6th ECCOMAS Conference on Smart Structures and Materials
SMART2013
Politecnico di Torino, 24-26 June 2013
E. Carrera, F. Miglioretti and M. Petrolo (Editors)
www.smart2013.com

HIGH PERFORMANCE VALVES FOR ADAPTIVE INFLATABLE STRUCTURES WITH FLOW DRIVEN CONTROL

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Key words: adaptive impact absorption, inflatable structures, high performance valves

Summary. *The paper presents a concept of new adaptive valves, which can be applied in the Adaptive Inflatable Structures for impact absorption - high-performance membrane and bistable snap-through valve. The main idea behind those concepts is to employ fluid flow in order to assist actuation of the system.*

1 THE CONCEPT OF ADAPTIVE INFLATABLE STRUCTURES (AIS)

Currently applied passive safety systems are not equipped with any kind of control devices and they are in no way controlled. Their dynamic characteristics remains unaltered and thus it is well adjusted to actual loading only in a narrow range.

Increasing safety standards in crashworthy structural design require new, innovative solutions. One of very promising fields of research is related to systems of adaptive impact absorption (AIA) [1,2]. Such systems provide real-time adaptation to detected dynamic load, which results in optimal energy dissipation. Recent fast development of the material technologies and, in particular, development in the field of functional (smart) materials and electronic measurement and control systems had created new possibilities of practical applications of the AIA systems.

Figure 1: NASA Mars Pathfinder, helicopter emergency landing system REAPS

One of the most effective types of AIA systems are Adaptive Inflatable Structures (e.g. fenders, barriers, airbags – fig. 1), which contain sealed chambers filled with compressed gas and equipped with controllable inflators and discharge valves (AIS cf. refs. [3-4]).

The proposed concept is based on application of compressed gas and controlling its pressure as an effective methodology allowing for adaptation of energy absorbing structures (airbags, fenders, barriers) to actual impact loading. Adaptive Inflatable Structures contain sealed chambers filled with compressed gas and equipped with controllable inflators and discharge valves. Pressure adjustment relies on appropriate initial inflation of particular chambers and control of the gas flow between the chambers and outside the structure during the impact. Appropriate change of the actual value of pressure in different parts of the structure enables adaptation to dynamic loadings of various energy, amplitude and location.

2 HIGH PERFORMANCE VALVES

From the point of view of application of Adaptive Inflatable Structures one of the most important challenges is design and development of the high performance controllable valve. Existing structures do not include solutions that ensure a appropriately fast opening and closing of the discharge valves, which is required for realization of the optimal pressure control strategy. Currently applied proportional valves are usually characterized by small possible outflow, large total mass and large inertia of the moving parts. The group of high speed, single step discharge valves does not allow for optimal control of the airbag compression process.

Actively controlled, commercially available valves applicable for AIA systems can be divided into two groups: electromagnetic valves (e.g. by Rexroth) and smart material based valves (e.g. MRF devices by Lord or piezoelectric valves by Cedrat). Eliminating electro-magnetic valves as too slow for larger blocking forces and MRF valves as to heavy for many applications, the piezo-based valves have to be considered, where so-called piezo-motors are too slow. Finally, piezo-valves based on piezo-stacks or so-called Amplified Piezo Actuators (APAs with stroke amplifcation) are the best possible options to be applied in classical systems (fig. 2).

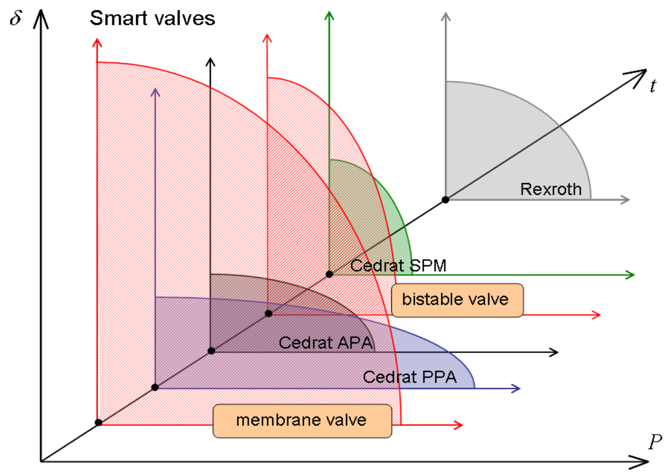

Figure 2: Comparison of valves' characteristics (P-blocking force, t-reaction time, δ-stroke).

