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# HIGH PERFORMANCE PNEUMATIC SHOCK-ABSORBERS FOR AERONAUTICAL APPLICATIONS

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## Abstract

*The paper is aimed at development of high performance shock-absorbers for aeronautical applications. This contribution concerns pneumatic dampers because of their lightweight, technical simplicity and low manufacturing costs. The concept of semi-passive devices is introduced and single reconfiguration technique is discussed for both single- and double-chamber shock-absorber. Presented general approach to optimal design of the semi-passive devices can be applied for design of different types of fluid-based absorbers, e.g. hydraulic or oleo-pneumatic dampers. The absorbers can be used as a suspension of light airdrop system as well as a part of landing gear of small UAV.*

## 1 Introduction

### 1.1 Motivation

Shock absorption phenomenon is present in many aeronautical systems. Problems of impact mitigation are discussed in papers concerning development of high performance landing gears [1-3], design of airdrop systems [4, 5] as well as techniques of structure self-protection [6, 7] that can be applied in space systems. Exemplary systems which are subjected to impact excitations are shown in Fig. 1.

Despite unquestionable progress in the field of smart sensors and actuators, which provide much better performance than systems used so far, a major part of absorbers used in practice are passive devices. This fact is caused by strict requirements for high system reliability and demand of fail-safe design. Nevertheless, efficiency of passive absorbers is limited and adaptation to impacts is impossible. The optimal response is obtained for particular operational conditions whereas, e.g., the airplane suspension should operate efficiently in typical landing conditions and simultaneously it has to meet requirements for maximum touchdown velocity specified in aviation regulations [8]. Excitations during these conditions are completely different [9]. This fact is the motivation to develop alternative solutions with adaptive capabilities.

(a)
(b)

**Fig. 1. Systems subjected to impacts (a) airdrop system [10], (b) unmanned airplane during touchdown – photo taken during SAE Aero Design West 2016.**

In this contribution the author discusses concepts of single reconfiguration technique aimed at adjustment of the system to different impact conditions and providing high performance which will be comparable with semi-active absorbers controlled in real-time [11]. The paper includes analyses of two pneumatic dampers: single-chamber absorber with gas release to the environment [12] and double-chamber absorber equipped with metering pin. Both devices ensure optimal impact response and adaptation to different loading conditions by means of single shape adjustment performed on selected system components.

## 1.2 Problem formulation

For the sake of clarity the design and analyses of the shock-absorbers are shown on example of 1 DOF system. Nevertheless, the results and conclusions from conducted research can be used for solving more complex impact absorption problems, which concerns systems with several DOF such as entire landing gear of the aircraft.

The object of mass $M$ is equipped with pneumatic absorber and it is subjected to the impact defined by initial relative velocity $v_0$. The operational gas is compressed during movement of the piston and in the case of single-chamber shock-absorber it is released through the valve to the environment (Fig. 2a). In contrast, use of double-chamber device (Fig. 2b) allows to transfer the gas from compressed chamber (no. 1) to decompressed chamber (no. 2).

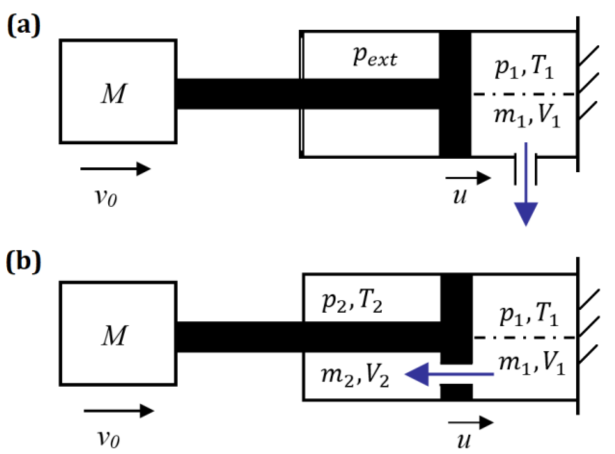


**Fig. 2. Schemes of the system under impact excitation, object equipped with: (a) single-chamber absorber, (b) double-chamber absorber.**

The time history of valve opening area $A_v(t)$ corresponds to the force response of the absorber being the function of internal pressure $p_1$ and external pressure $p_{ext}$ (or internal pressures $p_1$ and $p_2$ in case of double-chamber device). Internal pressures depends on the mass of gas $m$, volume $V$ and temperature $T$. Change of chambers volumes $V_1$ and $V_2$ is geometrically related to the piston displacement $u$ and thermodynamically related to gas state variables mentioned above. Detailed description of the applied model of pneumatic single-chamber as well as double-chamber shock-absorber can be found in [13].

Entirely closed valve results in high increase of absorber reaction force due to pneumatic spring effect, whereas finite value of valve area $A_v$ lead to slower gas compression because a particular amount of gas is released and as a result the system stiffness is decreased. For the actual state of the system, there exist a value of valve opening area for which pneumatic force starts decreasing. It means that the gas of pressure $p_1$ is no longer compressed although the volume $V_1$ decreases. It is also possible to find the valve opening which ensures constant value of absorber reaction force but to achieve this the valve area has to be variable in time [14].

