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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF NOVEL CONTROL METHODS FOR SELF-ADAPTIVE SHOCK ABSORBERS

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Abstract. This study explores numerically and experimentally innovative control strategies for self-adaptive shock absorbers designed to operate under varying impact conditions. The control problem is addressed with a fundamental constraint – a limited prior knowledge of excitation parameters. To tackle this challenge, state-dependent control methods with progressively enhanced adaptive capabilities are proposed and evaluated numerically. A dedicated experimental setup featuring a pneumatic adaptive shock absorber is developed to ensure validation of the proposed methods and facilitate their comparison. The system incorporates a fast-operating piezoelectric valve with a strain gauge for proportional opening control and enables optimal real-time response to unknown dynamic excitations. The conducted laboratory drop test results confirm the feasibility of the proposed control methods.

Key words: Adaptive Impact Absorption, Self-Adaptive System, Pneumatic Shock Absorber

1 INTRODUCTION

Mechanical impacts are common phenomena encountered in a wide range of systems. To safeguard structures and devices from the detrimental effects of such shocks, impact absorbers have been extensively developed and implemented. Their primary function is to reduce the transmitted loads by absorbing and dissipating the energy of the excitation. Energy absorbing devices are employed in diverse applications, such as vehicle crash protection [1, 2], bicycle suspensions [3], and landing gear systems [4, 5]. In these scenarios, the impact mitigation process occurs within a remarkably short time frame, often just a few to several tens of milliseconds, posing significant practical challenges for control systems. A key limitation arises from the inherent mechanical inertia of actuators, which restricts the operational speed of shock absorbers. However, ongoing rapid advancements in actuator technology, sensor systems, and embedded hardware controllers are paving the way for development of technically feasible shock absorbers designs. The examples include magnetorheological [6, 7] and electrorheological dampers [8], pneumatic [9, 10] and hydraulic shock absorbers [11, 12] equipped with piezoelectric valves, as well as systems utilizing shape memory alloys [13].

In contrast to typical methods used for impact mitigation, where pre-defined system response is executed using PID controller [14] with feedback from generated force or acceleration [15], the self-adaptive shock-absorbers are equipped with additional path-planning loop [16]. This loop, being simultaneously a basis for self-adaptive performance, enables optimization of the system response in the case of unknown excitation conditions and occurrence of process disturbances. Recently, two different approaches based on kinematic feedback for path-planning process have been developed. In the first method, the measurement of selected state variables allows for maintaining actually optimal system path [17, 18]. The alternative approach is based on the versatile concept Model Predictive Control (MPC) [19], which enables sequential control update and system response optimization at arbitrarily selected control horizon. In the proposed methods, the MPC framework is extended either by conducting repeated identification of process disturbances [20] or by introducing equivalent quantities that account for unknown disturbances and system parameters [21].

The main objective of the paper is to numerically and experimentally validate the performance and robustness of two methods developed for adaptive impact absorption, namely Bi-state HPC method and Continuous HPC method. Both methods are evaluated under impact scenarios involving a wide range of masses and initial velocities of the impacting object. The results from the numerical simulations are confirmed to a large extend by the experimental tests conducted using pneumatic cylinder equipped with piezoelectric valve.

2 CONTROL METHODS FOR ADAPTIVE IMPACT ABSORPTION

A basic example of an impact-absorbing system is a double-chamber (hydraulic or pneumatic) damper subjected to the impact of a rigid object with a given initial velocity (Fig. 1a). The damper contains a fast-operating controllable valve used to regulate fluid flow between the chambers (Fig. 1b) and a system of sensors that measure kinematic and thermodynamic response to impact loading. The system aims to absorb and dissipate impact energy while minimizing reaction force and deceleration of the impacting object. It is designed to operate autonomously and adapt to varying impact conditions. As a self-adaptive system, it provides a high level of robustness against unpredictable impacts and unknown process disturbances.

