Method of impact energy dissipation by the use of the pneumatic impact absorber with a piezo-valve.

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ABSTRACT: Presently, the important trend of "greening" the modes of transport is widely observed worldwide. One of the serious air-transport problems is the necessity of expensive recycling of degraded technical fluids, e. g. hydraulic oil, which is utilized in a wide class of air-vehicles being currently in service. Moreover, an important disadvantage of the hydraulic installations in the aeronautic vehicles is their large weight. To overcome these problems (in the field of aircraft undercarriages) a new type of shock absorber has been proposed, which eliminates the usage of the hydraulic fluid. The device utilizes a gas cylinder with a piston equipped with a fast actuated valve in order to control the reaction force of the absorber in real-time. This paper presents a study on an impact energy dissipation method by the use of the pneumatic impact absorber and the results of an experimental verification of the concept based on a technical demonstrator of such device (a shock absorber for a landing gear fabricated for an UAV). The study focuses on the energy absorbing capabilities of the device. A landing gear shock absorber is used as an example, but the general idea of the device is considered to be useful in other fields of application.

1 INTRODUCTION

Pneumatic absorbers (e.g. protective air bags) are incorporated in some methods of minimizing the contact force between an impacting body and the obstacle during a collision. In classical solutions dedicated to the dissipation of the kinetic energy of the impacting body, no adaptive control of braking force is applied (Harris Piersol 2002, Conway 1958). However, in some applications it is necessary to tune the level of the force during the process, in order to minimize its long term destructive influence (Mikułowski Holnicki-Szulc 2007). The techniques proposed previously, usually incorporated advanced fluids, which are expensive, heavy and difficult to recycle. Therefore, a new technique of the control of the deceleration process was proposed (Mikułowski et al. 2008). The adaptive impact absorber consisted of a cylinder with a piston and a piezo-valve in a by-pass configuration. The present research was focused on an improved solution with the piezo-valve positioned in the piston. The intensity of the gas flow through the valve in the piston was controlled in order to achieve the optimum deceleration level. The piezoelectric actuator was used to ensure sufficiently quick opening and closing of the valve. The advantage of the proposed semi-active approach is the decrease of the peak braking force in comparison to the passive braking of the impacting object. Furthermore, the semi-active control allows to adapt the behaviour of the device to the predetermined level of the impact energy and therefore to optimize the braking process. Possible applications for the device are rail cars, landing gears or precise docking systems.

2 CONDUCTED RESEARCH

The presented investigation was divided into three phases: a) problem definition, numerical analysis and determination of design requirements, b) development and verification of the piezo-actuated valve, c) development and tests of the adaptive absorber with the valve. At the first stage, the concept of the valve actuated by piezoelectric stacks was developed and numerically proven. On the basis of numerical simulation the piezo-valve and absorber were designed and fabricated. The following studies were devoted to testing the devices on dedicated laboratory stands.

3 SIMULATION OF ADAPTIVE PNEUMATIC LANDING GEAR

Numerical model of adaptive pneumatic absorber was developed and analyzed in previous paper by authors (Mikułowski et al. 2009). The model utilizes the assumption of uniform distribution of gas parameters in each chamber and analytical model of the gas flow through controllable valve. The proposed model enables to conduct simulations of the process of energy dissipation and to test various strategies of valve opening.

The aforementioned model was utilized to design adaptive pneumatic landing gear intended to be applied in UAV, i.e. to find optimal geometry of the absorber, optimal initial pressure and required properties of the valve. The initial data for the design of landing gear included:

- mass of the UAV: $M = 8{,}5kg$, maximal touchdown velocity: $V_0 = 3{,}3m/s$
- maximal admissible vertical deceleration during landing: $a_{\max} = 70m/s^2$
- maximal overpressure in compressed chamber of the absorber: $p_2^{\max} = 15atm$

Basic parameters of the adaptive absorber were determined by using balance of energy of the landing object and conditions of static equilibrium of the system after landing. The following parameters were obtained:

- length of the absorber: $h_0 = 0{,}11m$, length of the compressed chamber: $h_{02} = 0{,}095m$
- cylinder diameter: $d = 32mm$, piston rod diameter: $d_T = 12mm$
- initial pressure in absorber chambers: $p_0 = 6atm$

Further, thermodynamic part of the model was utilized to determine required parameters of the controllable valve :

- maximal pressure difference for which the valve remains airtight: $\Delta p = 8{,}5atm$
- maximal required mass flow rate : $q_{\max} = 14{,}8g/s$ (corresponding pressure difference: $\Delta p = 7{,}8atm$, corresponding upstream pressure $p_2 = 13{,}2atm$).