One of widely used goal functions, that has to be minimized during optimization of the absorber operation, is the maximum value of the reaction force (1).

$$\max F_{react}(t) = \min \qquad (1)$$

Simultaneously, the requirement (2) of entire impact energy dissipation within available absorber stroke $d$ has to be met.

$$\int_0^d F_{react}(\bar{u})d\bar{u} = \frac{1}{2}Mv_0^2 \qquad (2)$$

When we are able to appropriately control the gas release to provide constant value of absorber's reaction force, the optimal feasible solution of the formulated impact absorption problem will be two-phase operation of the shock-absorber:

- fastest possible increase of the reaction force – valve closed,
- maintaining constant reaction force of the value which ensures dissipation of entire impact energy within available stroke.

## 2 The concept of semi-passive pneumatic shock-absorbers

### 2.1 Proposed adaptation strategy

In order to ensure system operation consistent with optimal solution of the formulated min-max problem and provide as simple as possible adaptation mechanism, the concept of adaptable pneumatic shock-absorbers was elaborated.

The proposed adaptation strategy is composed of several short actions performed short time period before the impact:

- identification/prediction of excitation conditions,
- calculation of optimal impact mitigation scenario,
- reconfiguration of the system components.

After system reconfiguration the optimal response of the shock-absorber should be obtained in passive manner.

### 2.2 Single-chamber shock-absorber

#### *2.2.1 Device construction and passive operation*

In Fig. 3. the proposed semi-passive single-chamber pneumatic shock-absorber is shown. The optimal force response is obtained using two concentric cylinders, first with vents of proper shape and second cylinder with narrow slots. When absorber is subjected to impact excitation the relative movement of cylinders occurs. At the beginning of the process the gas is compressed because there is no overlapping area of slots and vents. After reaching the position $u_x$, which corresponds to the optimal value of absorber reaction force, slots and vents start overlapping and constant force value is maintained until the end of the stroke. The construction of proposed absorber demands introduction of the third phase of system operation, i.e., final exhaust of the gas. The reason for that is the fact that at the end of the impact absorption process some amount of gas remains in cylinders and internal overpressure has to be reduced to avoid rebound.

