

# On a pneumatic adaptive landing gear system for a small aerial vehicle

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**ABSTRACT:** The class of ultra-light aircraft becomes more and more popular among the enthusiasts of aviation due to low formal requirements of getting the pilot license and low costs of the equipment. Therefore, the training of the pilots starts to be a large-scale task. One of the most difficult operation for the inexperienced pilots is touch-down and it often happens to strike the ground with a high sink speed. In consequence the training machines are endangered of fast structural damage. A potential solution would be to mount a system of adaptive landing gear for light aircraft with a capability of recognition of the actual landing impact and tuning the landing struts in order to conduct the smoothest landing operation possible. In the case of the ultra-light aircraft class the weight of the components is the crucial task and therefore the low-weight pneumatic system is proposed for these application.

The paper presents a concept of an adaptive landing system and adequate control strategy for a small aerial vehicle. The objective of the work was to develop a fully functional model of the landing system and experimental verification of it. The system is based on the new pneumatic impact absorbers actuated via piezo-stacks. The concept assumes designing of the system with the capability of adaptation to actual energy of impact scenario identified by a dedicated sensing system for impact energy recognition.

The designed control system was dedicated to process the data from the system of impact energy recognition in order to perform the optimal landing scenario. The objective of the control strategy was minimization of the structure's deceleration peaks during the touch-down.

The presented results consist of numerical analysis of the adopted strategy of control and experimental verification of the concept on the dedicated experimental device. The results proved that the proposed method allowed minimization of the maximal deceleration level acting on the demonstrator.

## 1 INTRODUCTION

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.

Currently, the most popular type of landing gears is the oleo-pneumatic one, which is proved to have the best ratio of weight to absorbing efficiency in comparison to the other existing types of landing struts. The value of efficiency of the landing gears operated presently is reported as equal to 80% (Currey 1988). However, these passive devices operate optimally only for one, predefined landing scenario. In practice a strong variety of the landing conditions is observed, which is demonstrated by a wide range of vertical impact velocities. Therefore, the classical passive landing gears are not capable to withstand the high alteration of the landing conditions. Thus, the classical shock absorbers are tuned for the hardest allowable landing conditions for the reason of safety, which leads to shortening of their service life.

The presented problems in design of the landing gears might be omitted via utilization of the concept of pneumatic adaptive impact absorber presented in this paper. Primarily, a design of gas shock absorbers for landing gears will let reduce the effective weight of the structure. Secondly, 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 presented e.g. in (McGhee & Carden 1976), were followed by first experimental works in the 1980s (McGhee & Dreher 1982), 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).

This paper presents the results of a concept stage development of the pneumatic adaptive impact absorber (pAIA) controlled via piezo actuated valve. The pAIA concept follows a novel, more general concept of Adaptive Impact Absorption system, discussed in (Holnicki-Szulc 2008) and based on impact identification and optimal adaptation of a structural system, providing enhanced energy dissipation and minimisation of dynamic load level. The various formulations of crashworthiness-based structural design problem can be found e.g. in (Pedersen 2002), while the AIA concept has been first proposed in (Holnicki-Szulc et al. 1998).

## 2 THE CONCEPT OF ADAPTIVE PNEUMATIC LANDING GEAR

The concept of innovative adaptive landing gear for Ultra-light Aerial Vehicle (ULAV) is based on double chamber pneumatic cylinder equipped with active piezoelectric valve, which controls flow of the gas between the chambers (cf. Fig. 1A). Such device can serve as a shock absorber dissipating ULAV kinetic energy during landing as well as suspension utilized during taxiing and ground manoeuvres. Active adaptation of the pneumatic absorber to actual landing scenario contains the following steps:

- identification of the aerial vehicle's kinetic energy based on ultrasonic measurement of touchdown velocity
- determination of the optimal change of pneumatic force generated by the absorber,
- active control of the piezoelectric valve opening to provide optimal change of pneumatic force and optimal dissipation of energy during whole landing process.

Active control strategy is executed by control system (cf. Fig. 1B) where ULAV mass and touchdown velocity are introduced as known input parameters. Actual value of pneumatic force is used as a reference signal for closed-loop feedback system.