From the point of view of optimal control strategy for adaptive pneumatic absorbers, it is necessary to provide fast increase of generated force in the initial phase of impact, followed by maintaining constant force level. Such strategy requires real-time control of valve opening. As it was shown in [4], a quasi-optimal energy dissipation can be achieved by application of a two-stage control strategy. The algorithm requires fast opening of the flow followed by closing of the discharge valve in the final stage of the process. This has to be done at precisely selected time instants.

The above mentioned control methodology can be effectively realised by the innovative, controllable valves presented in the paper: high performance valve which utilizes bistable snap-through effect and high performance membrane valve. The patent-protected operating principles of both valves are completely novel and substantially different from currently applied solutions.

2 HIGH PERFORMANCE BISTABLE VALVE

The controllable valve which utilizes bistable snap-through effect is equipped with two independent elastic shell elements with two stable configurations, which are aligned in the initial configuration such that the flow of the gas is totally blocked (fig. 3). Opening of the valve is performed by controllable snap-through of the first shell element which causes creation of the flow channel. Closing of the valve is performed by controllable snap-through of the second shell element which causes alignment of the both shells and blocking the gas flow.

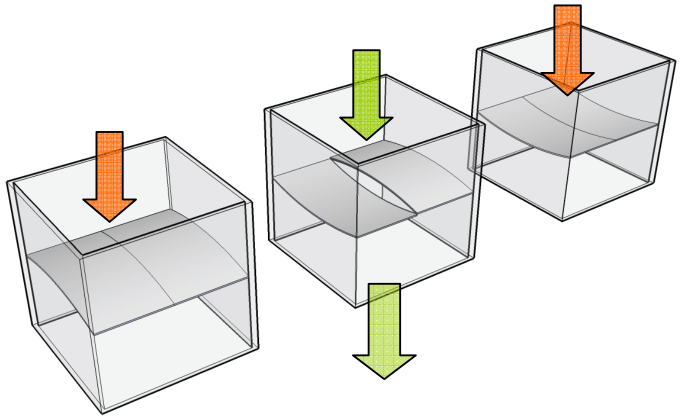

Figure 3: Simple bi-stable valve: initial closed state, intermediate open state, final closed state

Single shell elements or matrix of shell elements are planned to be located in the additional mounting of an arbitrary shape tailored to the geometry of the system (fig. 4) where the valve is planned to be installed. The design of the valve may utilize elastic shell elements of various geometry, e.g. part of the cylinder or hyperbolic paraboloid. Elastic shell elements can be made of metallic materials, polymer or functional composites.

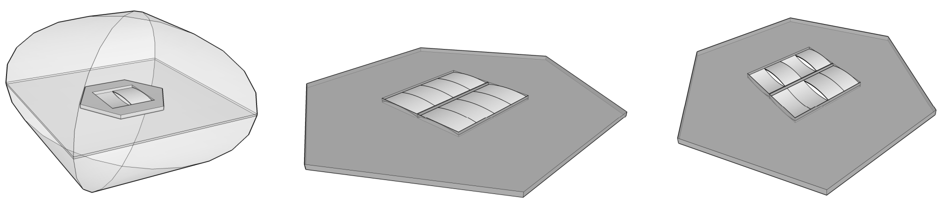

Figure 4: General view: absorber equipped with bistable valve, the valve composed of a matrix of bistable shell elements

The method of triggering the snap through effect is not arbitrarily predefined since it depends on range of operating pressures of the particular valve and its future application. Proposed valves will utilize the following types of actuation of snap-through effect:

- actuation by point load generated by classical linear actuator (e.g. piezoelectric or magnetostrictive),
- thermally or piezo-electrically induced deformation of convex or concave side of the shell (by shape memory alloys or macro fibber composites),
- controlled change of boundary conditions of shell element including enforced change of displacement, rotation angle or application of external bending moment,
- actuation by magnetic field generated by electric current or permanent magnets.