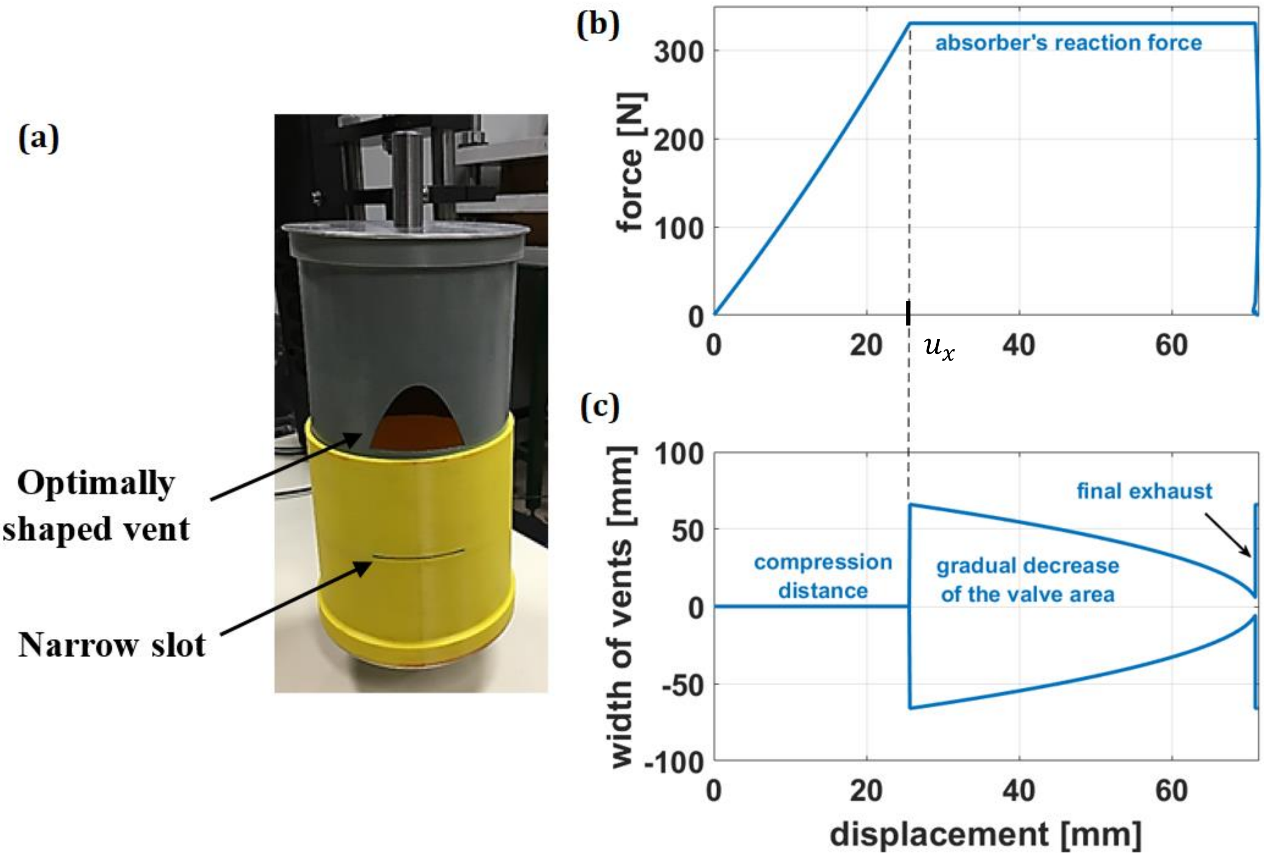


**Fig. 3. Proposed single chamber pneumatic shock-absorber: (a) prototype device prepared using 3D printing technology, (b) optimal reaction force of the absorber in case of no initial overpressure, (c) shape of the vent ensuring optimal response of the absorber during overlapping of slots and vents.**

The relative displacement $u_x$, further called 'compression distance', is determined using energy balance obtained by integration of the object's equation of motion with assumption of adiabatic gas compression during first phase of absorber operation. Inverse dynamics method applied for determination of optimal valve area $A_v(u)$ was presented and discussed in details in previous work [12]. Assuming that absorber has a particular number of slot-vent pairs *n* and slots are rectangles of height *h*, the optimal width of vents *w* as a function of relative displacement *u* can be calculated from the formula:

$$\frac{A_v(u)}{n} = \int_u^{u+h} w(\bar{u})d\bar{u} \qquad (3)$$

The number of conducted simulations as well as experimental tests have shown that the simplified formula for vent shape can be applied:

$$\frac{A_v(u)}{n} = w(u)h \qquad (4)$$

In order to ensure the reader that such simplification is reasonable, the influence of slot height *h* = 5 mm on the effective valve area and force response of the absorber is shown in Fig. 4.

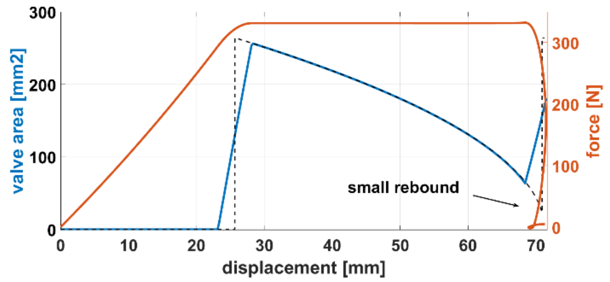


**Fig. 4. Influence of not infinitesimal height of the absorber slots - system response in case of h = 5 mm.**

The numerical simulation was conducted for system with parameters collected in Tab. 1.

**Table 1. Parameters of simulated and manufactured pneumatic shock-absorber.**

| ***M*** **[kg]** | $v_0$ **[m/s]** | $p_0$ **[kPa]** | $T_0$ **[K]** |
|---|---|---|---|
| 5 | 2.5 | 101.3 | 293.15 |
| ***L*** **[mm]** | **∅*D*** **[mm]** | ***d*** **[mm]** | **Slot-vent no.** |
| 150 | 150 | 72.5 | 2 |

The height of the slot which is not infinitesimal or in other words the finite width of the vent near displacement equal to $u_x$ leads to smoothening of the force response of the absorber. As a result small rebound is observed at the end of absorber stroke. Nevertheless, the final performance of the device is very close to theoretical optimal solution. The prototype manufactured for experimental validation of the concept has two slots of height *h* = 2 mm [12] so the feasible solution can be even closer to the optimal one.

### 2.2.2 Adaptation mechanisms

In order to ensure optimal response of the system in various excitation conditions, the shape of absorber's vents should be determined for all possible impact conditions. The influences of $\pm 10\%$ change of mass *M* or initial velocity $v_0$ are shown in Fig. 5a and Fig. 5b respectively.

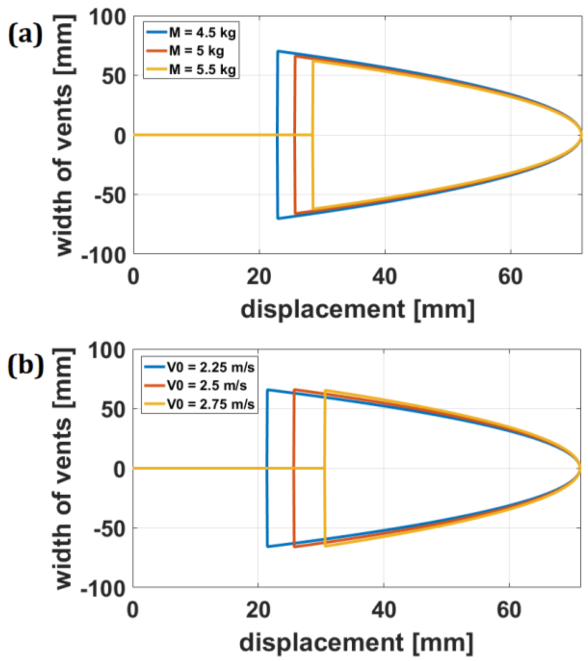


**Fig. 5. (a) optimal shapes of the vent for different masses of the amortized object *M*, (b) optimal shapes of the vent for different initial velocities $v_0$.**

It can be noticed that the most important parameter necessary for successful adaptation of the absorber is the compression distance $u_x$ Indeed, the character of vents' shape is slightly different for various impact conditions but the influence of it is much smaller. In further discussion the advantage will be taken from this inference.