In the following step, numerical model of pneumatic landing gear was developed and simulations of the landing process were conducted, see Fig.1.

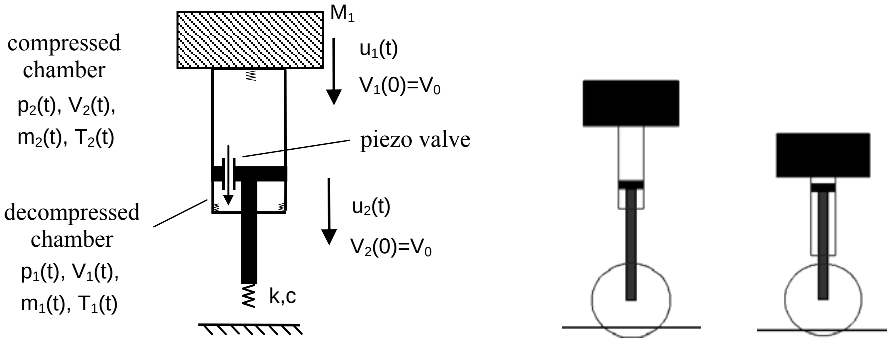

Figure 1 a) Considered model of adaptive pneumatic landing gear, b) Visualization of the landing process: intermediate and final stage of landing

Two control strategies were implemented:

- adjustment of time instant and level of constant valve opening
- real-time control of the valve opening during landing (Pulse Width Modulation)

In the first strategy the valve remains closed during the initial stage of landing in order to enable a fast increase of the force generated by the absorber. The time of valve opening and flow resistance coefficient (representing valve opening) are adjusted by means of optimization procedure which minimizes force generated by the absorber, taking into account the constraint imposed on maximal absorber stroke.

In the second strategy the valve also remains closed during the initial stage of the process. Optimal level of the force generated by the absorber is determined by using energy conservation law, which indicates the equality of potential and kinetic energy of the landing object and energy dissipated by the absorber and the wheel.

$$\Delta E_{K1} + \Delta E_{P1} + \Delta E_{K2} + \Delta E_{P2} = D_{ABSORBER} + D_{WHEEL}$$

Alternatively, the time of valve opening can be determined from the kinematical condition:

$$a_1(t) = \frac{V_1^2(t)}{2(d_{\max} - (u_1(t) - u_2(t)))}$$

where $d_{\max} = 0{,}085m$ is assumed and denotes maximal stroke of the absorber. In further part of the landing process the valve is simultaneously opened and closed in order to maintain constant force generated by the absorber. The signal that controls valve opening I_n depends on actual value of force generated by the absorber:

$$I_n = 1 \quad \text{if} \quad F > F_{OPT} + \Delta F_{TOL}$$

$$I_n = 0 \quad \text{if} \quad F < F_{OPT} - \Delta F_{TOL}$$

$$I_n = I_{n-1} \quad \text{if} \quad F_{OPT} - \Delta F_{TOL} < F < F_{OPT} + \Delta F_{TOL}$$

where: ΔF_{TOL} is assumed tolerance of the force level. The above strategy enables to stop the landing object by using a minimal level of the force generated by the absorber and therefore with minimal deceleration of the landing object. During the final stage of the process, when velocity of the landing object is relatively small, the force generated by the absorber is gradually reduced in order to obtain the state of static equilibrium of the landing object. The results are depicted in Fig. 2 and Fig. 3.