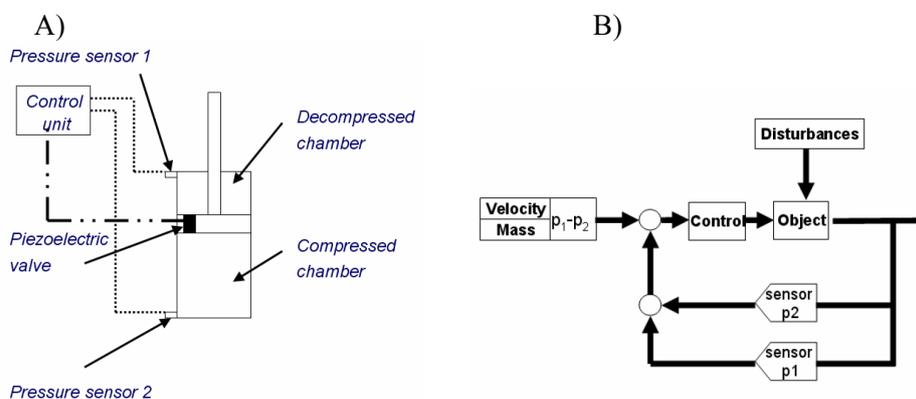


Figure 1. A) Concept of the pneumatic absorber, B) Scheme of the control system.

### 3 MODELLING OF ADAPTIVE PNEUMATIC LANDING GEAR

The proposed pneumatic system was modelled numerically in order to find the optimal geometry of the pneumatic cylinder, range of required pressures and valve parameters to be applied in ULAV absorber.

Initially the model based on assumption of uniform gas pressure  $p(x, y, t) = p(t)$ , gas density  $\rho(x, y, t) = \rho(t)$  and gas temperature  $T(x, y, t) = T(t)$  was developed. Considered pneumatic system is described by equation of motion of the falling mass  $M_1$  and equation of motion of the piston  $M_2$  which take into account contact force arising between the falling mass and the piston rod  $F_C$  and friction force  $F_F$  caused by the cylinder sealing, (cf. Fig. 2A):

$$M_1 \ddot{u}_1 - M_1 g + F_C = 0 \quad (1)$$

$$M_2 \ddot{u}_2 - M_2 g - p_1 A_1 + p_2 A_2 - F_C + F_F = 0 \quad (2)$$

$$\begin{aligned} F_C &= k(u_2 - u_1)^2 + c(u_2 - u_1)(\dot{u}_2 - \dot{u}_1) \quad \text{if } u_1 - u_2 \geq 0 \\ F_C &= 0 \quad \text{if } u_1 - u_2 < 0 \end{aligned} \quad (3)$$

$$F_F = F_F^* \text{ if } \dot{u}_2 > 0, \quad F_F = -F_F^* \text{ if } \dot{u}_2 < 0, \quad F_F = 0 \text{ if } \dot{u}_2 = 0 \quad (4)$$

Gas filling both chambers is described by the ideal gas law:

$$p_1 V_1 = m_1 R T_1, \quad p_2 V_2 = m_2 R T_2 \quad (5)$$

Assumed model of the flow correlates the mass flow rate and pressure difference between the chambers by the viscous resistance coefficient  $C_V(t)$  and hydrodynamic resistance coefficient  $C_H(t)$  which depend on the geometry and actual position of the valve head:

$$\Delta p = C_V(t) \dot{m} + C_H(t) \dot{m} |\dot{m}| \quad (6)$$

The balance of the heat transferred to each fluid chamber  $dQ$ , enthalpy of the gas added to (removed from) the chamber  $dm_{in} \bar{H}_{in}$  ( $dm_{out} \bar{H}_{out}$ ), change of gas internal energy  $d(m\bar{U})$  and the work done by gas  $dW$  is given by the first law of thermodynamics for an open system:

$$dQ + dm_{in} \bar{H}_{in} - dm_{out} \bar{H}_{out} = d(m\bar{U}) + dW \quad (7)$$