Now, let me introduce schemes of mechanisms which can be used for adjustment of the compression distance and vent shape. On the beginning, we have to choose the vent shape which will be cut in the one of absorber's cylinders. We can choose the widest vent and then lengthen it. As a result the adaptation will be realized by appropriate decrease of the vent. Alternatively, the global optimization problem can be formulated in order to find a compromise solution for all possible impact conditions. When the shape of vents is selected and cut precisely in the cylinder, we can move our attention to the adaptation mechanism. The compression distance $u_x$ can be easily shortened or lengthened using moveable shutter as shown in Fig. 6a. For more optimal response of the absorber the additional shutters can be used to increase or decrease the width of vents (Fig. 6b). Side shutters can be mounted at the appropriately selected angle to ensure possibly best resembling of the optimal vent shape, which is calculated for predicted values of $M$ and $v_0$. If the designed mechanism does not allow to obtain a exactly desired shape of vents, e.g. shutters are perpendicular as shown in Fig. 6b, the next optimization problem can be formulated to find a new, actually best value of $u_x$ and to determine required opening of side shutters. According to the practice implementation of proposed approach the optimization processes should be done offline and lookup tables should be used.

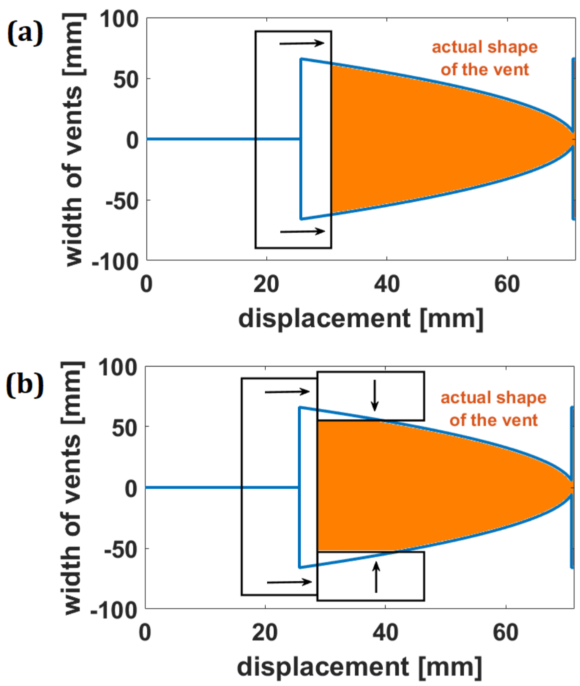


**Fig. 6. (a) mechanism for compression distance adaptation, (b) mechanism for compression distance and vent shape adjustments.**

### *2.2.3 Simplified adaptation strategy*

In this section a brief discussion on the simplified adaptation technique is shown. According to the conclusion formulated during analyses of the change of optimal valve opening in case of different values of object mass and various initial velocities (Fig. 5), the proposed adaptation strategy will be based exclusively on the adjustment of compression distance $u_x$. In turn, the shape of absorber's vent is calculated for nominal impact conditions, as shown previously in Tab.1. The value of $u_x$ is changed to the optimal value calculated for particular mass $M$ and initial velocity $v_0$. In Fig. 7. the suboptimal responses of the absorber are shown. Although the character of the reaction force is quite similar to optimal case, some rebounds of the system occur. Depending on the application and operational requirements the designer of the system, which can be equipped with proposed absorber, should decide if such behaviour is acceptable or if additional re-shaping of the vents is necessary.

The performance of the absorber equipped with side shutters mounted at the proper angle will not be presented because the obtained system response has entirely optimal character and only level of reaction force is changed.

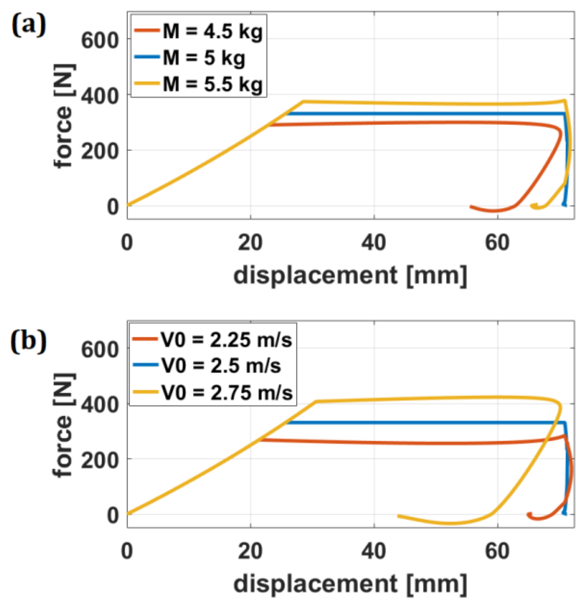


**Fig. 7. Suboptimal response of the absorber in case of compression distance adaptation: (a) different masses of the amortized object, (b) different initial velocities of the object.**