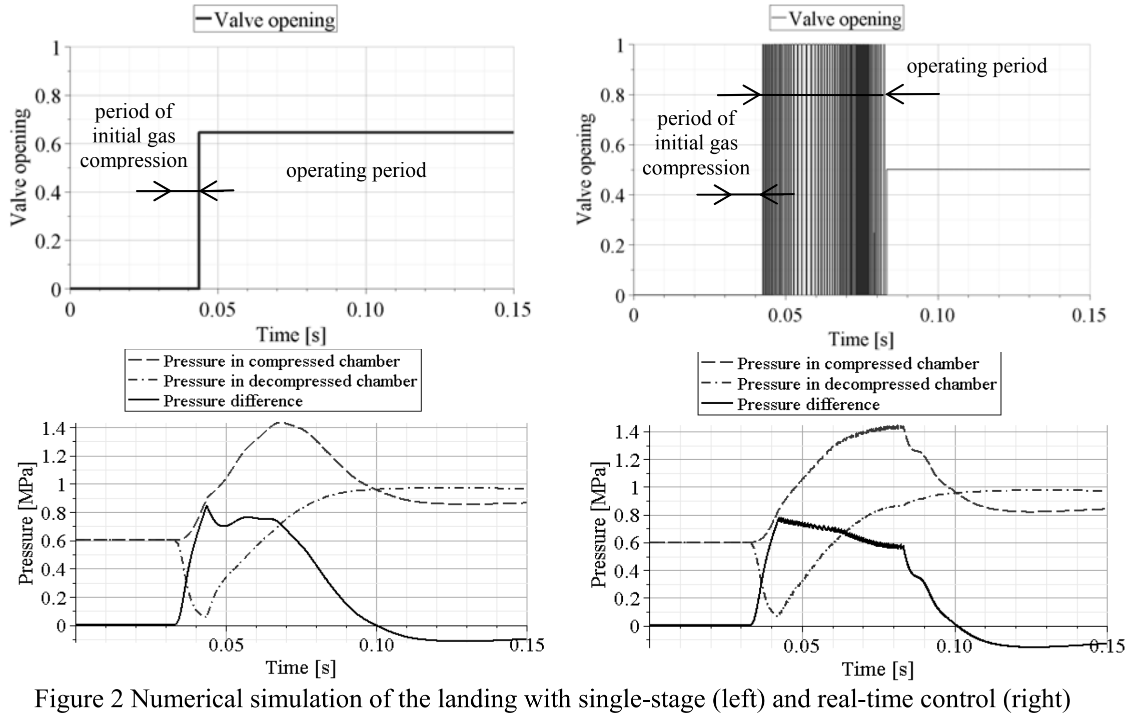

Figure 2 Numerical simulation of the landing with single-stage (left) and real-time control (right)

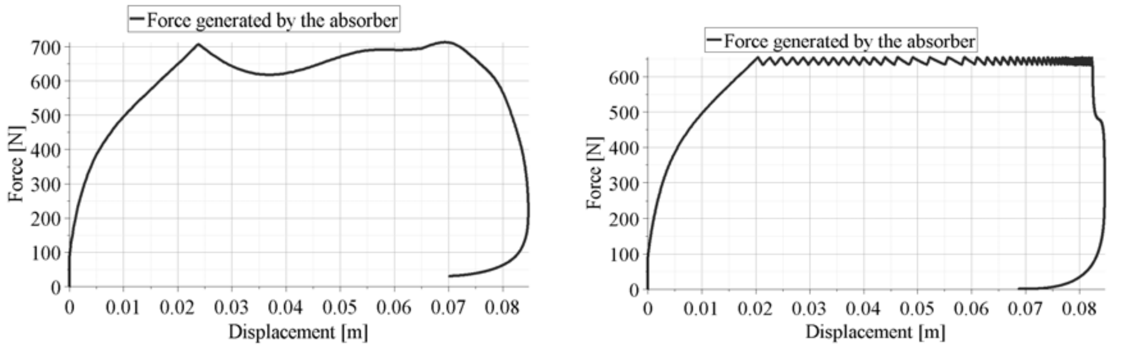

Figure 3 Force generated by the absorber with single-stage (left) and real-time control strategy (right)

	Single-stage control	Real-time control
Maximal generated force	712N	654N
Maximal deceleration	79,19m/s^2	71,94 m/s^2
Absorber efficiency	83,9%	**90,4%**
Landing gear efficiency	72,6%	**76,7%**

Table 1 Comparison of quantitative results obtained for adaptive pneumatic landing gear with single-stage and real-time control strategy

4 TESTS OF PIEZO ACTUATED VALVE

The core element of the Adaptive Impact Absorber (AIA) is a piezo-valve – shown in cross-section view in the two pictures below (Fig. 4). This valve enables the flow of fluid between two sides of the piston inside the cylinder of the absorber. When the gas flow ratio is controlled, the reaction force of the absorber could be adjusted.