Specific gas enthalpy, specific gas energy and work done by gas are defined as:

$$\bar{H}_{in} = c_p T_{in}; \quad \bar{H}_{out} = c_p T; \quad \bar{U} = c_v T; \quad dW = p dV \quad (8)$$

Finally, flow of heat across the walls of the cylinder is described by equation:

$$\dot{Q} = \lambda A (T_{ext} - T) \quad (9)$$

where  $\lambda$  is the heat conductivity coefficient of the cavity wall and  $A$  is the total area of the cavity walls. If the wall of the cavity is perfect insulator ( $\lambda = 0$ ) or when the process is very fast, adiabatic conditions are fulfilled and no heat transfer through the chamber walls occurs:  $dQ = 0$ . In a very general case of adiabatic process equation (7) reads:

$$\frac{\dot{T}}{T} = \left( \chi \frac{T_{in}}{T} - 1 \right) \frac{\dot{m}}{m} - (\chi - 1) \frac{\dot{V}}{V}, \quad \chi = \frac{c_p}{c_v} \quad (10)$$

In case when there is no gas inflow into the considered chamber equation (10) can be solved analytically:

$$\frac{T}{T_0} = \left( \frac{m_0 V}{V_0 m} \right)^{1-\chi} \quad \text{or} \quad \frac{p}{p_0} = \left( \frac{m_0 V}{V_0 m} \right)^{-\chi} \quad (11)$$

Finally, when no flow of the gas occurs (i.e. mass of the gas in the cavity remains constant) we obtain well known equation:

$$pV^\chi = p_0V_0^\chi = \text{const.} \quad (12)$$

Resulting system of four nonlinear ordinary differential equations was solved numerically by fourth order Runge-Kutta method by means of Maple software and satisfactory correspondence with experimental results was obtained (cf. Fig. 8). The typical response of pneumatic absorber with constant valve opening is presented in Figure 2B.

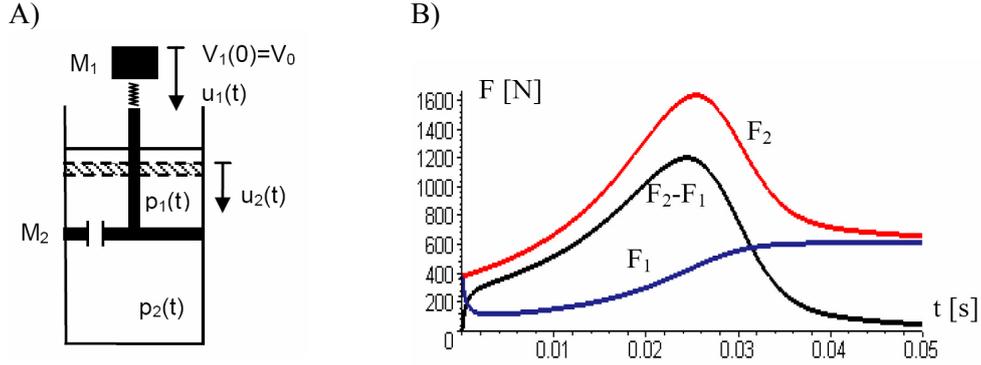


Figure 2. A) Basic model of pneumatic absorber, B) Response of a passive system: pneumatic force generated in upper and lower chamber and resultant pneumatic force.

Let us analyze basic dynamic properties of the simplified 1dof model of pneumatic absorber which neglects change of gas temperature, friction force, gravity and cross section of piston rod and which is described by the equation:

$$M\ddot{u}(t) + \frac{m_2(t)RT_0A}{V_{20} - u(t)A} - \frac{(m - m_2(t))RT_0A}{V_{10} + u(t)A} = 0 \quad (13)$$

According to Eq.(13) the considered pneumatic absorber, also the one with constant in time valve opening, is a system with variable in time nonlinear stiffness. During downward piston motion the stiffness of the lower chamber decreases and stiffness of the upper chamber increases providing energy dissipation. Obviously, in case when the valve is closed ( $C_V \rightarrow \infty$ ) mass of the gas in both chambers is constant and the system acts as double spring with constant in time nonlinear stiffness.