### *2.2.4 Experimental tests*

For fast experimental validation of the concept of system operation the prototype device was designed and manufactured using 3D printing technology. The first goal was to ensure tightness of cylinders in case of no overlapping area of slot-vent pairs. Simultaneously, efficient relative movement of cylinders had to be provided. To achieve this the manufacturing conditions and tolerances for dimensions of cylinders have been selected carefully, and finally a lubricant was applied on the connection of cylinders. The gas release was obtained by using two slots and two corresponding vents. The values of shock-absorber parameters have been assumed the same as values used in numerical simulations. The only difference is the excitation conditions. For simulation purposes the impact was modelled by the mass with initial velocity, whereas the excitation during laboratory tests was kinematic. In order to provide correspondence between simulations and experiments the applied kinematic excitations had to resemble system kinematics in case of optimal impact absorption process. The prototype of the absorber was mounted in the laboratory test stand as shown in Fig. 8. The kinematic excitation was realized using fast hydraulic actuator. The reaction force of the absorber was measured directly using dedicated force sensor.

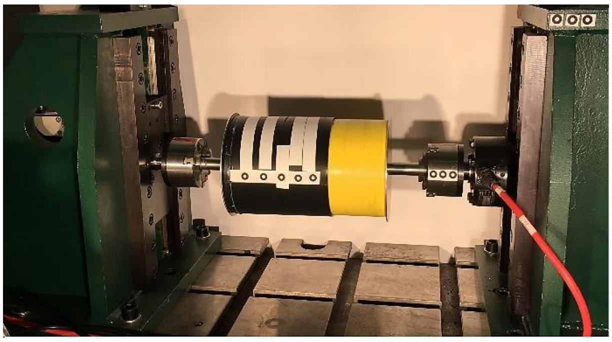

**Fig. 8. The prototype of the proposed single-chamber pneumatic shock-absorber during experimental tests.**

The set of different kinematic excitations (Fig. 9b) was applied to measure the absorber reaction force (Fig. 9a) in nominal conditions of optimal impact absorption (excitation 2) as well as the suboptimal response in case of different loading conditions. The force-displacement response of the system (Fig. 9c) corresponds well to the results obtained in numerical simulations.

After phase of fast gas compression the reaction force is maintained at almost constant level until the end of absorber stroke. In case of kinematic excitations 1 and 3 the lack of adaptation mechanism results in suboptimal response of the shock-absorber. Nevertheless, the obtained performance is much better than performance achieved by the use of typical absorbers with constant valve opening. The small oscillations of the absorber reaction force correspond probably to elastic deformations of the cylinders. The nonzero value of final reaction force is caused by the remaining overpressure inside the absorber. This results from the fact that the prototype device did not have wide opening for the final exhaust of the gas.

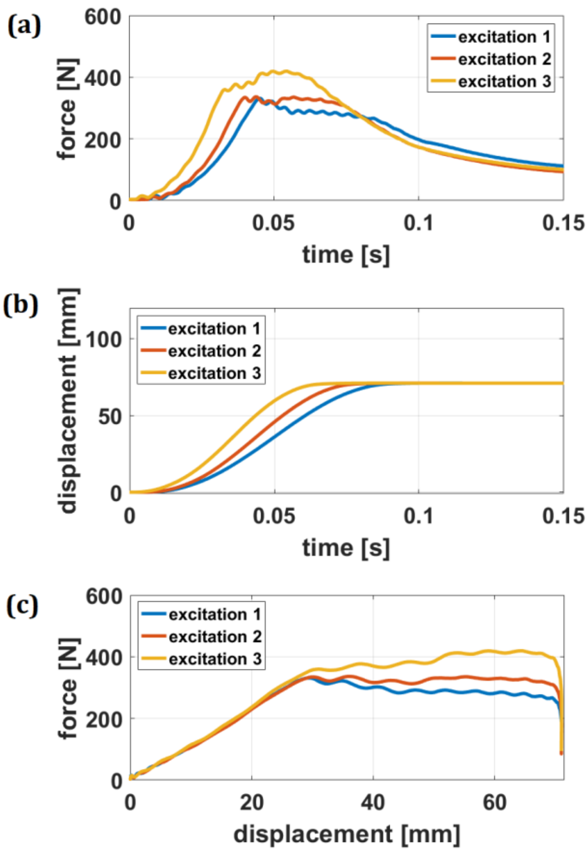


**Fig. 9. (a) measured force response of the absorber, (b) applied kinematic excitations, (c) obtained force-displacement characteristics of the absorber.**

The conducted experimental tests have proved feasibility of the concept of proposed absorber operation.