The proposed control concept assumes online bi-directional exchange of data between the damper and the control system. The signals transmitted from the damper to the control system include piston displacement and deceleration, gas pressures, gas temperatures and actual valve opening. Conversely, the signals transmitted to the damper's valve include required deceleration or required valve opening, and the control voltage supplied to the valve.

The problem of Adaptive Impact Absorption (AIA) is defined here using a state-dependent kinematic formulation that is consistent with fundamental principles governing the operation of self-adaptive systems. The proposed approach involves determining a time-dependent control signal which minimizes the objective function, defined as integral of the difference between the actual impacting object's deceleration $\ddot{x}$ and its currently optimal (required) value $\ddot{x}_{req}$.

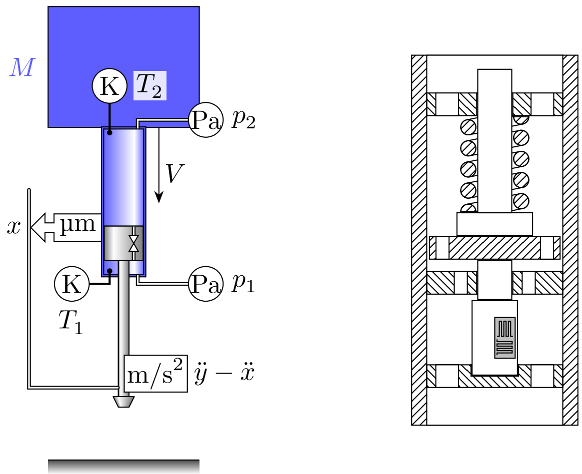

Figure 1: Pneumatic damper with controllable valve under impact excitation

This yields the following dynamic optimization problem:

$$\text{Find } u^* = \underset{u_{\min} \le u(t) \le u_{\max}}{\arg\min} \int_0^{t_{max}} \left(\ddot{x}(u,t) - \ddot{x}_{req}(u,t)\right) dt \tag{1}$$

where u is the searched control signal and t_{max} indicates final time of the process when the impacting object stops. The required impacting object's deceleration $\ddot{x}_{req}$ is determined using the condition of stopping the impacting object using the remaining stroke of the piston $d - x(u,t)$:

$$\ddot{x}_{req} = -\frac{v^2(u,t)}{2(d - x(u,t))} \tag{2}$$

which is called the Kinematic Optimality Condition (KOC). It is assumed that the optimization problem (1) is solved using mathematical model of the considered impact-absorbing system, but without the knowledge about the values of impacting object mass and its initial velocity as well as possible disturbances of the process (e.g. friction forces or fluid leakage).

To address this challenge, two control methods utilizing state-dependent path-tracking (Bi-state Hybrid Prediction Control and Continuous Hybrid Prediction Control) have been developed, Fig. 2. Both methods provide an approximate solution of the dynamic optimization problem (1) by employing different realizations of the path-tracking process.

Specifically, the Bi-state HPC method (Fig. 2) is based on direct tracking of the required deceleration path. In this approach the Path Control Algorithm utilizes KOC to determine the currently optimal deceleration value. This required deceleration is then followed by applying two extreme control signal values, resulting in commutative opening and closing of the valve. In contrast, the Continuous HPC method (Fig. 2) focuses on tracking the required change of valve opening. In this approach, the Path Control Algorithm is followed either by a block enforcing closed valve position (executed at the beginning of the process) or Inverse Dynamics Prediction block, which determines the necessary change of valve opening during the process (executed