In the further step, the equation of gas state can be combined with differential equation of the flow  $p_2(t) - p_1(t) = -C_V \dot{m}_2(t)$  to find analytical formulae for pressures  $p_1$  and  $p_2$  (and resultant pneumatic force generated by pneumatic absorber) in terms of piston displacement and valve opening:

$$p_1(t) = \frac{\left( \left( m \int_0^t \frac{e^{\int_0^t \frac{V}{(V_{10}+u(t)A)(V_{20}-u(t)A)C_V} dt}}{(V_{20} - u(t)A)C_V} dt + m_{10} \right) e^{\int_0^t \frac{V}{(V_{10}+u(t)A)(V_{20}-u(t)A)C_V} dt} \right) RT_0}{V_{10} + u(t)A} \quad (14)$$

$$p_2(t) = \frac{\left( \left( m \int_0^t \frac{e^{\int_0^t \frac{V}{(V_{10}+u(t)A)(V_{20}-u(t)A)C_V} dt}}{(V_{10}+u(t)A)C_V} dt + m_{20} \right) e^{\int_0^t \frac{V}{(V_{10}+u(t)A)(V_{20}-u(t)A)C_V} dt} \right) RT_0}{V_{20} - u(t)A} \quad (15)$$

Therefore equation of motion can be written in a simplified manner:

$$M\ddot{u} + \frac{f_1 \left( \int_0^t f_2(u, C_V) dt \right)}{V_{20} - uA} - \frac{f_3 \left( \int_0^t f_4(u, C_V) dt \right)}{V_{10} + uA} = 0 \quad (16)$$

According to Eq.(16) pneumatic force generated by the absorber depends not only on the actual piston displacement but also on the time history of piston displacement and time history of valve opening. The pneumatic force is not a direct function of the actual piston velocity and actual valve opening, what is a typical feature of hydraulic shock absorbers. However, as a consequence of displacement history dependence, the response of the pneumatic system changes considerably for slow and fast impacts of the same kinetic energy.

From thermodynamical point of view the process of energy dissipation can be explained most easily for pneumatic absorber working under adiabatic conditions. In such system two thermodynamic processes take place simultaneously during impact: kinetic energy of the impacting body is changed into gas internal energy and irreversible flow of the gas between high and low pressure chamber occurs. The second process does not change gas internal energy but increases gas entropy. When entropy of a system raises a smaller part of internal energy can be transformed into mechanical work and thus kinetic energy of impacting object is being dissipated. After impact the heat transfer through the cylinder walls begins and the surplus of internal gas energy is reduced.

#### 4 ADAPTIVE CONTROL OF PNEUMATIC ABSORBER

Numerical model introduced above enables simulation of *adaptive pneumatic landing gear* where gas migration is controlled and adjusted to actual impact scenario. Both in case of semi-active and fully active control the change of valve opening is modelled by the variation of flow resistance coefficient  $C_V(t)$  which is treated here as a control variable.

In case of semi-active control initial pressure and constant in time valve opening can be adjusted to mass and velocity of the hitting object. Optimal initial pressure is close to constant pressure which is required to stop the impacting body by using the whole stroke of the cylinder. Optimal valve opening depends both on the impact parameters and initial pressure. The increase of valve opening causes change of system characteristics from nonlinear elastic to dissipative and decrease of maximal pneumatic force generated by the absorber (cf. Fig. 7A for experimental results). When the valve opening is too large the pneumatic force is not sufficient to stop the piston and the collision with the cylinder bottom occurs. Optimal valve opening enables utilization of the whole cylinder stroke and causes that the resultant pneumatic force is minimal.

In case of active control the valve opening is actively changed during the analysis depending on actual response of the system. Active control strategy is composed of two steps (cf. Fig. 3): initial increase of total absorber force  $F(t) = p_2(t)A_2 - p_1(t)A_1$  caused by compression of lower chamber and decompression of upper chamber while closed valve and maintaining the absorber force on the constant level by controlling gas migration between the chambers.