The snap-through effect was analysed with the use of different numerical models. In the elaborated models the arch of initial cylindrical shape was subjected to three following types of excitation in order to investigate snap-through phenomenon:

- distributed loading *p(x)* perpendicular to the surface of the arch modelling gas pressure, which may possibly cause uncontrolled snap-through effect;
- point force *F(t)* applied in the middle of the arch which models excitation caused by linear actuator aimed at obtaining fully controlled snap-through effect;
- thermal excitation *T(t)* causing uniform shortening of the arch as possible alternative method for obtaining controlled snap-through effect.

As it can be observed from the fig 5, the arch subjected to a point load is bended and it undergoes relatively large deformation before the snap-through effect occurs. In turn, since a cylinder is a special shape for pressure loading, in initial configuration the arch is almost not bended and, moreover, for particular value of pressure the axial force remains nearly constant along the arch. Although the first effect diverges as the structure deforms, the second one holds. The consequence is that deformation of the structure before snap-through and corresponding deflection of the central point (fig.5) are much smaller than in case of point load. The above intrinsic difference in force- and pressure- induced snap effect which will be effectively utilized in the construction of the valve.

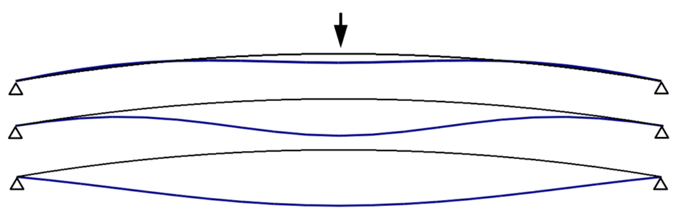

Figure 5: Snap-through of arch caused by point load: a) state just before snap-through, b) snap-through, c) state just after snap-through

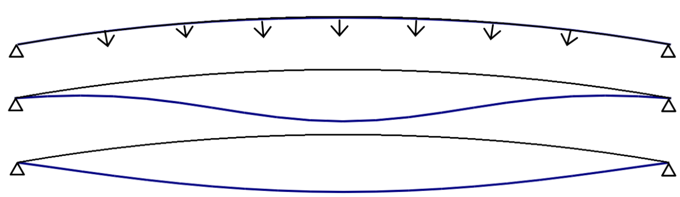

Figure 6: Snap-through of arch caused by distributed pressure loading: a) state just before snap-through, b) snap-through, c) state just after snap-through

Exemplary numerical simulations of the snap-through effect in elastic elements of the valve caused by thermal excitation are presented in fig. 6. Shortening and extension of the layers were conducted by application of elements with uni-directional thermo-mechanical coupling and continuous control of temperature (its linear decrease and increase for upper and lower layer, respectively). In all considered cases after reaching critical deformation of the layers and critical deflection of the entire arch, a sudden transition to new stable configuration had occured.