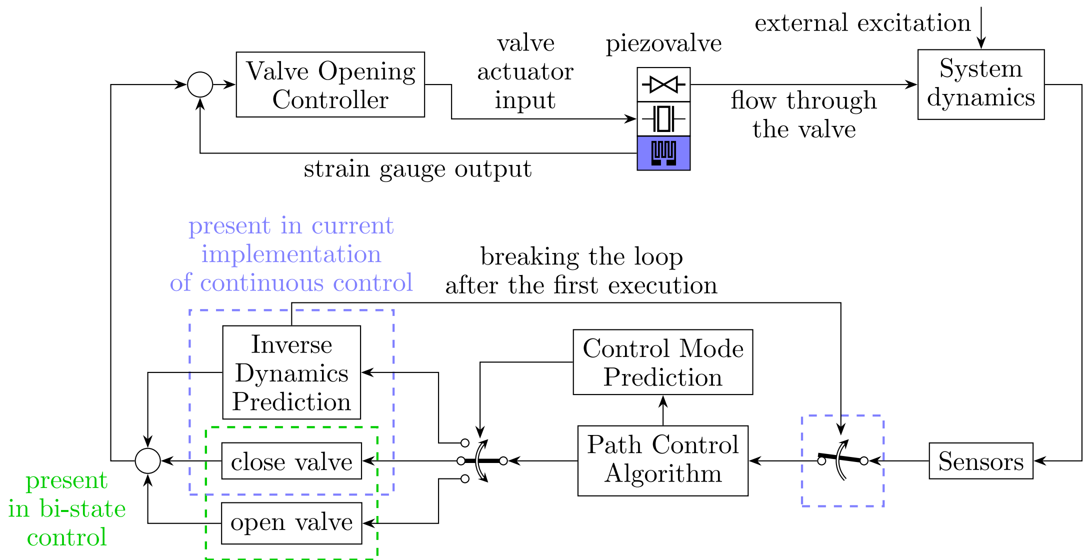

Figure 2: Scheme of Bi-state HPC method and Continuous HPC method

only once when the KOC is satisfied). The required valve opening is further followed using PI controller with feedback from actual deceleration.

3 NUMERICAL INVESTIGATION OF THE CONTROL METHODS

The objective of conducted numerical study is to evaluate the performance of Bi-state and Continuous HPC methods under impact scenarios involving various impacting object masses and initial velocities. The response of the system is computed using a mathematical model based on equations describing the motion of the impacting object, the thermodynamic energy balance, the cotrolled gas flow through the valve and the operation of the control system. The last two equations incorporate the inertial effects related to the gas flow and the valve piston motion.

3.1 Bi-state Hybrid Prediction Control

The baseline case for Bi-state HPC method involves an impact characterised by two parameters: $M = 11.4\,\mathrm{kg}$ and $V_0 = 1.4\,\mathrm{m/s}$. The computed changes of applied control, obtained opening of the valve, required deceleration and obtained deceleration are presented in Fig. 3. In the considered case, the valve's time constant is assumed as $T_0 = 1\,\mathrm{ms}$, which is a typical value for piezoelectric valves. The maximum control signal is $U_m = 200\,\mathrm{V}$ and corresponds to maximum valve's head displacement $d_v^{max} = C = 50\,\mu\mathrm{m}$, which ensures regular fluctuations of the deceleration during the entire process.

The effects of **changing the impacting object mass** (using a scaling factor of 1.5 for both increase and decrease cases) are presented in Fig. 4 The conducted simulations allow to make the following observations:

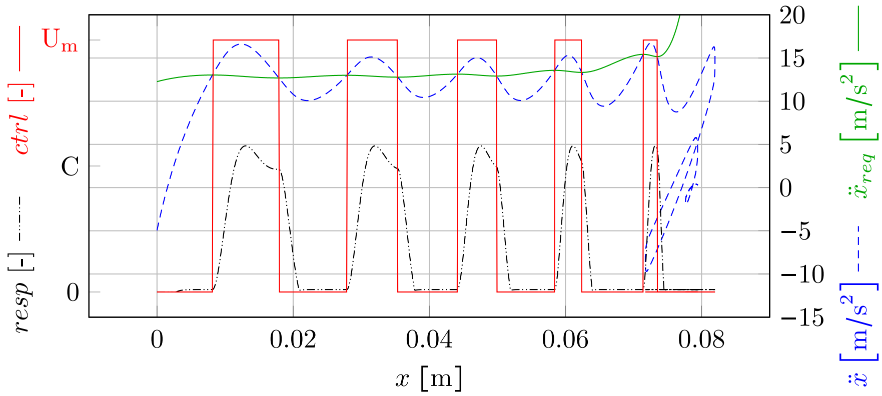

Figure 3: Operation of Bi-state HPC method for $M = 11.4\,\mathrm{kg}$ and $V_0 = 1.4\,\mathrm{m/s}$

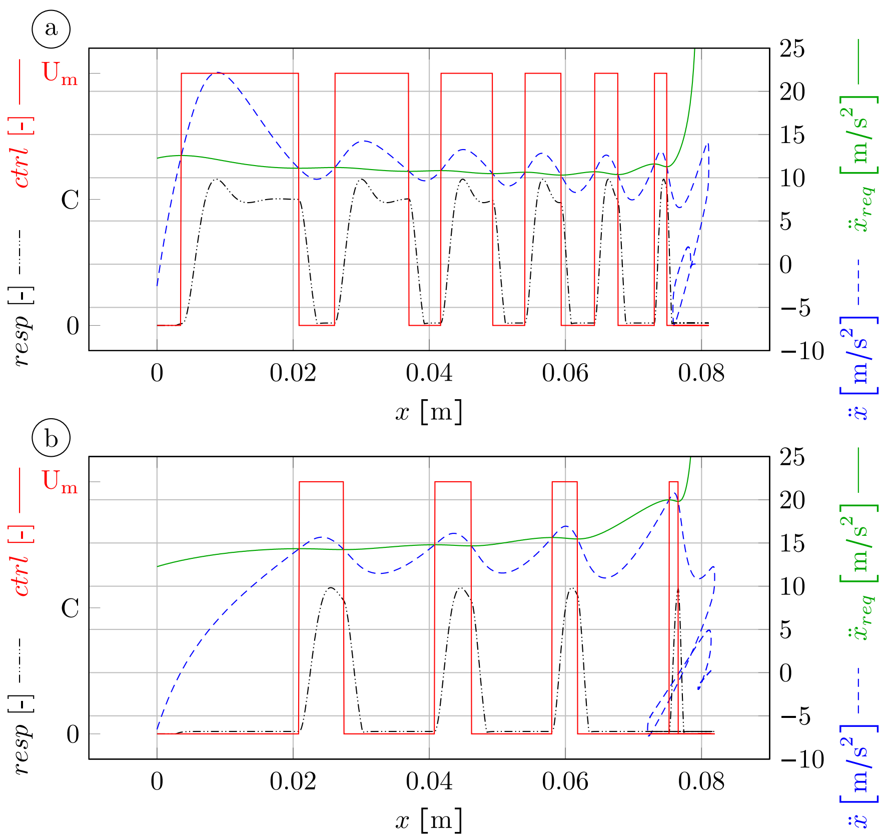

Figure 4: Comparison of Bi-state HPC method operation for small and large mass of the impacting object

- Decreasing the impacting object's mass causes more frequent occurrence of the time intervals when the valve is opened and more frequent fluctuations of deceleration. The gradual decline of the required deceleration corresponds to decrease of both the maximal and minimal deceleration values during the subsequent fluctuations. The peak deceleration occurs at the beginning of the process, during the first valve opening.

- Increasing the impacting object mass leads to fewer occurrences of time intervals when the valve is opened and fewer corresponding fluctuations of deceleration. The gradual raise of required deceleration corresponds to increase of the maximal deceleration value during the subsequent fluctuations. In this case, the peak deceleration appears near the process end, with the magnitude being highly sensitive to the exact mass value.

