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# An Adaptive Pneumatic Shock-Absorber with a Piezo-valve under Harmonic Loading

**Grzegorz MIKUŁOWSKI, Rafał WISZOWATY***
Institute of Fundamental Technological Research
Pawinskiego 5B, 02-106 Warsaw, Poland
gmikulow@ippt.pan.pl, rwisz@ippt.pan.pl

## ABSTRACT

An adaptive pneumatic shock absorber with a piezo-valve was designed for real-time impact energy dissipation. The device was a piston-cylinder type with a fast actuated (less than 2 ms) piezo-valve positioned inside the piston. The principle of operation of the device was to keep the reaction force on a predefined level by means of managing of the gas flow between the internal chambers of the shock absorber. The internal chambers were defined by spaces in the cylinder on both sides of the piston. The proper control of the valve, which connected the two chambers, allowed to adjust the instantaneous pressure drop between them. The pressure drop was a decisive factor that influenced the total reaction force of the shock absorber.

The presented investigation was conducted using the MTS Test System experimental setup in order to perform measurements of stiffness and viscous effects in the domain of frequency of excitation. The shock absorber under investigation was fixed between a stiff base and a piston rod of the hydraulic actuator that was used for the mechanical excitation.

The conducted set of experimental tests included measuring of the following set of quantities: frequency of harmonic excitation, reaction force of the absorber, displacement of the piston, velocity of the piston, gas pressure in both chambers.

The presented research was focused on characterization of the response of the device to harmonic excitation. The study was aimed at identification of limits of the device in terms of its controllability and adaptability.

**Keywords:** *adaptive devices, Adaptive Impact Absorption, AIA, pneumatic shock-absorbers, piezo stack, piezo-valve.*

## 1 INTRODUCTION

There exists a class of applications that are endangered to the repetitive shock loadings. Examples of such devices are airframes, in which chassis absorb and dissipate the energy of impact within each touchdown. The durability of these structures is the key factor for the safety of the users.

At the same time more and more strict regulations force to look for engineering solutions that do not influence the pollution of the environment. For that reason it is reasonable to investigate designs that eliminate medium that are difficult to recycle. It is widely observed movement to limit usage of toxic liquids in aerospace industry in order to ”green” this mode of transport. One of the potential possibilities of elimination of the liquids is using shock absorbers based on gas. The classical gas shock-absorbers have 50 % efficiency which is highly inefficient, because similar size



* Corresponding author

oleo-pneumatic absorbers have 80% efficiency [1]. In this work we studied a gas shock absorber with an active control of the pressure inside, which improved the efficiency of the gas absorber to 90 %.

The adaptive shock absorber was equipped with a real time controlled piezoelectric valve that was able to manage the gas flow between internal chambers of the absorber and therefore to introduce adaptive impact energy absorption process [2].

This paper introduces the idea of impact energy absorption with the gas shock absorber, discusses the control system for the device and presents results of testing of the device under harmonic excitation.

## 2 METHOD OF IMPACT ENERGY DISSIPATION

The realization of adaptive dissipation of kinetic energy of an impacting body, was conducted with the developed device called Adaptive Impact Absorber (AIA). The element that made this device different from passive shock absorbers (having cylinder and the piston) was a piezo-valve placed inside the piston. The presence of this valve enabled a controlled flow of the fluid between two sides of the piston (Fig. 1). The medium filling the cylinder was nitrogen.

The AIA was equipped with two pressure transducers that had analog outputs. The outputs were fed forward to a control unit which computed the actual value of the force acting on the piston (Fig. 1) – a reaction force. The reaction force of AIA was the sum of forces acting on the piston and piston rod in their axis (including friction force). Dependently on the value of the force, the output of the controller circuit was driven high or low – in order to open or close the valve respectively.