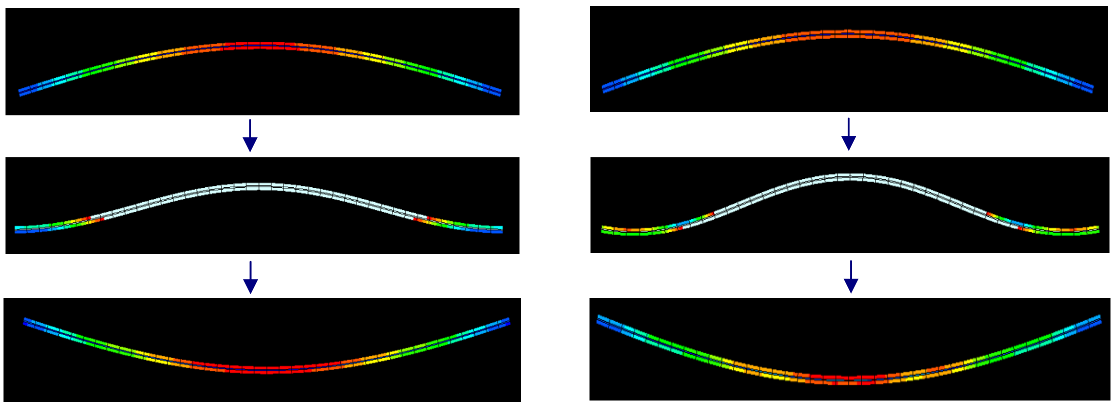

Figure 7: Snap-through of three-layer arch caused by induced deformation of the layers: a) shortening of the top layer, b) elongation of the bottom layer

Prediction of bi-stable shapes for arbitrary shells of double curvature is, in general, more demanding numerical task. In conducted numerical simulations, the movement of middle point of the hyperbolic paraboloid was blocked and vertical point loads were applied in the corners (in reverse direction in two groups of opposite corners). As the absolute value of forces increased, the shell had gradually deformed until sudden transition to a new completely different equilibrium configuration, being almost symmetrical to the initial one, had occurred (fig. 8). The simulations were conducted for two distinct types of kinematic boundary conditions:

- edges of the shell could move freely in horizontal directions,
- certain points of shell edges were fixed in horizontal direction.

The above condition strongly affects the value of critical force required to induce snap-through effect. In the first case deformation of the structure is less confined and, as a result, the snap-through occurs at small deformation and the corresponding critical force is relatively low. Moreover, the snap-through effect is very sudden and it is followed by strong vibrations of the structure. In turn, the structures of the second type undergo larger deformation before the snap through occurs and require larger critical force. The difference is the most distinct for shell with fixed centres of edges for which a configuration being intermediate of paraboloidal shapes is clearly observed (fig. 8). Another intrinsic difference is that after decrease of the external loading, the system with unblocked edges returns to the configuration approximately similar to initial one, i.e. the snap-back phenomenon occurs. In contrast, the structure with fixed corners remains in second configuration when applied forces are reduced to zero.

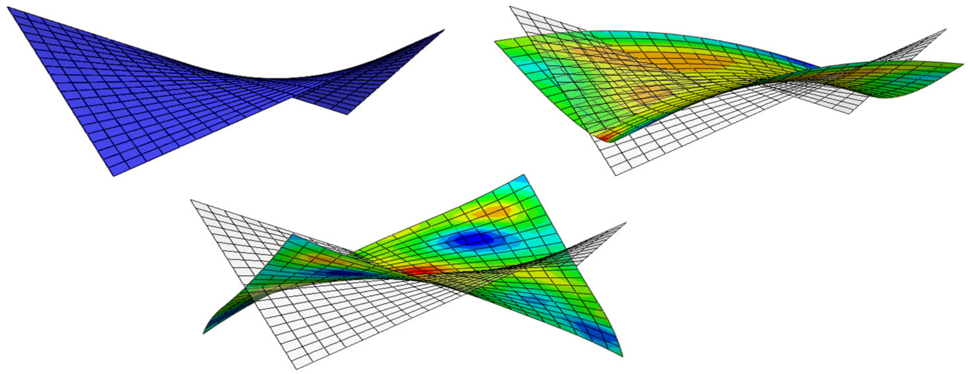

Figure 8: Snap-through of hyperbolic paraboloid (rectilinear surface) caused by points loads applied at corners: a) initial configuration, b) intermediate stage of the process, c) final configuration

The bistable, high-performance valve can be designed as multi-stage system, in the form of matrix of controllable shell elements. Multi-stability of such valve is obtained by exploiting all combinations of two possible configurations of each bistable element. Figure 9 presents diverse constructions of the valve, which utilize shell elements being a segment of cylinder or hyperbolic paraboloid. In each case all elements are aligned in the initial configuration such that they totally block the gas flow. Control of the valve opening is performed by sequentially controlled snap-through of chosen shell elements which allows for opening or closing of the appropriate number of flow channels. Proposed multi-stage valve can be considered as controllable semi-permeable membrane for both mechanical and biological applications.