The example demonstrates that variations in mass value significantly alter the response of the system controlled by Bi-state HPC method. Better performance with more regular fluctuations of deceleration can be achieved by adjusting the maximum valve opening or maximum value of applied control signal. Specifically, for the decreased mass the maximum valve opening has to be enlarged, while for the increased mass the maximum control signal has to be reduced along with precise calibration to current mass value.

The effects of **changing the impacting object's initial velocity** (using a scaling factor of 1.3 for both increase and decrease cases) are depicted in Fig. 5. Although the results of velocity changes are not so evident, the following observations emerge:

- Reduced impacting object velocity results in lower value of the required deceleration (due to modified system kinematics) and significantly more frequent occurrence of time intervals when the valve is open. The largest value of deceleration can occur either at the beginning of the process or at its very end depending on the exact value of impacting object's velocity.

- Increased impacting object velocity leads to higher value of required deceleration and fewer occurrences of time intervals when the valve is open. The largest deceleration typically occurs at the end of the process, with magnitude strongly dependent on impacting object's initial velocity. Moreover, notably larger rebound of the impacting object is observed at the end of the process.

The example shows that variations in impacting object's initial velocity primarily affect the final stage of system response. The occurrence of the final deceleration peak can be prevented by precise tuning of maximum valve opening or maximum control signal, while reducing object rebound often requires change of control strategy at the end of the process.

The entire numerical analysis concerning mass and velocity dependence demonstrates that response of the system controlled by Bi-state HPC method is very sensitive to both these values. Moreover, the adjustment of control parameters aimed at obtaining regular deceleration fluctuations is relatively complicated and its outcomes cannot be easily predicted a priori.

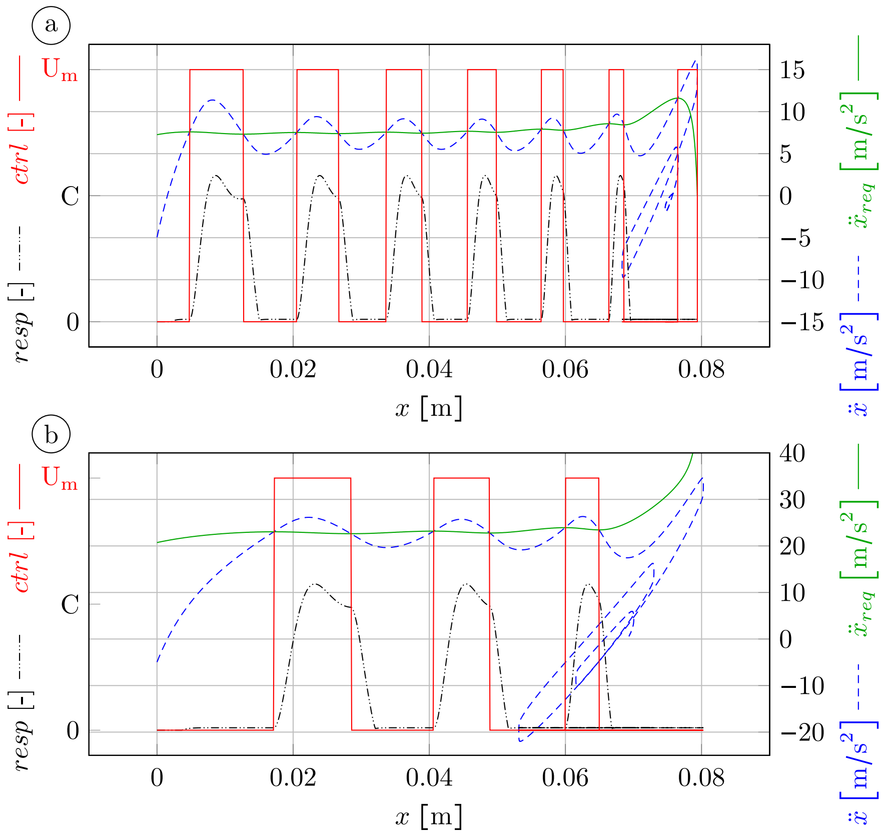

Figure 5: Comparison of Bi-state HPC method operation for small and large velocity of the impacting object