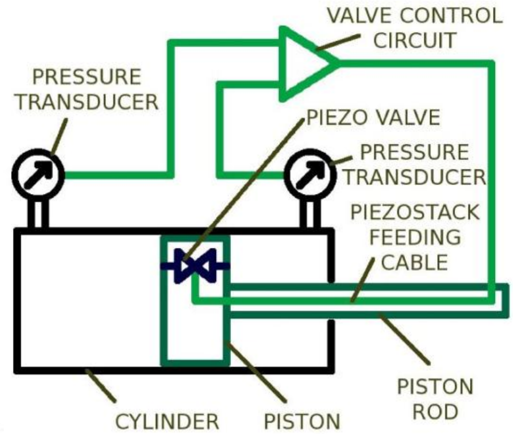


*Figure 1 - Schematic diagram of an Adaptive Impact Absorber*

While the AIA served as an impact energy absorber, it enabled to realize the predefined control strategy of the reaction force [3], which was optimized for minimization of the deceleration of impacting bodies. This strategy consisted of two stages (Fig. 2.):

1) initial compression of the gas to a predefined level, by moving the piston inside the cylinder while the valve was permanently closed,
2) deflecting the piston inside the cylinder while the valve openings were updated to keep a constant value of the reaction force;

The reaction force value maintained during the second stage of the controlled period was set on a level, that allowed utilization of the whole admissible piston stroke inside the cylinder. The value of the impacting body initial kinetic energy was the necessary information to estimate the parameters for the control algorithm and it must have been estimated before the impact occured.

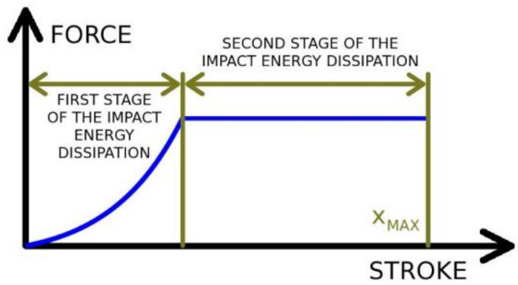


*Figure 2 - Two stages of the kinetic energy dissipation with the use of AIA.*

## 3 STRUCTURE OF THE DEVICE

The pneumatic shock absorber – AIA is presented in Fig. 3. Maximum stroke of the piston of this device was 100mm and it was equipped with two ball joints.

*Figure 3 - The pneumatic adaptive shock absorber.*

The valve placed inside the piston was equipped with the piezoelectric actuator [2]. The actuator allowed to control the gas flow through the valve in order to regulate the reaction force value of the AIA. Opening, as well as closing of the valve within 1ms, enabled to apply a double-stage valve control strategy – the piezo-valve could have been either closed or fully opened.

The piezoelectric actuator was supported on the valve housing (Fig.4.) [4]. While the actuator elongated, it moved two plates having bores through and caused thereby shifting one plate apart from another. Presence of a gap between the two plates was necessary for gas to flow through the valve because the bores in both of the plates were located in a way that they did not overlap mutually when plates were aligned. When the actuator contracted to its initial longitude, the moveable plate was shifted back by the spring which resulted in closing of the valve.

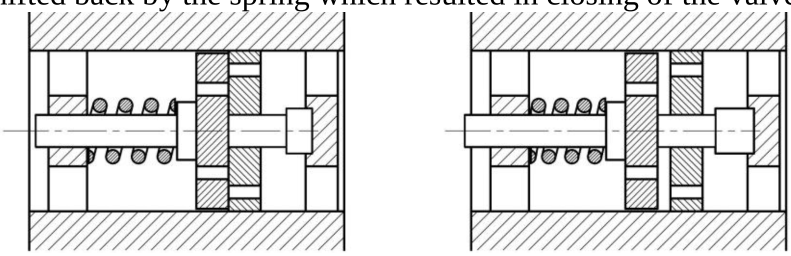

*Figure 4 - Simplified cross section views of the closed and opened valve.*

## 4 CONTROL ALGORITHM AND THE CONTROLLER

The scheme of the algorithm implemented on the controller is depicted in Fig. 5. Two pressure transducers, which were used to measure the pressures inside the cylinder, were connected to a 12-bit A/D converter that was integrated with MCU unit with ARM Cortex-M3 core. This converter could have operated with the frequencies up to 200 kHz and it was equipped with a multiplexer that enabled to manage with up to 8 input signals. The system enabled keeping constant value of the reaction force of the absorber while moving the piston.