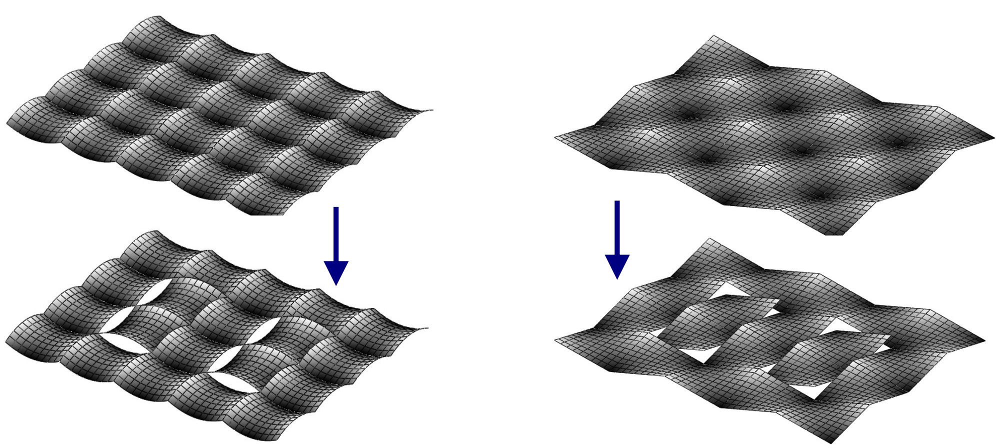

Figure 9: The valve equipped with matrix of shell elements: initial closed state, one of possible configurations of valve opening

2 HIGH PERFORMANCE MEMBRANE VALVE

Patented concept [5] of the HPV is utilizing a flow energy drive method, using the energy of the flow to move and seal working parts of the valve. This concept reduces needed power of a control system and significantly improves the valve response time, allowing for high flow rate. Basic configuration of the valve allows for three operation steps depicted in fig. 10.

The HPV consist of two surfaces made of elastic membranes and two exploding control rings. Initially valve remains closed, while the airbag is being inflated. When the control system sends a triggering signal, external control ring is released allowing external working surface to open and to start gas outflow.

