A FEASIBILITY STUDY OF A PNEUMATIC ADAPTIVE IMPACT ABSORBER

Grzegorz Mikułowski
Institute of Fundamental Technological Research

**Cezary Graczykowski, Piotr Pawłowski, Krzysztof Sekuła,
Arkadiusz Mróz, Jan Holnicki-Szulc**
Institute of Fundamental Technological Research
e-mail: gmikulow@ippt.gov.pl

A concept of a new adaptive impact absorption device is presented. The proposed approach is based on the pneumatic principle combined with a controllable piezo-actuated valve. The main importance of the idea is introduction of an active management of the gas migration between two chambers of the device in a way that allows real-time adaptive impact absorption. The investigation was focused on proving the concept for a landing gear of a small Unmanned Aerial Vehicle (UAV). All experimental, analytical and numerical results obtained in the research were verified against each other and the results showed that the concept seems to be feasible for utilisation in the considered UAV.

---

keywords: adaptive impact absorption, adaptive landing gear, adaptive pneumatic system, ultrasonic position measurements, piezo-valave, semi-active control

Introduction and definition of the concept

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%. 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. 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 presented e.g. in [3], were followed by first experimental works in the 1980s [4], 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 [1] 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 [6], while the AIA concept has been first proposed in [5].

The concept of pneumatic adaptive landing gear for Unmanned Aerial

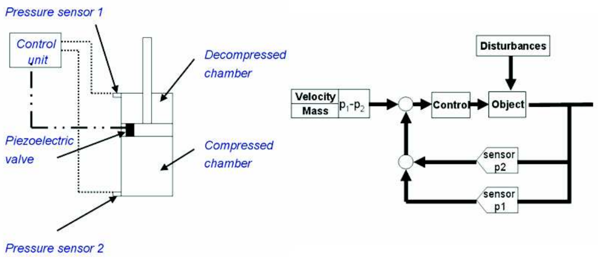

Figure 1: a) Concept of adaptive pneumatic absorber, b) Scheme of control system.

Vehicle (UAV) is based on double chamber pneumatic cylinder equipped with active piezoelectric valve which controls flow of the gas between cylinder chambers, cf. Fig.1a. 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 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 (cf. Fig.1b) 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.

Modeling and control of adaptive pneumatic absorber

The proposed adaptive device was modelled numerically in order to assess system effectiveness and to find optimal geometry, range of pressures and valve parameters to be applied in final design of UAV absorber. Introduced model is based on assumption that gas pressure, density and temperature are uniform across cylinder chambers: $p(x,y,t) = p(t)$, $\rho(x,y,t) = \rho(t)$, $T(x,y,t) = T(t)$.

The 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 caused by the cylinder sealing F_f, cf. Fig.2.

$$M_1\ddot{u}_1 - M_1 g + F_C = 0 \tag{1}$$

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

$$F_c = k(u_2 - u_1)^2 + c(u_2 - u_1)(\dot{u}_2 - \dot{u}_1) \quad if \quad u_1 - u_2 \geq 0 \tag{3}$$

$$F_c = 0 \quad if \quad u_1 - u_2 < 0 \tag{4}$$

$$F_F = F_F^* \; if \; \dot{u}_2 > 0, \quad F_F = -F_F^* \; if \; \dot{u}_2 < 0, \quad F_F = 0 \; if \; \dot{u}_2 = 0 \tag{5}$$

Gas filling both chambers is described by equation of state:

$$p_1 V_1 = m_1 R T_1 \;, \quad p_2 V_2 = m_2 R T_2 \tag{6}$$

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

$$\Delta p = C_V(t)\dot{m} + C_H(t)\dot{m}\,|\dot{m}| \tag{7}$$

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

$$dQ + dm_{in}\overline{H}_{in} - dm_{out}\overline{H}_{out} = d(m\overline{U}) + dW \tag{8}$$

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

$$\overline{H}_{in} = c_p T_{in}, \overline{H}_{out} = c_p T, \overline{U} = c_V T, dW = pdV \tag{9}$$

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

$$\dot{Q} = \lambda A (T_{ext} - T) \tag{10}$$

where λ is the heat conductivity coefficient of the cavity wall and A is the total area of the cavity walls. Resulting system of nonlinear ordinary differential equations was solved numerically by fourth order Runge-Kutta method by means of Maple software and satisfactory agreement with experimental results was obtained.

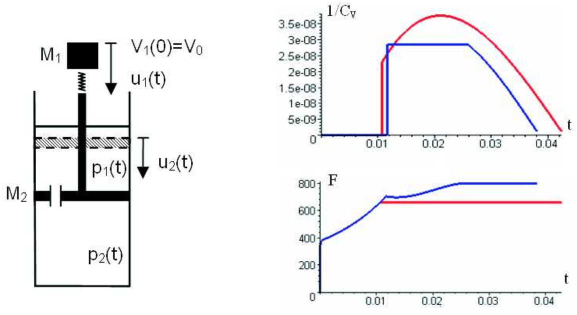

Figure 2: a) Simplified scheme of pneumatic absorber, b) Active control strategy with and without constraints imposed on valve opening: optimal change of flow coefficient (top); resulting force (bottom)

Introduced numerical model enables simulation of adaptive pneumatic landing gear where gas migration can be controlled and adjusted to actual impact scenario. Both in case of semi-active and fully active system the change of valve opening is represented in numerical model by variation of flow resistance coefficients $C_V(t)$, $C_H(t)$ which are treated as control variables.