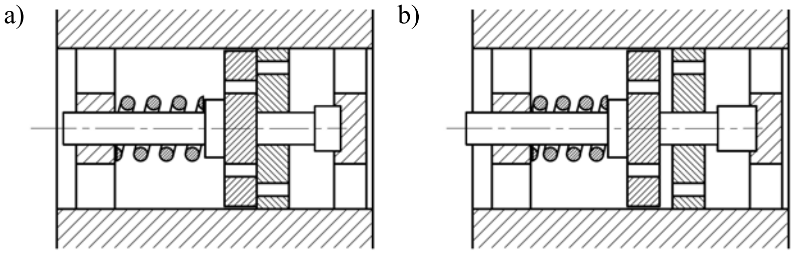

Figure 4 Cross-sectional view through the valve: a) closed, b) opened.

Fig. 4 a) depicts the piezo-valve schematically in closed (a) and opened (b) position. Two plates with holes are tight when they are aligned. Moving one plate apart from the other one enables the flow of fluid through the valve. To ensure small dimensions and a compact structure of AIA, it is advisable to locate the valve in the piston of the absorber. This results in dimensional constraints of the valve. Short operating time also requires the use of the piezo-stacks for opening and closing the valve. As it is shown in the pictures, the opening of the valve is achieved by elongation of the piezo-stack (marked on the right hand sides of both pictures) and closing is done by the spring connecting one of the plates with housing.

To predict the value of the kinetic energy of the impacting body that could be efficiently dissipated by the use of the absorber equipped with the piezo-valve, a set-up was developed (Fig. 5) consisting of two containers (Iwaszko 1999, Beater 2007), three pressure sensors p_0, p_1, and p_2, three thermocouples T_0, T_1, and T_2, pressure regulator and investigated piezo-valve. In experiments, the valve was examined under a variety of flow conditions in order to acquire its characteristics.

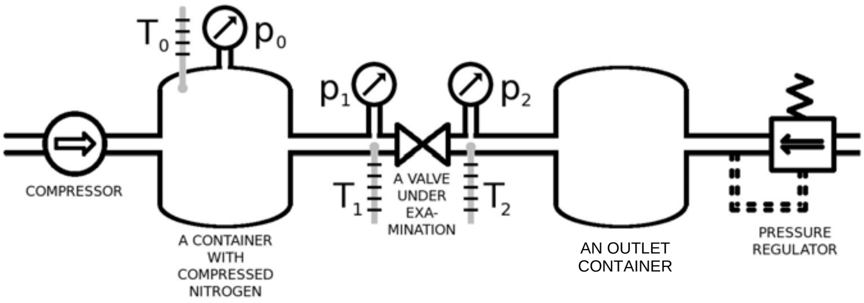

Figure 5 Scheme of the set-up applied to examination of the valve.

The dependencies of the mass flow rate in the function of inlet pressure p_1 and pressure drop on the valve p_1-p_2, were obtained (Fig. 6). The presented surface was obtained by spanning it on the curves obtained in the series of experiments. The presented result indicates that mass flow rate depends on the pressure difference on the valve and on inlet pressure level.

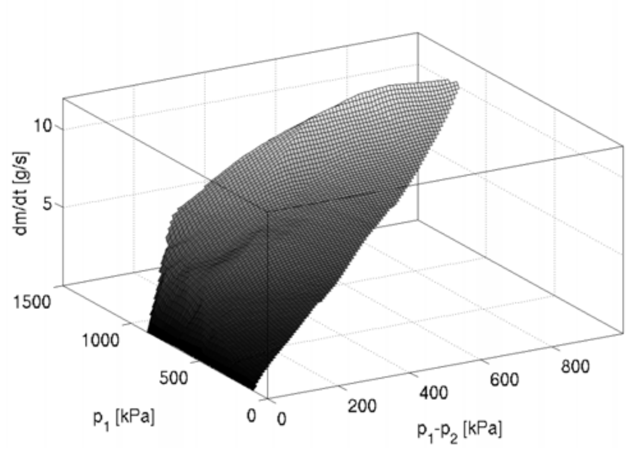

Figure 6 Mass flow rate dependency in the function of the inlet pressure p_1 and the difference between the inlet and outlet pressures (p_1-p_2).