3.2 Continuous Hybrid Prediction Control

For the Continuous HPC method, the baseline case employs the same mass and initial velocity of the impacting object: $M = 11.4\,\mathrm{kg}$ and $V_0 = 1.4\,\mathrm{m/s}$. The valve's time constant is assumed significantly larger than in the Bi-state HPC method ($T_0 = 10\,\mathrm{ms}$) in order to obtain comparable path-tracking precision, while the maximum valve's head displacement is assumed as previously: $d_v^{max} = C = 50\,\mu\mathrm{m}$. The computed changes of applied control, required valve opening, obtained valve opening, required deceleration and obtained deceleration are presented in Fig. 6. The executed control process includes three stages: i) keeping the valve closed to reach the required deceleration, ii) applying the maximum control signal to reach the required valve opening and iii) precise adjustment of the control signal to track the required time-history of valve opening.

The effects of **changing the impacting object mass** (decrease and increase by factor of 1.5) are depicted in Fig. 7, revealing the following observations:

- Decreasing impacting object mass results in shorter initial stage of the process when the valve remains closed and lower value of required constant deceleration (determined using

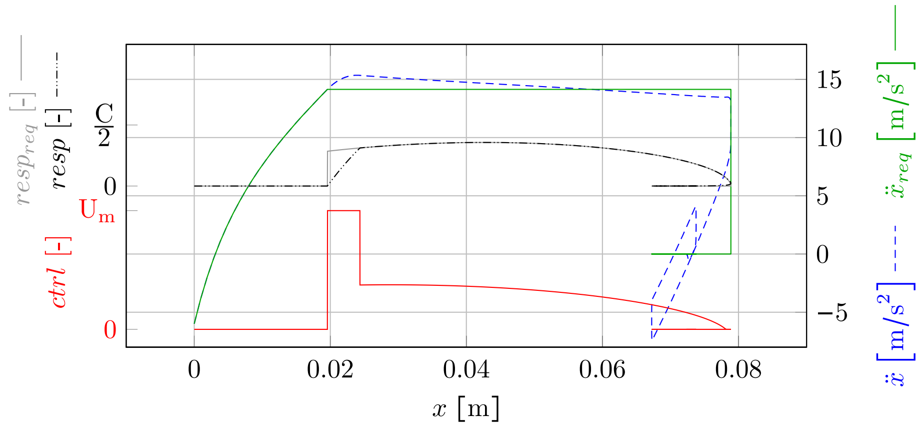

Figure 6: Operation of Continuous HPC method for $M = 11.4\,\mathrm{kg}$ and $V_0 = 1.4\,\mathrm{m/s}$