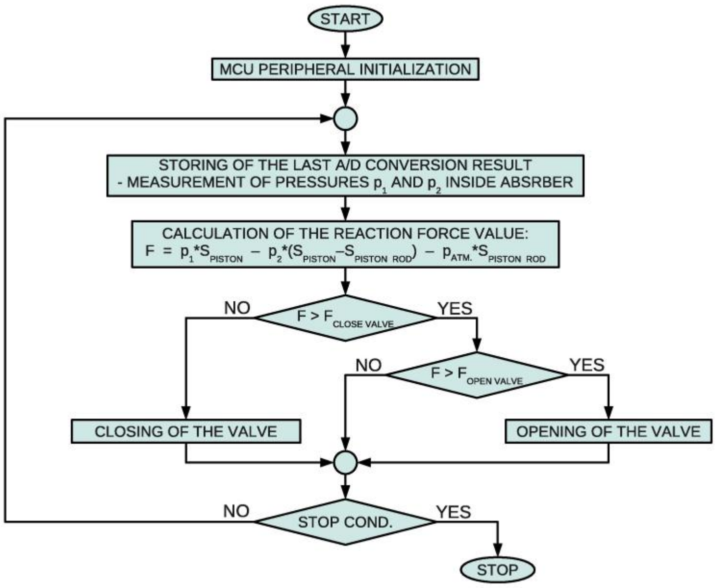


*Figure 5 - Algorithm realized in interrupts on MCU unit.*

After initialization of the counter/clocks, A/D converter and other peripherals, the interrupts coming from them were regularly activated. Inside the interrupt handler, at the first step the results of the last A/D conversion were stored in variables symbolically denoted in Fig. 5 as $p_1$ and $p_2$. These values were referred to pressures in the cylinder. After that the reaction force was computed – it depended on these two values $p_1$ and $p_2$, area bounded by cylinder walls in its cross-section view (denoted by $S_{PISTON}$), and the area of the outline of cross section of the piston rod (denoted by $S_{PISTON\ ROD}$). The following areas were depicted in Fig. 6.

Also atmospheric pressure $p_{ATM}$ had a contribution to the force acting on the piston rod along its axis.

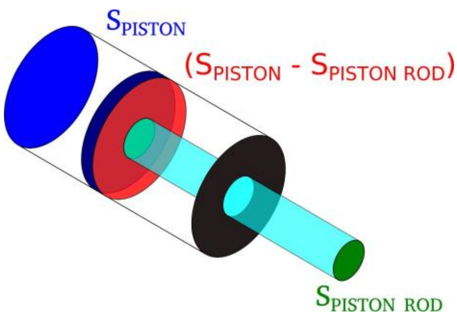


*Figure 6 - Schematic view of the absorber consisting of cylinder with the piston. On one side of the piston the gas inside the cylinder is acting on it at area $S_{PISTON}$ and on the other side the gas is acting on the piston at area ($S_{PISTON} – S_{PISTON\ ROD}$).*

Next, the computed force was compared to two values ($F_{CLOSE\ VALVE}$, $F_{OPEN\ VALVE}$ ) and – dependently on the result of the comparison – the state on the peripheral output of MCU was driven high or low (what caused opening or closing of the valve). If the action had not been stopped manually after clearing the current interrupt, the next interrupt would have been generated and the sequence described above repeated.

The algorithm utilized in the system could work properly provided that pressure $p_2$ acting on the area ($S_{PISTON} – S_{PISTON\ ROD}$) of the piston is not greater than pressure $p_1$ acting on area $S_{PISTON}$ –

on the other side of it – and the resultant force caused by these two pressures was directed from the area filled with the gas having pressure $p_1$ to the area with pressure $p_2$. Such a situation could take place due to the difference between corresponding areas of the piston – $S_{PISTON}$ and ($S_{PISTON}$ – $S_{PISTON\ ROD}$) – on both sides of it. Opening of the valve inside the piston resulted then in increasing of the considered force instead of decreasing it. In the range of pressures occurring in the system these conditions could not appear.

To prevent the piezoactuator from a mechanical damage due to too steep edge in driving signal, output of the voltage relay (denoted by 6 in Fig. 7) were equipped with 33 Ω resistors. It caused that the rise time and the fall time of the driving signal was not shorter than 1 ms (when the piezo-actuator was connected to the output of the voltage rely). On the other hand, this time was sufficiently short to operate the valve quickly enough to keep the constant value of the reaction force under an impact conditions. The capacitance of the utilized piezo-actuator was equal to 7 µF.