5 EXPERIMENTAL VERIFICATION ON THE DROP TEST STAND

During the third phase of the investigation, the outcomes of the numerical computations were verified versus the results of experiments conducted with a model of adaptive landing gear (Fig. 7). The experimental program for the presented part of the research was aimed at confirmation of the design assumptions and correctness of the packaging concept. The development of the optimal control strategy for the device was out of the scope of the presented study.

Figure 7 Drop-test stand with adaptive absorber

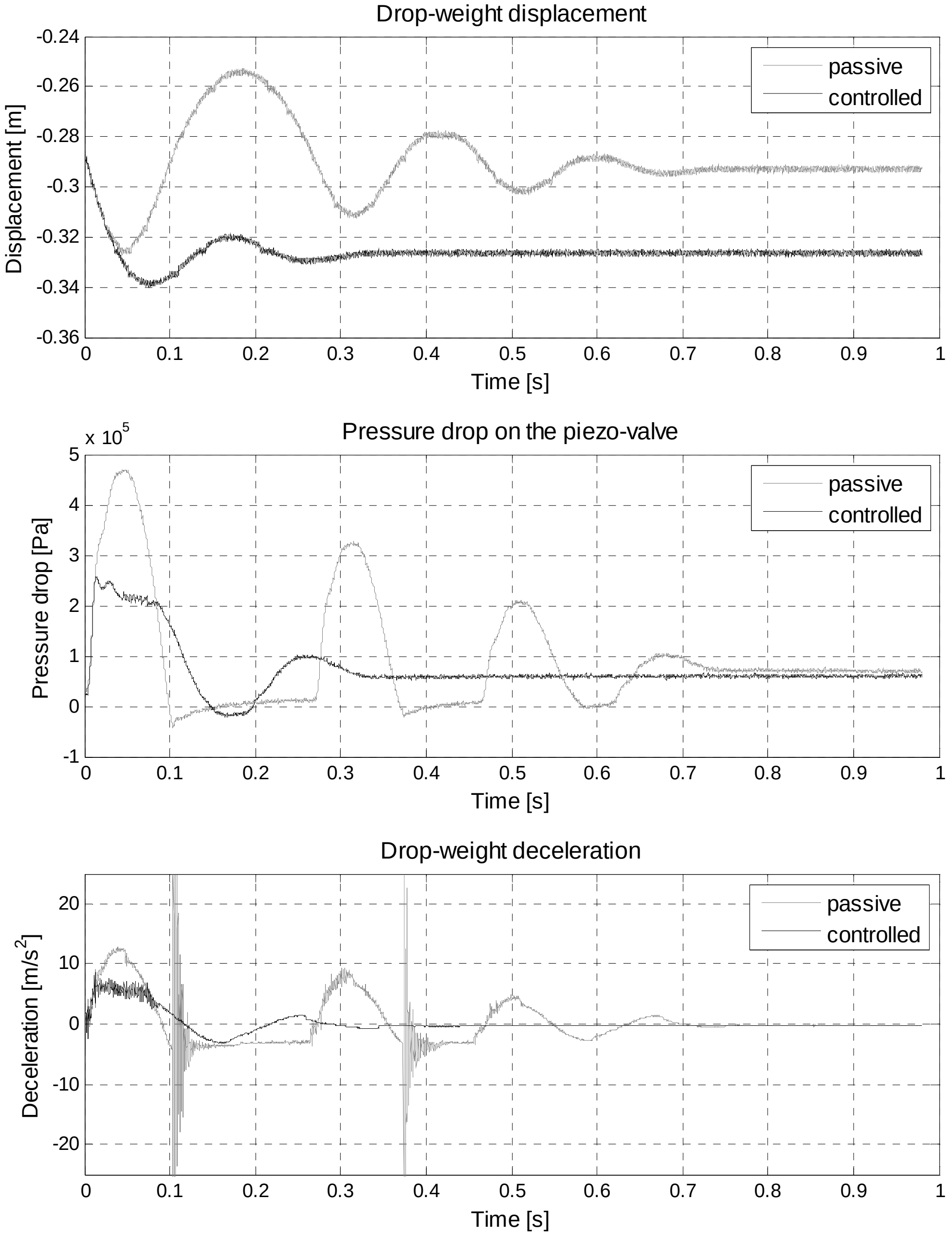

Figure 8 Comparison of two modes of the absorber operation: passive and active.