## 2.3 Double-chamber shock-absorber

### *2.3.1 Device design and adaptation*

The idea of obtaining variable gas release using overlapping vents and slots can be extended for the case of double chamber shock-absorber. In this case the more convenient technical solution is a use of metering pins of variable shape and holes placed in the absorber piston. Metering pins play the analogous role as vents in the single-chamber shock-absorber, while holes in the piston correspond to the slots in the single-chamber device.

In Fig. 10a the optimal response of the double-chamber pneumatic shock-absorber is shown. In order to obtain such good response the operation of the device has to be divided into two phases. The first phase corresponds to the fastest possible increase of reaction force due to lack of gas transfer between chambers (Fig. 10b) resulting in compression of the gas located in chamber 1 and decompression of the gas in chamber 2. When the optimal value of compression distance $u_x$ is reached and further maintaining of constant value of reaction force will provide dissipation of entire impact energy within available stroke, the gas transfer between chambers has to be enabled. The area of the valve between chambers in proposed device will be defined as a projection area appearing between metering pins and walls of corresponding holes. The height of the piston influences similarly the performance of the absorber as height of the slot in single-chamber absorber but there is a slight difference. Namely, the first phase of absorber operation lasts until displacement being a sum of $u_x$ and piston height $h_p$ is reached. Only further movement corresponds to gas transfer between the chambers. In case of significant height of the piston, the value $h_p$ can be taken into account during determination of the compression distance $u_x$. Also the shift of cross section corresponding to the valve area should be considered. Moreover, the process of flow through the canal should be simulated using more detailed models.

In further discussion, the height of the piston $h_p$ will be assumed to be very small. As a result the diameter of metering pin $d_{mp}$, ensuring appropriate values of valve area $A_v(u)$ created due to movement of piston with holes relative to metering pins, can be calculated using simple formula:

$$d_{mp}^2 = d_h^2 - \frac{4A_v(u)}{n\pi} \tag{5}$$

where $d_h$ is the diameter of holes in the piston.

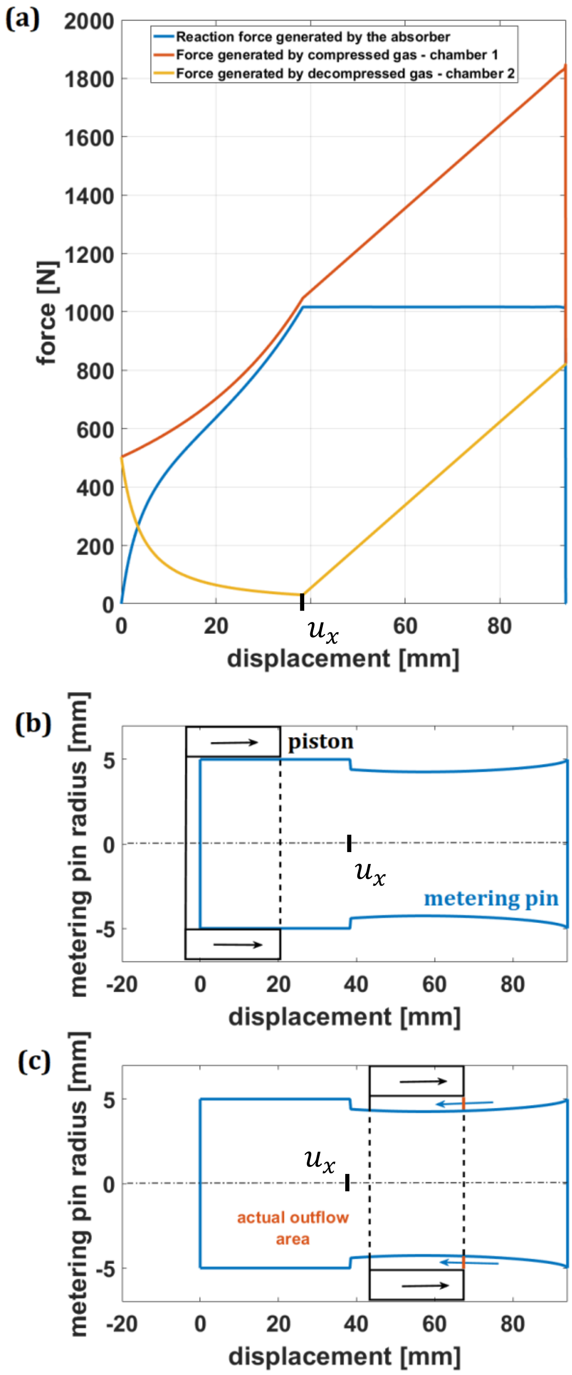


**Fig. 10. (a) optimal force response of pneumatic double-chamber shock-absorber, (b) piston movement relative to metering pin during first phase of operation – no gas release, (c) piston movement relative to optimally shaped metering pin during transfer of the gas between chambers.**

The procedure of determining the optimal valve area $A_v(u)$ is based on the solution of inverse dynamics problem and it is not presented in this paper which is aimed at development of single reconfiguration method for adaptation to different impact conditions. More information about applied method can be found in [12-14].