## 5 TESTING EQUIPMENT AND THE TESTING PROGRAM

The developed pneumatic absorber was tested under cyclic excitation on a servo-hydraulic stand. The cyclic deflection of the absorber was carried out by means of MTS hydraulic actuator controlled by an electronic module with the data acquisition functionality [5]. The acquired data was: displacement of the piston, axial reaction force of the absorber.

The setup configured and applied for the investigation is depicted in Fig. 7.

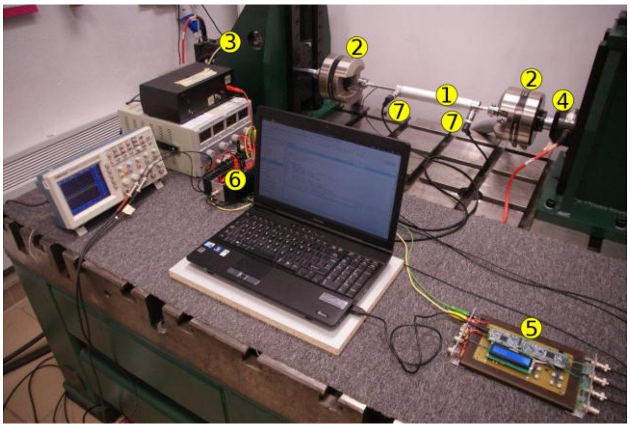


*Figure 7 -. Setup used during experiments.*

The setup consisted of the tested absorber (1) fixed to the force transducer (4) and, on the other side, to the hydraulic actuator (3) by means of two hydraulic grips (2). The piezo-valve mounted inside of the absorber (1) was connected through the voltage relay (6) to the controller (5) based on MCU unit. The gas pressures inside the cylinder of the absorber (1) were monitored with two pressure transducers (7). The signal of pressure difference calculated from the transducers (7) was utilized by the controller (5) or opening or closing the piezo-valve.

The testing program was conceptualized in order to examine the operability of the system, to test several working conditions and to determine the limits of the device's performance. The basis for the test was sinusoidal excitation with amplitude +/-40 mm. The parameters which were modified during the tests were: frequency of the excitation, initial gas pressure inside of the absorber, the value of the desired reaction force value. The frequency of the excitation had the following values: 1 Hz, 3 Hz, 5 Hz, which corresponded to the maximal values of the velocity as following: 0,26 m/s, 0,8 m/s, 1,3 m/s. The initial gas pressures during the tests were: 100 kPa, 300 kPa, 500 kPa. The desired reaction force values were: 100 N, 200 N, 300 N. For each test the initial temperature of the gas inside of the absorber was 24 deg C.

## 6 RESULTS OF THE TESTS AND DISCUSSION

Fig. 8 depicts the reaction force-displacement curves for the tests with the initial gas pressure value $p_0$ = 100 kPa where the frequency parameter was modified. As it is presented the device responded fast enough to maintain the demanded force level for all of the tested frequencies. The efficiency of the energy absorption defined after Currey [1] was 62 %.

Fig. 9 and Fig. 10 depict the reaction force-displacement curves for the tests with the initial gas pressure value $p_0$ = 300 kPa and 500 kPa where the frequency parameter was modified. The device responded correctly only under the frequency of excitation 1 Hz and 3 Hz. The curves acquired by the frequency 5 Hz indicated an uncontrolled rise in the value of the force which was caused by the limitation of the maximal mass flow rate on the valve for this conditions. The tendency was that the region of uncontrollable force was related to the frequency of excitation. The higher frequency and therefore higher velocity of the piston's movement induced higher requirement for the mass flow rate on the valve, which was not possible to be delivered in the considered range of the pressure difference. The efficiency of the energy absorption dependently on the value of initial pressure was appropriately 90 % and 91 % [6].

