaptive inflatable Structures, Shock and Vibration, Vol. 16, No. 4, (2009), pp. 335-353

[6] G. Mikulowski, R. Wiszowaty, Pneumatic Adaptive Absorber: Mathematical Modelling with Experimental Verification, Mathematical Problems In Engineering, Article No. 7074206 (2016)

[7] P.Pawłowski, M. Ostrowski, C. Graczykowski, High performance valves for adaptive inflatable structures with flow driven control, Smart2013, 6th Eccomas Thematic Conference On Smart Structures And Materials, 2013-09-03/09-06, Torino (IT), (2013),pp.1-10

[8] K. Sekuła, C. Graczykowski, J. Holnicki-Szulc, On-line impact load identification, Shock and Vibration, Vol. 20, No. 1, (2013), pp. 123-141

[9] Faraj, C. Graczykowski, Adaptable Pneumatic Shock Absorber, Journal of Vibration and Control, in review, (2018)

[10] C. Graczykowski, R. Faraj, Development of control systems for fluid-based adaptive impact absorbers, Mechanical Systems and Signal Processing, in review, (2018)

[11] R. Faraj, C. Graczykowski, Hybrid Prediction Control for self-adaptive fluid-based shock absorbers, Journal of Sound and Vibration, in review, (2018)

[12] C. Graczykowski, Mathematical models and numerical methods for the simulation of adaptive inflatable structures for impact absorption, Computers and Structures, Vol. 174, (2016), pp. 3-20

[13] C. Graczykowski, Inflatable Structures for Adaptive Impact Absorption, Ph.D. Thesis, IPPT PAN (2011)