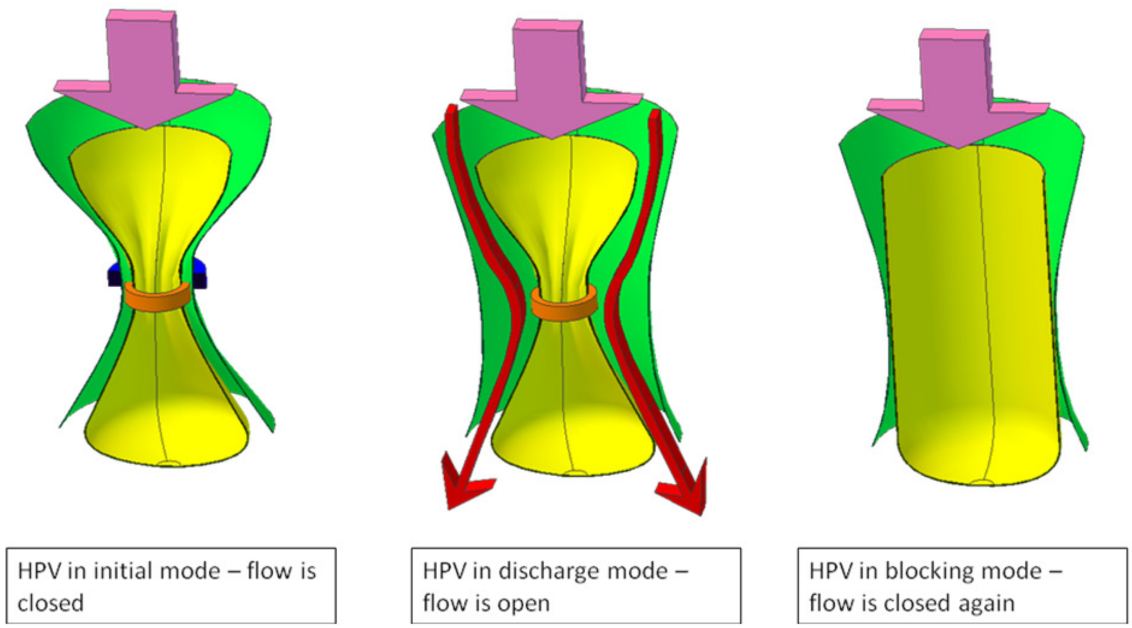

Figure 10: The HPV sequence of operation (beginning from left hand side)

After another triggering signal, an internal control ring may be released allowing internal valve surface to expand and therefore close the gas flow. An internal HPV surface uses the dynamic pressure to expand in the initial phase. The pressure difference caused by the channel geometry, due to the Bernoulli law, helps fully inflated internal shell to seal a gap between surfaces. When flow stops, and pressure gradient exists, the final configuration of the valve due to static pressure keeps surfaces contacted.

An experimental setup was build to prove the concept of the valve. System consist of a tank equipped with pressure and temperature sensors, a Venturi type flow meter, control valve operated by a pneumatic actuator and transparent test chamber. An exploding control rings of the valve are powered by a high voltage control system. All operations and measurements are controlled and collected by the NI Lab-View driven real-time computer.