Numerical results concerning double-chamber shock-absorber have been obtained for the object of the mass $M$ equal to 10 kg and initial velocity $v_0$ of 4 m/s. Parameters of the shock-absorber are collected in Tab. 2.

**Table 2. Parameters of analyzed system equipped with double-chamber shock-absorber.**

| $M$ [kg] | $v_0$ [m/s] | $p_0$ [kPa] | $T_0$ [K] |
|---|---|---|---|
| 10 | 4 | 400 | 293.15 |
| $L$ [mm] | $\emptyset D$ [mm] | $u_0$ [mm] | $\emptyset d_h$ [mm] |
| 100 | 40 | 6 | 10 |

In order to propose a relevant mechanism providing single reconfiguration of the system for adaptation to predicted impact conditions, the shape of metering for different masses of the amortized object and different initial velocities was calculated and presented in Fig. 11.

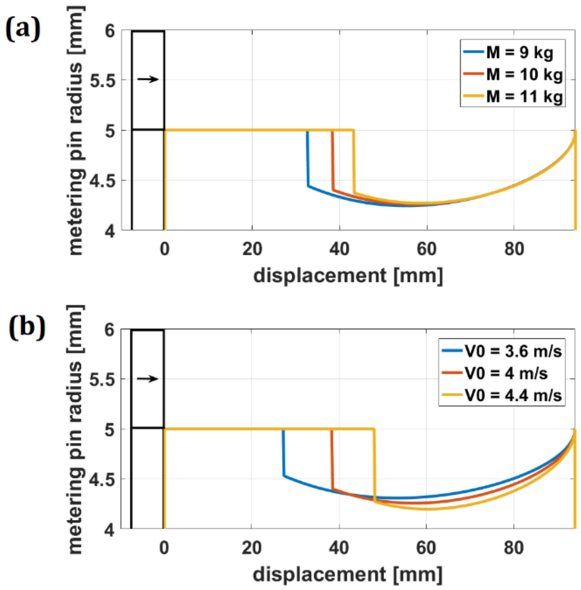


**Fig. 11. (a) optimal shapes of metering pin for different masses of amortized object, (b) optimal shapes of metering pin for different initial velocities.**

The shape change of metering pin depends more on the value of initial velocity of decelerated object than on the value of object's mass. It is intuitive effect because energy that has to be absorbed and dissipated is a quadratic function of velocity and linear function of mass. The interesting fact is that for masses varied by $\pm 10\%$ about half of the metering pin shape is almost the same and the visible difference is caused by increase or decrease of compression distance. Change of initial velocity of the object results in completely different shape of metering pin.

### *2.3.2 Metering pin re-shaping for adaptation to different impact excitations*

In Fig. 12a the scheme of proposed adaptation mechanism is shown. In order to easily change the shape of metering pin, it should be divided into two main parts:

- a ring which can move along metering pin axis and in result it ensures adjustment of the compression distance,
- a core of metering pin which should be designed as a morphing structure which is able to change its external shape.

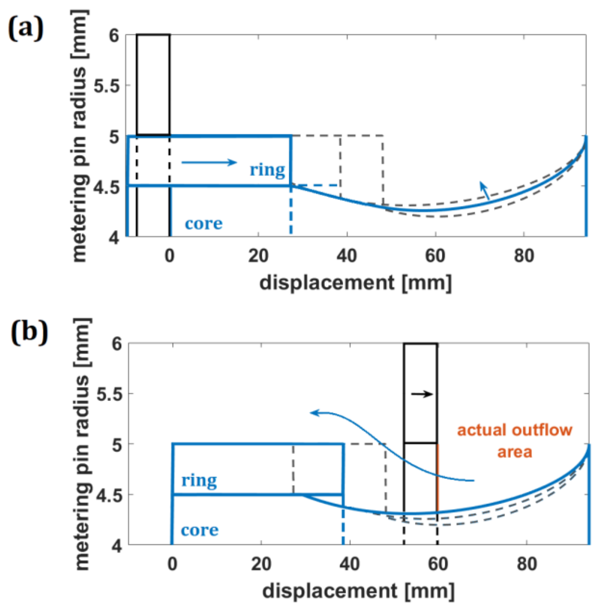


**Fig. 12. (a) scheme of the mechanism for adaptation of metering pin shape, (b) gas flow between chambers during second phase of system operation.**

Appropriate position of the ring ensures change of compression distance, which plays a significant role because it relates to the level of reaction force that should be maintained possibly constant during second phase of the impact absorption process. If the gas flow between chambers start too early, probably a part of impact energy will not be dissipated and the piston will hit the absorber bottom. In contrast, if gas flow start too late, the objective of absorber optimization (minimization of the reaction force) will not be even approximately fulfilled.

In Fig. 12b the operation of adapted system is shown. In presented example the compression distance was lengthened due to displacement of the ring and the shape change of metering pin core.

