OPTIMAL AND PREDICTIVE CONTROL OF SEMI-ACTIVE FLUID-BASED DAMPERS UNDER IMPACT EXCITATION

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1. Introduction

Semi-active fluid-based dampers consist of two chambers filled with hydraulic or pneumatic fluid and connected by the orifice, which is equipped with fast-operating valve controlling the actual rate of fluid flow. The most often used types of fluid-based shock-absorbers are semi-active hydraulic and pneumatic dampers with fast electro-mechanical or piezoelectric valves. These devices can be used in both vibration suppression problems and impact mitigation problems. Although many control strategies have been successfully developed for protection against vibration, the problem of optimal impact absorption has not gained sufficient attention of researchers and has not been completely solved so far.

2. General formulation of the impact mitigation problem

In the considered impact absorption problem the damper is subjected to the impact of a rigid object of mass M moving with initial velocity v_0 and external force $F_{ext}(t)$, as shown in Fig. 1a. The objective of the control problem is to find the change of valve opening in time $A_v(t)$, which provides absorption and dissipation of the entire impact energy with minimal value of total discrepancy between force generated by the absorber F_{abs} and its theoretical optimal value F_{abs}^{opt}, see Fig. 1b (black and red lines, respectively).

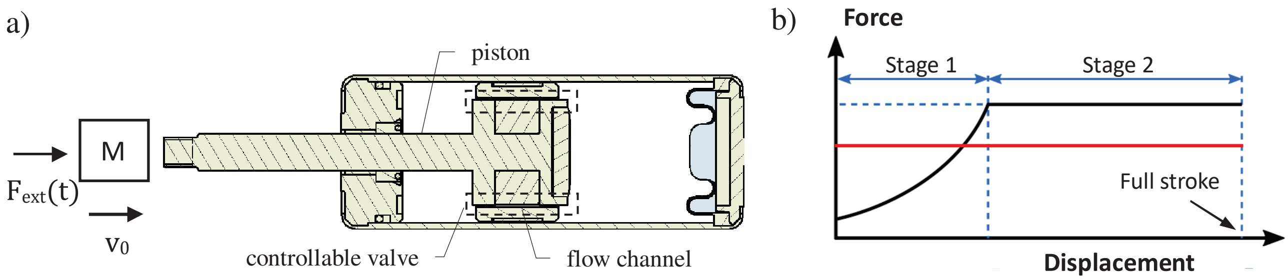

Fig. 1: a) The problem considered: damper subjected to the impact excitation, b) force-displacement characteristics: red – theoretical optimal force, black – schematic optimal change of force obtained using pneumatic damper

The direct mathematical formulation of the impact mitigation problem, which has been studied in detail by the authors reads:

(1a) Minimize: $\int_0^T \left(F_{abs}(A_v(t)\,,t) - F_{abs}^{opt}\right)^2 dt$

(1b) With respect to: $A_v(t) \geq 0$

(1c) Subject to: $\int_d \vec{F}_{abs} d\vec{s} = E_{imp}^0 + E_{imp}^{ext} = \frac{1}{2}Mv_0^2 + \int_d \vec{F}_{ext} d\vec{s}$

The solution of the above control problem is straightforward (and for pneumatic damper assumes the form shown in Fig. 1b) only in a very special case when: a) no limitations on maximal valve area and valve operation speed are considered, b) the impact excitation is a priori known and the theoretical value of optimal force F_{abs}^{opt} can be directly calculated. In the opposite situation, the solution of the impact mitigation problem requires application of the advanced methods of control theory. In particular, the control problem with valve operation constraints requires the optimal control methods, while the control problem with unknown excitations and disturbances requires the paradigm of Model Predictive Control.

3. Optimal control of dampers with valve operation constraints

The exact solution of the impact mitigation problem taking into account valve operation constraints can be found when impact excitation (impacting object mass, its initial velocity and time-history of external force) are entirely known before the process. In such a case, the theoretical optimal value of force F_{abs}^{opt} equals:

$$F_{abs}^{opt} = \frac{Mv_0^2}{2d} + \frac{\int_d \vec{F}_{ext} d\vec{s}}{d} \tag{2}$$

where d is absorber stroke. Consequently, the problem of optimal impact absorption takes the form:

(3a) Minimize: $\int_0^T \left[F_{abs}(A_v(t), t) - \left(\frac{Mv_0^2}{2d} + \frac{\int_d \vec{F}_{ext} d\vec{s}}{d}\right)\right]^2 dt$

(3b) With respect to: $A_v(t)$ such that $A_v(t) \in \langle A_v^{min}, A_v^{max} \rangle$ and $\frac{dA_v(t)}{dt} \leq V_v^{max}$

(3c) Subject to: condition of energy absorption (1c)

The above formulation constitutes classical optimal control problem, which can be solved using the Pontryagin's maximum principle and direct methods based on discretization of the control function in time and conversion to the classical optimization problem. Implementation of both methods entails different challenges, which will be briefly analyzed and discussed.

4. Predictive control of dampers subjected to unknown impact excitation

In the situation when the external excitation is not a priori known, the above force-based formulation and the corresponding optimal control methods cannot be directly applied. Instead, the problem has to be reformulated into its kinematic version, the so called *state-dependent path-tracking*, based on minimization of the actual and currently optimal value of deceleration, which is continuously updated during the process:

(4a) Minimize: $\int_0^T \left[\ddot{u}(A_v(t), t) + \frac{\dot{u}(t)^2}{2(d - u(t))}\right]^2 dt$

(4b) With respect to: $A_v(t)$ such that $A_v(t) \in \langle A_v^{min}, A_v^{max} \rangle$ and $\frac{dA_v(t)}{dt} \leq V_v^{max}$

(4c) Subject to: condition of energy absorption (1c)

In such a case, the efficient approach is application of Model Predictive Control, which assumes repetitive solving of the control problems defined at finite time horizons of arbitrary length Δt:

(5) Minimize: $\int_{t_i}^{t_i + \Delta t} \left[\ddot{u}(A_v(t), t) + \frac{\dot{u}(t_i)^2}{2(d - u(t_i))}\right]^2 dt$

The approximate solution of this problem can be based on the proposed by the authors methods including Hybrid Prediction Control (HPC) [1] and Adaptive Model Predictive Control (AMPC) [2]. The HPC provides efficient impact mitigation by using system kinematics measurements, prediction of the valve operation mode and prediction of the required change of valve opening. In turn, the AMPC additionally utilizes equivalent model parameters which compensate the presence of disturbances in order to improve system performance at each control step. Both these methods will be discussed in detail during presentation.

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