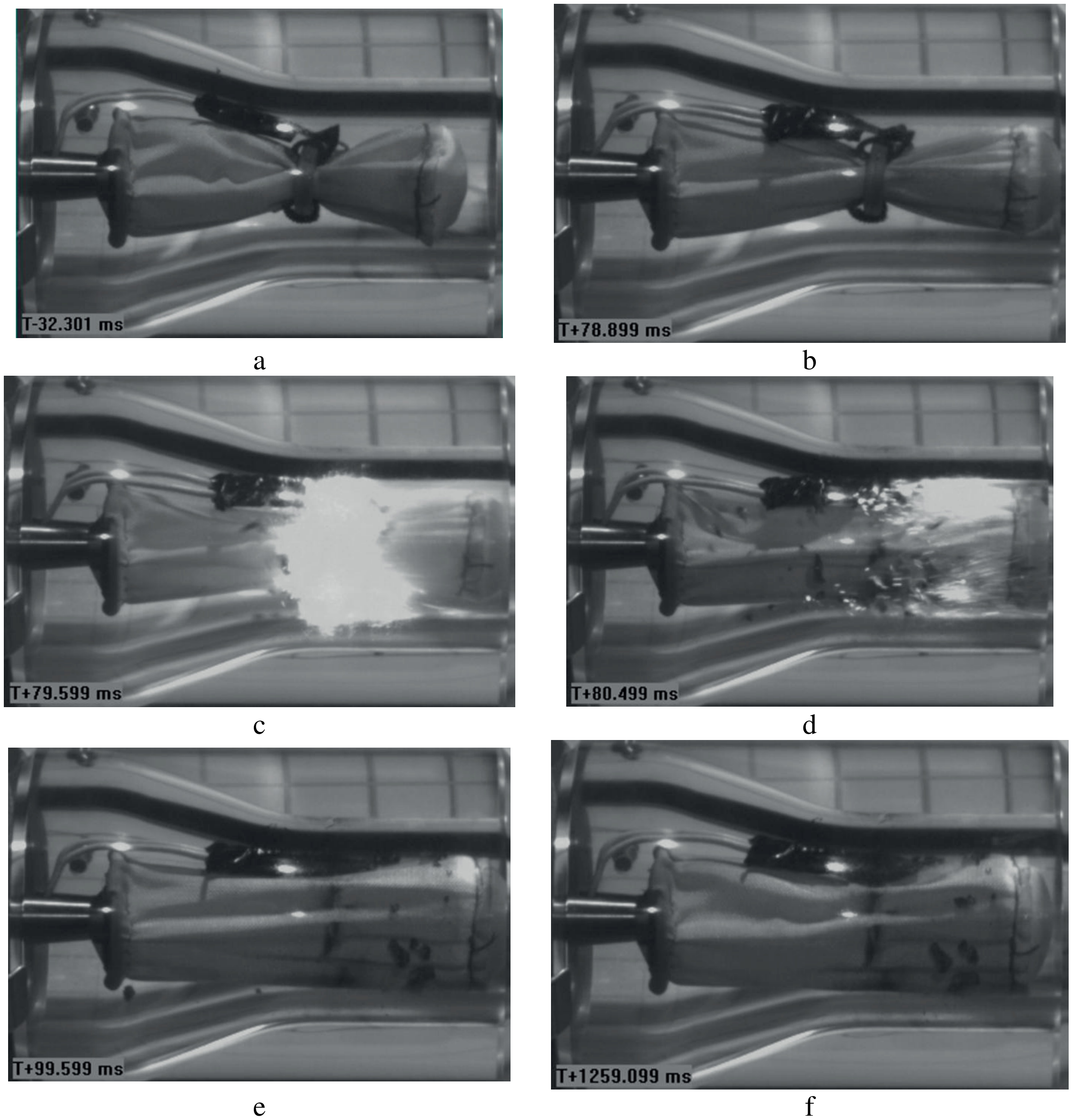

Figure 11: The HPV sequence of operation (beginning from left hand side)

Test chamber was observed by Phantom V5.1 high speed camera, registering footage at 10kfps, whose selected pictures are shown in fig.11 (please note a different time base to the rest of the measurements). First picture (a), taken before the flow started, shows the internal surface of the HPV not being loaded by pressure.

Second photograph (b) depicts the surface being pressed by the stream and constrained by waist ring, causing the flow to be partially opened. Two next pictures (c,d) document explosion of the ring, occurred after triggering signal, whose fragments are visible, followed by the initiation of release of the surface. At the next picture (e) expanded and sealed external surface is visible, still arresting small fragments of the waist ring. Last photograph (f) shows free surface after the stop of the flow.

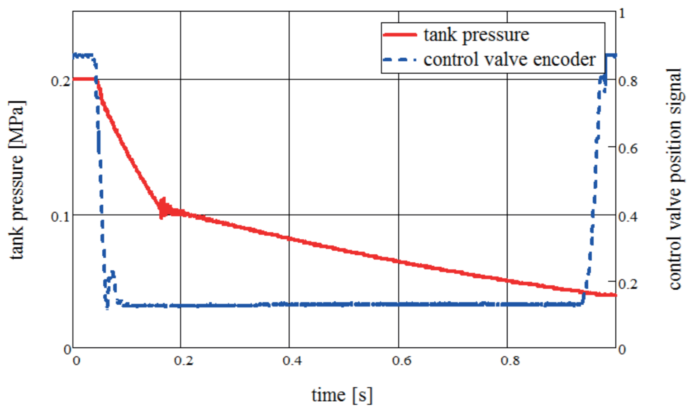

Figure 12: Test results: tank pressure and control valve position signals

Results presented in fig. 12 show that the HPV concept feasibility was proved. The closing stage of the valve operation is very effective, providing 6.4 times difference of discharge coefficient between closed and open stage. All results were obtained on initial prototype, whose geometry and surface quality improvement may significantly increase the performance of the valve.

ACKNOWLEDGEMENT

Financial support of the National Center for Research and Development (project Innovative, high performance valves for adaptive pneumatic impact absorbers LIDER/24/130/L-3/11/NCBR/2012) is gratefully acknowledged.

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