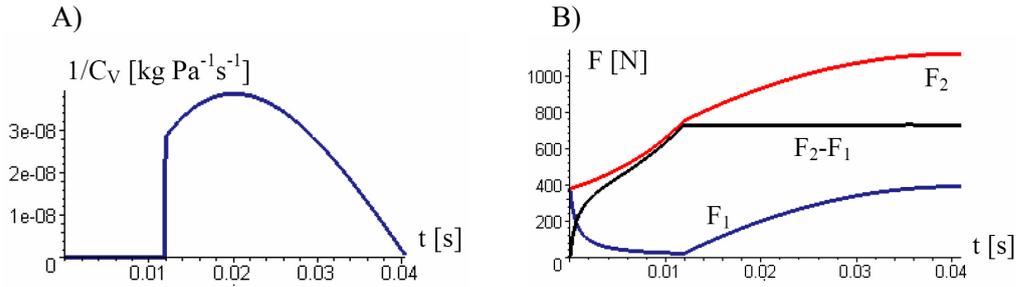


Figure 3. Active control strategy: A) optimal valve opening B) pneumatic force in upper ( $F_1$ ) and lower chamber ( $F_2$ ) and resultant pneumatic force ( $F_2-F_1$ ).

Development of active control strategy without constraints imposed on maximal valve opening is based on the following steps (cf. Fig. 3):

- computation of force level required to stop the hitting object using whole absorber stroke (by integrating equation of motion over displacement and utilizing recognized impacting mass and velocity)
- computation of valve opening required to maintain constant force level (by solving system differential equation with absorber force imposed)

Alternatively, maintaining constant value of pneumatic force can be realized by fast commutative opening and closing of the valve (on/off control strategy) depending on the relation of optimal pneumatic force to actual one. Such method enables simplification of the control algorithm and helps to avoid the difficulties related to the hysteresis of the electric valve. On the other hand it requires application of the valve with much shorter response time.

Limitation of maximal valve opening requires different control strategy for minimization of absorber force (cf. Fig. 4B), i.e:

- full opening of the valve at the beginning of the ‘active stage’
- optimization of force level which triggers the valve opening

In case when the constraint on valve opening is imposed and active the whole stroke of the cylinder can not be utilized, the time of impact process is shortened and therefore larger maximal value of the maximal value of pneumatic force and piston acceleration (cf. Fig. 4)

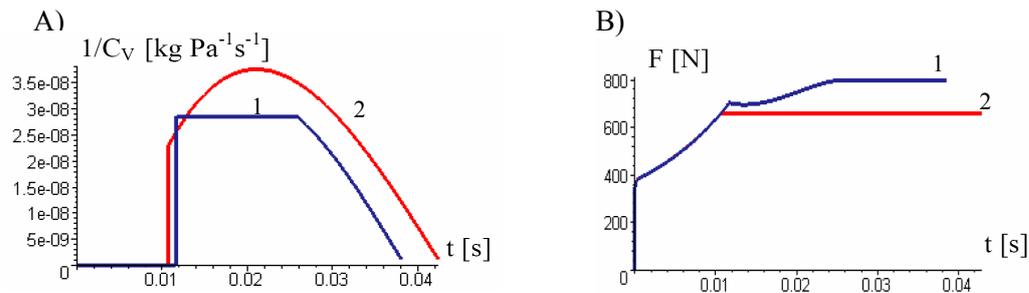


Figure 4. Active control strategy with (1) and without (2) constraints imposed on maximal valve opening: A) optimal change of flow coefficient; B) resulting pneumatic force.

## 5 VERTICAL VELOCITY IDENTIFICATION

Recognition of the landing conditions before touchdown is a very important part of the pAIA concept. Performing optimal control of the damping force, generated by the shock absorber in order to obtain the optimal energy dissipation, requires information about the kinetic energy related to vertical velocity in the last phase of the aircraft's approach.

The proposed ultrasonic identification system should provide short-range measurements of the sink speed of the aircraft by means of set of three sensors, establishing the position of the

aircraft in respect to the surface of the landing area, determine position of centre of gravity of the aircraft and its vertical kinetic energy. The mass of the aircraft should be estimated according to the payload and fuel consumption.