At the presented stage of the investigation, the drop-test stand was used with the absorber mounted to the drop-weight of 9 kg at initial height of 0,1 m, which corresponds to the initial velocity 1,4 m s^{-1}, where the impact energy was estimated for 8,3 J. The experimental procedure included two stages. The first, where the absorber operated as passive pneumatic device with the valve closed during impact. At the second stage the valve's operation was controlled in order to maintain a predefined value of pressure difference between the absorber's chambers and therefore to maintain the reaction force of the absorber on the predetermined level. In both cases the initial gas pressure in the absorber was 450 kPa and the predefined level of expected pressure difference was 210 kPa. The data acquisition setup included: gas pressure sensors inside the absorber's chambers, accelerometer fixed on the drop-weight, displacement sensor indicating position of the drop-weight in reference to the base plate of the stand.

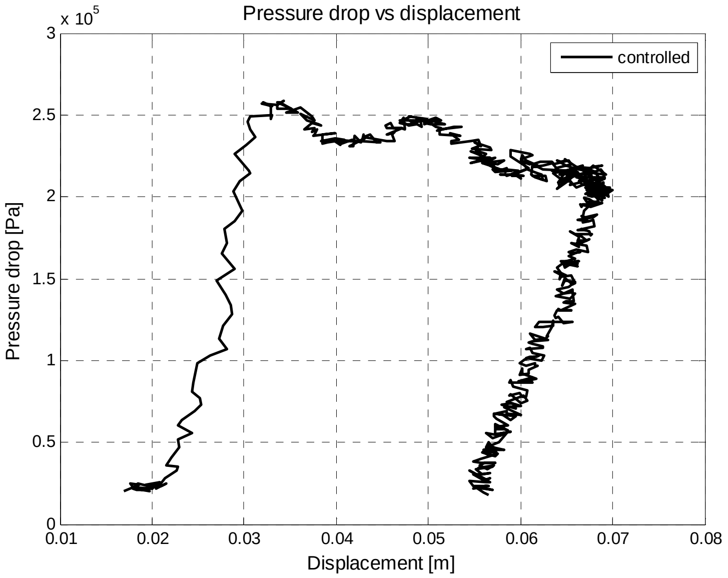

Figure 9 Pressure difference on the piezo-valve during the impact loading in the domain of the piston stroke.

The results of the absorber's operation are presented in Fig. 8. The graphs demonstrate evolution of three parameters (drop-weight displacement, gas pressure difference, drop-weight deceleration) in time domain for two cases: passive and controlled. In the first tested case, when the absorber had almost ideal elastic characteristic (except the friction losses) three bounces are demonstrated at 0,1 s, 0,27 s and 0,58 s time instants. In comparison, 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 0,35 s. Also the control procedure introduction decreased the maximum deceleration level of the drop-weight from 12 m/s^2 to 8 m/s^2.

Fig. 9 depicts the pressure difference between the absorber's chambers in the domain of the landing gear deflection during the impact loading. The efficiency of the landing gear calculated in accordance to the method proposed by (Conway 1958, Currey 1988) was 71% in the presented trial. The value is in agreement with the numerical predictions presented in Table 1 independently on the impact energy.

6 CONCLUDING REMARKS

The presented study was divided into numerical and experimental phases. Conducted numerical experiments indicated that:

- Conducted simulations confirmed the feasibility of proposed concept of dissipating kinetic energy of the landing object by means of double-chamber pneumatic absorber
- Results of simulations indicated that both proposed control strategies allow to avoid rebound of the landing object and to obtain favorable, almost constant level of force generated by the absorber
- Real-time control of valve opening enables to obtain unprecedented very high efficiency of the absorber which exceeds 90%.

The results of experimental research indicated that:

- The maximum flow rate measured on the fabricated piezo-valve was predicted on the stage of numerical design.
- The absorber under impact loading responds fast enough to be controlled in real-time (0.5 kHz update rate).

- The measured efficiency of the landing gear was 71% and was in agreement with the numerical predictions.
- The example application in this study was landing gear shock absorber, although the device is considered to applicable in other fields.

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