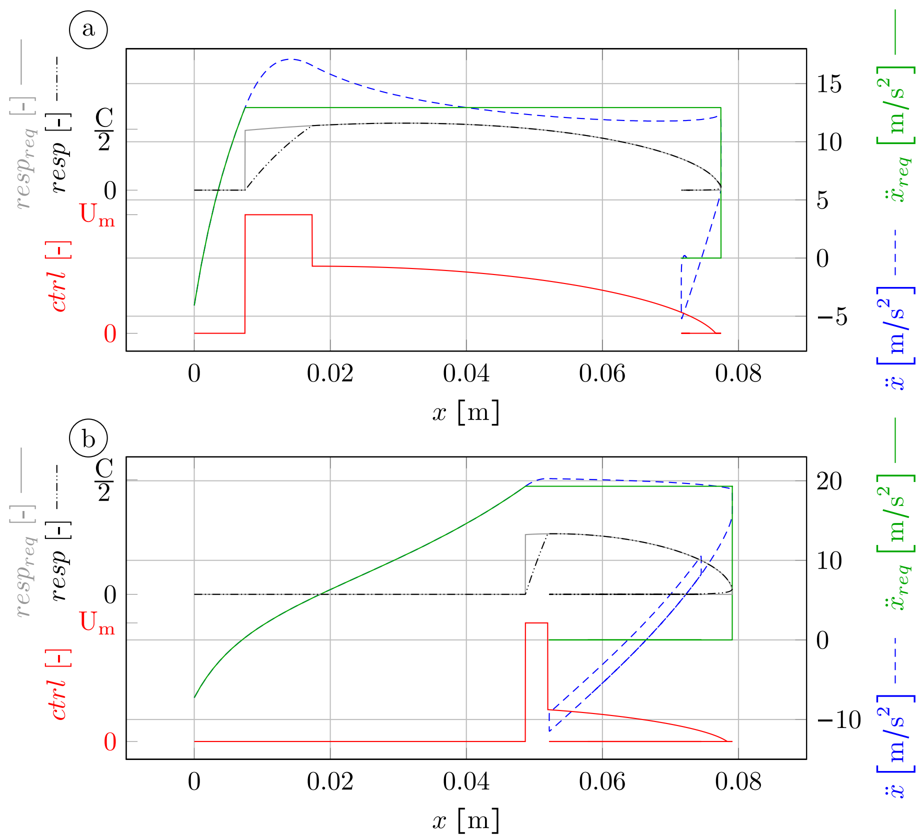

Figure 7: Comparison of Continuous HPC method operation for small and large mass of the impacting object

KOC). The obtained deceleration exceeds the required one at the first part of the control process and drops below it during the second part.

- Increasing impacting object mass leads to longer initial stage with the closed valve and larger value of the required deceleration. The obtained deceleration more closely follows the required one, exceeding it slightly almost during the entire process. Moreover, the rebound of the impacting object substantially increases.

The example shows that change in mass value modifies deceleration path-tracking accuracy and entire performance of the method. The most adverse effects include exceed of the required deceleration for small masses and increased impacting object's rebound for large masses. Both effects can be effectively mitigated by decreasing the value of valve's time constant T_0.

The effects of **change of impacting object velocity** (decrease and increase by factor of 1.3) show similar trends to those observed in the case of mass modification, i.e.:

- Decreasing the impacting object's initial velocity causes decrease of the required constant deceleration level, which is exceed during the first part of the control process and not reached during the second part.

- Increasing the impacting object velocity results in higher level of required constant deceleration, its slight exceeding during almost the entire process and increase of rebound.

The entire numerical investigation of the Continuous HPC method reveals that despite the use of larger valve's time constant, the path-tracking accuracy is similar or higher than in the Bi-state HPC method. Moreover, the Continuous HPC method is less sensitive to changes of impacting object's mass and its initial velocity. Finally, the adverse effects such as overshoot of the required deceleration (for small masses and velocities) and increased impacting object rebound (for large masses and velocities) can be effectively mitigated by decreasing the valve's time constant. Therefore, the superiority of the Continuous HPC method in adaptation to various impact scenarios is clearly confirmed.

4 EXPERIMENTAL TESTING OF THE CONTROL METHODS

In order to further investigate the performance of the HPC methods and their dependence on the mass and initial velocity of the impacting object, a number of experiments has been conducted. The tests have been carried out in laboratory conditions using uniquely designed pneumatic adaptive absorber (PAA), which consists of a pneumatic cylinder and a piston connected to a single-sided piston rod. Gas transfer between the internal volumes of the cylinder is provided by fast-actuated valve incorporated inside the piston [10]. The valve's actuation mechanism is based on a multilayer piezoelectric actuator, which enables its full opening or closing within $1\,\mathrm{ms}$ timeframe. The actuator is equipped with a strain gauge sensor, which allows for monitoring of its current elongation and computation of the corresponding valve head displacement. Additionally, the investigated absorber is equipped with two pressure sensors located inside cylinder volumes, two temperature sensors and displacement encoder measuring position of the piston.