In semi-active system initial pressure and the valve opening are set to optimal values and valve opening remains constant during the whole landing process. Optimal valve opening for each value of initial pressure is the one for which the largest stroke of the pneumatic cylinder is used and the rebound of the hitting object does not occur.

In active system the valve opening is actively changed during the analysis depending on actual response of the system. Active control strategy is composed of two stages (cf. Fig.2b): i) initial increase of absorber force caused by compression of lower chamber and decompression of upper chamber while closed valve and ii) maintaining the absorber force on the constant level by controlling gas migration between the chambers. Development of active control strategy for fully active system with no constraints imposed on valve opening is based on the following steps:

- computation of force level required to stop the hitting object using whole absorber stroke (by integrating Eqs.(1,2) over displacement and utilizing recognised value of impacting mass and velocity)
- computation of valve opening required to maintain constant force level (by solving system of differential equations with imposed value of absorber force)

Limitation of maximal valve opening requires different control strategy for minimization of absorber force (cf. Fig.2b):

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

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 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, 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 [2]. 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

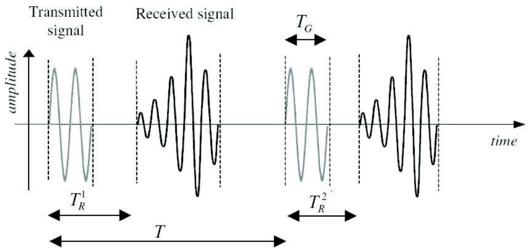

Figure 3: Ultrasonic signals in time domain.

of ultrasonic wave propagation in air (343m/s at 20^0C), T_R^i - return time of reflected wave. The vertical velocity can be calculated by differential methods. General block diagram of the system is presented in the Fig. 4.

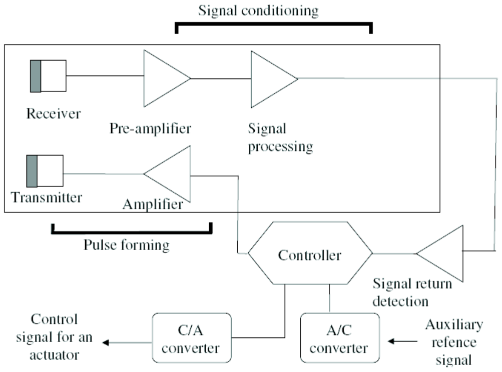

Figure 4: Ultrasonic signals in time domain.

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. 5 left). The pneumatic cylinder was equipped with a piezo-valve (cf. Fig. 5 right) characterised by response time equal 2 ms .

Primarily a comparison was conducted, between operation of the pneumatic cylinder for two values of the initial internal pressure: p_{01} = 1bar and p_{02} = 3bar. The parameters of impact for the drop test were fixed: mass = 27.2kg, drop height = 0.4m. The test was conducted in two cases: with valve opened and closed. In result it was verified that increased initial internal pressure: p_{02} = 3bar, improves absorbing efficiency of the device (cf. Fig. 6A).

Figure 5: Experimental stand.

Another test conducted on the lab-scale stand was verification of the system's control strategies under impact loading. The same conditions of impact were established for these tests. Two control strategies were verified: semi-active and active in accordance with the definition formulated in the introductory section of the paper. Comparison between the results obtained with the semi-active and the active control strategies (Fig. 6B) pronounced reduction of the maximal transferred load value by 30% in the case of the active control strategy.

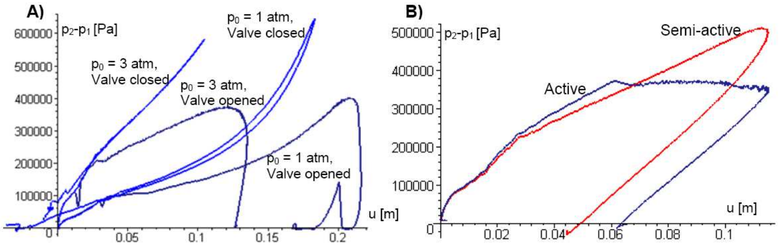

Figure 6: A - Comparison of the energy absorption capability for two values of initial pressures in the cylinder, B - Comparison of the pressure difference in the cylinder's chambers for semi-active and active control modes.

Conclusions

The concept of innovative adaptive pneumatic landing gear utilizing active control of gas migration was presented and positively 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. 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 piezoelectric valve assembly will be designed. Optimal geometry and parameters of absorber will be proposed and verified on full scale drop testing stand as well as in field tests.

Acknowledgements

The authors would like to gratefully acknowledge the financial support through the Polish research projects: "Aeronautica Integra", "MAT-INT" PBZ-KBN-115/T08/2004 (2005-2008), "SAFE-STRUCT" 3T11F00930 (2006-2009).

References

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

[2] Kock W.E., Radar, Sonar and Holography, An Introduction, Academic Press, 1973

[3] McGhee J.R., Carden H.D., A Mathematical Model of an Active Landing Gear for Load Control during Impact and Roll-out, NASA Technical Note, NASA TN D-8080, 1976

[4] McGhee J.R., Dreher R.C., Experimental Investigation of Active Loads Control for Aircraft Landing Gear, NASA Technical Paper 2042, 1982

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

[6] Pedersen C. B. W., On Topology Design of Frame Structures for Crashworthiness, Ph.D. Thesis