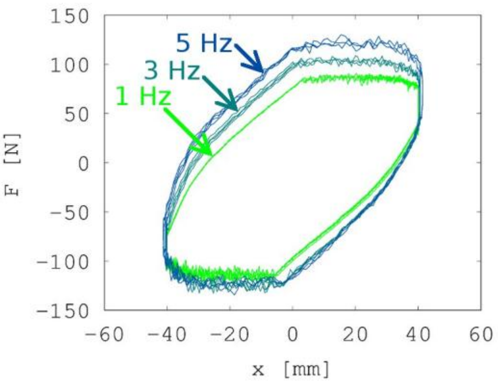


*Figure 8 – Reaction force of the absorber in the domain of piston's displacement, initial gas pressure p0=100 kPa, initial gas temperature T0 = 24 deg C.*

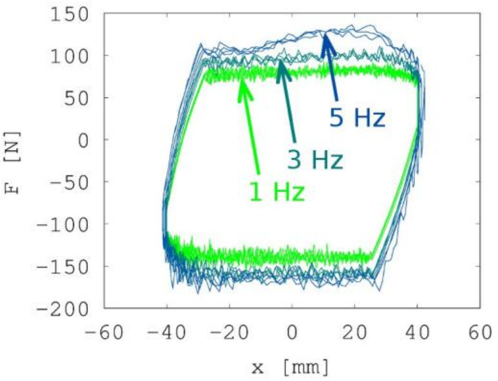


*Figure 9 - Reaction force of the absorber in the domain of piston's displacement, initial gas pressure $p_0$ = 300 kPa, initial gas temperature $T_0$ = 24 deg C*

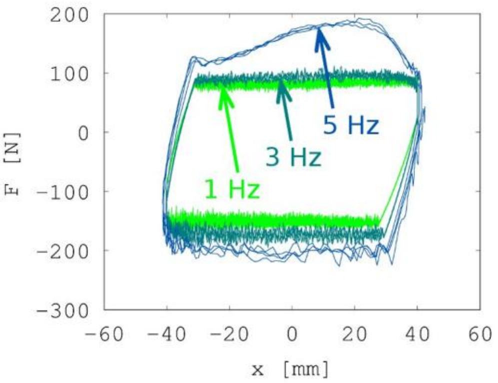


*Figure 10 – Reaction force of the absorber in the domain of piston's displacement, initial gas pressure $p_0$ = 500 kPa, initial gas temperature $T_0$ = 24 deg C*

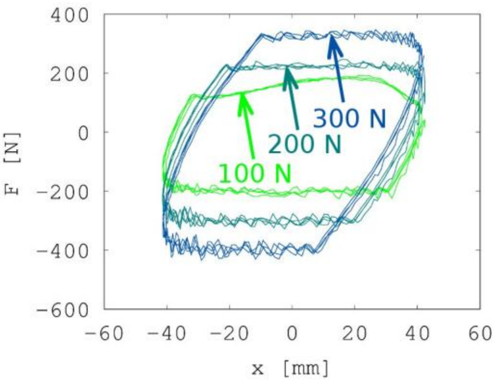


*Figure 11 – Reaction force of the absorber in the domain of piston's displacement for several reference levels, initial gas pressure $p_0$ = 500 kPa, initial gas temperature $T_0$ = 24 deg C*

Fig. 11 depicts three force-displacement curves acquired for three values of the desired reaction force levels: 100 N, 200 N, 300 N. The test was conducted with the initial pressure value $p_0$ = 500 kPa and the frequency of excitation was 5 Hz. The result acquired on the level of 100 N was characterised by a region where the force was not in the demanded range. The phenomenon was due to the fact that the mass flow rate on the valve was not sufficient. This effect was noticeable only during the compression of the device (upper part of the curve). During the extension of the device the effect did not occur. The reason for the phenomenon occurring was discrepancy in the desired pressure difference level between the both cases: compression and extension. The absorber was non symmetric and the required pressure drop in the compression phase was lower than in the extension phase. The lower pressure drop can provide not sufficient mass flow rate of the gas [7] what led to the inaccurate operation of the absorber. In comparison the curves 200 N and 300 N in Fig. 5 indicate the expected operation of the device, which is connected to the higher demanded levels of the pressure drop on the valve.

## 7 CONCLUDING REMARKS

- The designed controller allowed to maintain accurately the predefined values of the reaction force.
- For the tested range of excitations the pneumatic absorber was characterised by efficiency factor up to 90 %.
- The performance of the device is directly dependent on the value of maximal mass flow rate on the piezo-valve. The appropriate value of this parameter can be achieved only on a defined level of the pressure drop on the valve.

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