The measuring system consists of an ultrasonic transmitter, a receiver and a signal processing controller unit. The general principle of echolocation is well known and widely utilised in radar and sonar applications (Kock 1973). The transmitter sends periodically (with pulse repetition time  $T$ ) a short ultrasonic impulse. The generated wave is reflected and returns to the receiver after time  $T_R^i$ . The distance is one-half the round trip time divided by the propagation speed of the signal:  $L^i = 0.5 c T_R^i$ , where:  $c$  is the velocity of ultrasonic wave propagation in air (343m/s at 20degC),  $T_R^i$  - return time of reflected wave (cf. Fig. 5). The vertical velocity can be calculated by differential methods. General block diagram of the system is presented in the Figure 6.

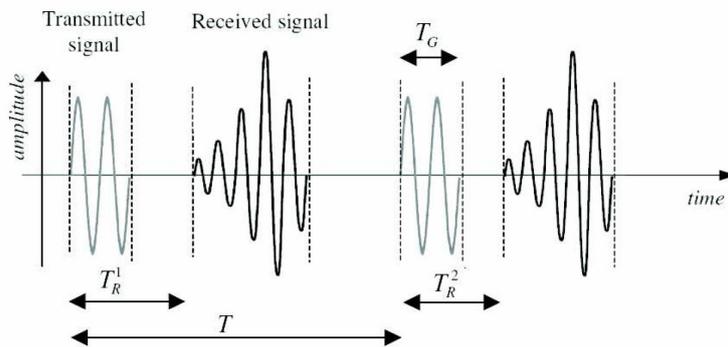


Figure 5. Ultrasonic signals in time domain.

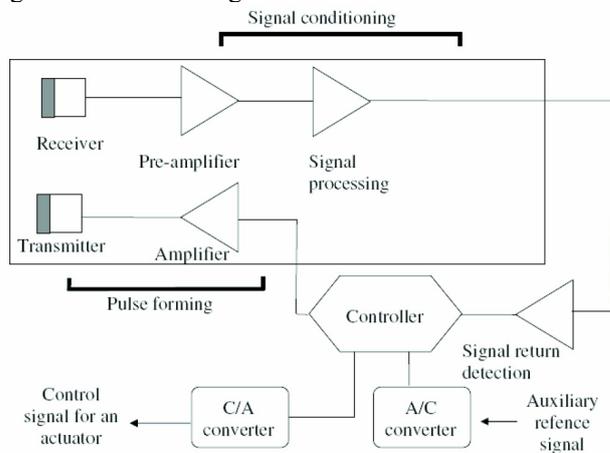


Figure 6. Scheme of the controller.

## 6 EXPERIMENTAL TESTS AND RESULTS

The presented previously hardware concepts were implemented in a lab-scale experiment and verified on a drop test stand (cf. Fig. 7 left). The pneumatic cylinder was equipped with a piezo-valve (cf. Fig. 7 right) characterised by response time equal 2 ms .

The initial series of the conducted tests was devoted to verification of the developed numerical model of pneumatic shock absorber against the experimental results. The reference experiment was defined as drop of a known mass on the pneumatic shock absorber positioned vertically. The parameters of impact for the drop test were fixed: mass = 27.2kg, drop height = 0.4m and these were established as reference case for all the tests described in this

paper. Figure 8 depicts the comparison between numerical and experimental results obtained during the research.

Secondarily a comparison was conducted, between operation of the pneumatic cylinder for two values of the initial internal pressure:  $p_{01} = 1\text{bar}$  and  $p_{02} = 3\text{bar}$ . The test was conducted for two cases: with the valve opened and closed. In result, it was verified that increased initial internal pressure:  $p_{02} = 3\text{bar}$ , improves absorbing efficiency of the device. The results are depicted in Figure 9A where the process of impact energy dissipation was conducted on 30% shorter stroke in the case of initial internal pressure  $p_{02} = 3\text{bar}$ .



Figure 7 Experimental stand and piezo-valve.