The experiments are conducted using a dedicated laboratory drop test stand, which consists of a drop tower and a guided drop cart which carries the tested absorber and a loading mass. The stand is equipped with an encoder to measure cart displacement, an accelerometer mounted at the drop cart and a load sensor at the bottom interface with the ground. The experimental setup enables efficient implementation of Bi-state and Continuous HPC methods, as well as thorough investigation of the dynamic response of the pneumatic absorber under impact loading.

The exemplary experimental results demonstrate the performance of the system with implemented Bi-state HPC method, in which the control signal is switched between two extreme states. The test parameters are set to $M = 8.9\,\mathrm{kg}$ and $V_0 = 1.4\,\mathrm{m/s}$, closely matching those used in the numerical simulation for the decreased impacting object mass. Fig. 8 presents plots of the measured deceleration of the drop cart, the required deceleration (computed online) and the applied control signal. The experimental results indicate that after the deceleration peak at the beginning of the process, the system successfully tracks the required deceleration path and ensures dissipation of the entire impact energy. Moreover, the characteristic deceleration pattern involving the initial peak followed by fluctuations in the later phase closely resembles the numerical results presented in Fig. 4a. Thus, the example validates the applied approach to system modelling and confirms the correctness of the conclusions drawn from the conducted numerical simulations.

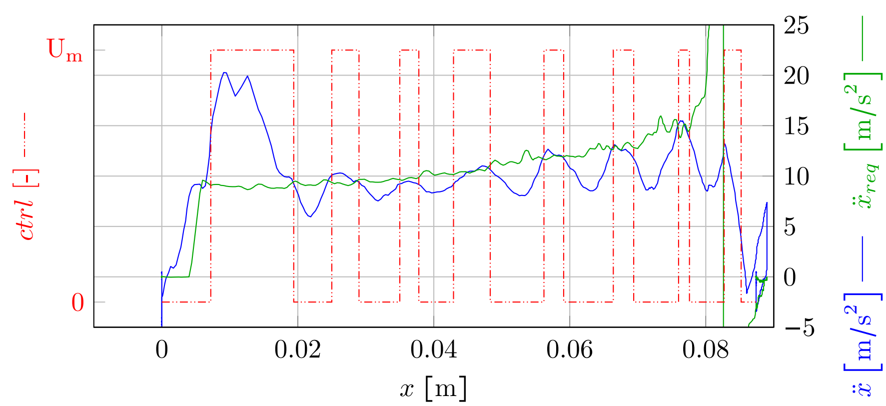

Figure 8: Experimental results of Bi-state HPC operation for $M = 8.9\,\mathrm{kg}$ and $V_0 = 1.4\,\mathrm{m/s}$

5 CONCLUSIONS

The Bi-state HPC and Continuous HPC are two control methods developed for self-adaptive shock absorbers designed to mitigate impact loading. The methods employ different approaches to tracking the required system path (direct tracking of required deceleration and tracking the required valve opening) and use different path-tracking techniques (bi-state control and PI control). The conducted numerical simulations show that Bi-state HPC method performs relatively well when control system parameters (valve time constant and maximum valve opening) are adjusted to the current impact scenario. However, the path-tracking accuracy deteriorate when the impacting object mass and its initial velocity change, often resulting in a significant exceeding of the required deceleration level.

In contrast, the Continuous HPC method provides efficient tracking of the required system path using a valve with larger time constant and smaller maximum opening. Additionally, the applied path-tracking process demonstrates greater robustness to changes of impacting object mass and its initial velocity, so the method has higher overall adaptation capabilities to diverse impact scenarios. Due to its superiority, the Continuous HPC method constitutes better solution for impact mitigation problems and will be further developed in the future.

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