### 2.3.3 Simplified adaptation strategy

In this section, similarly as for single-chamber shock-absorber the analyses of simplified adaptation technique of metering pin is provided. In Fig. 13. the force responses of the absorber excited by the impacts defined by 10% higher values of the object mass $M$ and initial velocity $v_0$ are shown. In case of higher mass value the adaptation of compression distance by the move of ring and no change of the core shape leads to the response close to optimal. In contrast, the increase of initial velocity causes the necessity of shape adjustment of metering pin core.

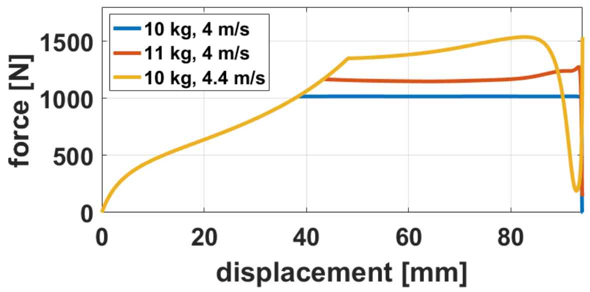


**Fig. 13. Force response of double-chamber shock-absorber in case of 10% higher values of the mass or initial velocity – only compression distance adapted.**

## 3 Conclusions

The presented research was aimed at development of high performance pneumatic shock-absorbers which can be used in aeronautical applications. Adaptive capabilities of proposed absorbers have been revealed and simplified adaptation mechanisms were discussed. The obtained response of proposed absorbers is significantly better than response of typical passive dampers with constant valve opening. Moreover, the performance achieved during system adaptation to predicted impact conditions is comparable with performance of smart semi-active devices controlled in real-time. The significant advantage of the proposed solutions is simplicity of their construction and possibility of fail-safe design. The presented general approach to the design of semi-passive pneumatic devices can be applied for elaboration of other types of fluid-based absorbers.

In particular, the following content was presented in the paper:

- elaboration and analyses of adaptation techniques for semi-passive absorbers – single-chamber as well as double-chamber device,
- proposal of simplified adaptation mechanisms and investigations of their influence on the system response,
- experimental study concerning operation of the single-chamber pneumatic shock-absorber.

Further research will concern development and practical implementation of dedicated mechanisms serving for adaptation of the absorber by means of single system reconfiguration. In addition, the author will make an effort to meet the requirement of fail-safe design.

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## References

[1] Ghiringhelli G L. Testing of semi-active landing gear control for a general aviation aircraft. *AIAA Journal of Aircraft*, Vol. 37, No. 4, pp 606-616, 2000.

[2] Jankowski Ł, Mikułowski G. Adaptive landing gear: optimum control strategy and improvement potential.

*Proc of the Int Conf on Noise and Vib Eng*, Leuven, Belgium, 2006.
[3] Batterbee D C, Sims N D, Stanway R, Wolejsza Z. Magnetorheological landing gear: a design methodology. *Smart Mater Struct*, Vol. 16, pp 2429-2440, 2007.
[4] Baruh H, Elsayed E A. Experimental design of a folded-structure energy-absorption system. *Int J Mater and Prod Tec*, Vol. 56, No. 4, pp 341–362, 2018.
[5] Wang H, Rui Q, Hong H, Li J. *Airdrop Recovery Systems with Self-inflating Airbag: Modeling and Analysis*. 1st edition, National Defense Industry Press, 2017.
[6] Mróz A, Holnicki-Szulc J, Biczyk J. Prestress accumulation–release technique for damping of impact-born vibrations: application to self-deployable structures. *Math. Probl.* Eng, Vol. 2015, 720236, pp 1-9, 2015.
[7] Jankowski Ł, Graczykowski C, Pawłowski P et al. Adaptive Self-Protection against Shock and Vibration. *Adv Sci Tech*, Vol.101, pp 133-142, 2017.
[8] Federal Aviation Regulations (FAR), Part 23 – Airworthiness Standards: Normal, Utility, Acrobatic and Commuter Category Airplanes.
[9] Mikułowski G, Jankowski Ł. Adaptive Landing Gear: optimum control strategy and potential for improvement. *Shock Vib*, Vol. 16, No. 2, pp 175-194, 2009.
[10] https://www.army.mil/article/178928/647th_quartermaster_co_jpads_operations_on_target, 29.06.2018.
[11] Mikułowski G, Wiszowaty R. Pneumatic Adaptive Absorber: Mathematical Modelling with Experimental Verification. *Math. Probl.* Eng, Vol. 2016, 7074206, pp 1-14, 2016.
[12] Faraj R, Graczykowski C, Holnicki-Szulc J. Adaptable pneumatic shock-absorber. *J Vib Control*, under review, 2018.
[13] Graczykowski C. Mathematical models and numerical methods for the simulation of adaptive inflatable structures for impact absorption. *Comput Struct*, Vol. 174, pp 3-20, 2016.
[14] Graczykowski C, Faraj R. Development of control systems for fluid-based adaptive impact absorbers. *Mech Syst Signal Pr*, under review, 2018.

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