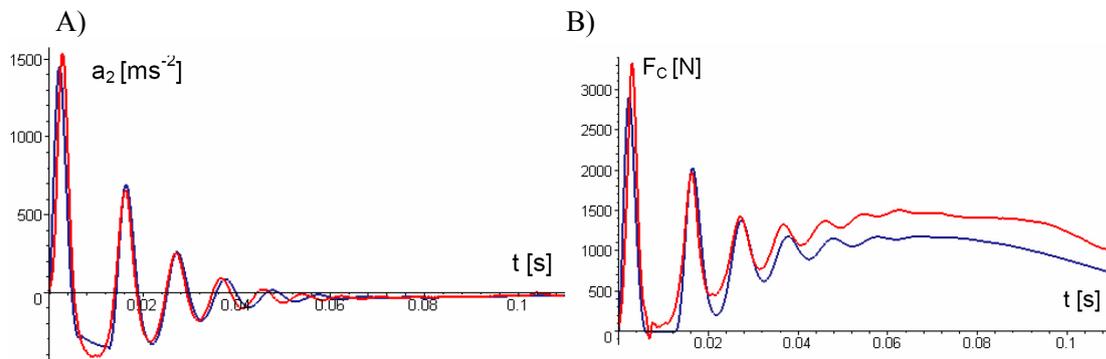


Figure 8 Comparison of the experimental and numerical results on the example of the piston's acceleration  $a_2$  and contact force  $F_c$  in time domain.

The third part of tests conducted on the lab-scale stand was verification of the control strategies for the system under impact loading. The same conditions of impact were established for these experiments. Two control strategies were verified: semi-active and active as defined in the section 4. Comparison between the results obtained with the semi-active and the active control strategies (cf. Fig. 9B) pronounced reduction of the maximal transferred load value by 30% in the case of the active control strategy.

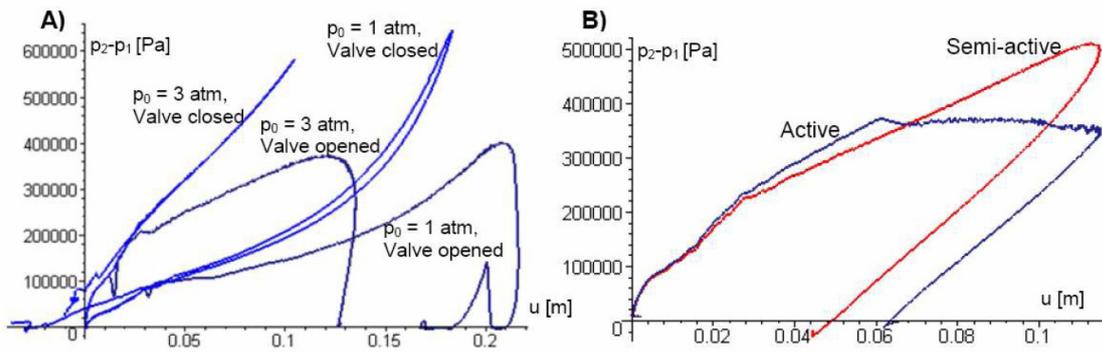


Figure 9. A - Comparison of the energy absorption capability for two values of initial pressures in the cylinder, B - Comparison of the pressure difference in the cylinder's chambers for semi-active and active control modes.

## 7 CONCLUSIONS

The concept of innovative adaptive pneumatic landing gear utilizing active control of gas migration was presented and verified. Introduced numerical model was used to develop control strategy and to assess the benefits of semi-active and fully active system over the passive one. It was also utilized to choose optimal absorber dimensions, gas pressure and valve parameters required for considered range of impact energies. Experimental verification has proved that the efficiency of piezo-actuated valve is sufficient for executing required gas migration and that the control strategy can be performed fast enough. Applied control strategy provided reduction of pneumatic force generated by the absorber by 30% and mitigation of hitting object rebound. Both numerical and experimental results confirm that concept is feasible to be applied in small aerial vehicle. In further stages of research more compact and coherent valve assembly will be developed. Optimal design of semi-active pneumatic absorber will be proposed and verified on full scale drop testing stand as well as in field tests.

## ACKNOWLEDGEMENTS

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