Vibration Attenuation by Semi-active Dampers

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Abstract. This contribution deals with the optimization of a tractor's cab's vertical acceleration. The mathematical model of the simplified system is derived. The acceleration of the chassis is considered as the actuating variable. In the optimization the acceleration of the tractor's cab is minimized under the constraint of a maximum displacement between the cab and the chassis. The optimization result is used to get a smallest limit for the maximum of acceleration in case of active damping and acausal damping control. So the optimization result is a lower bound.

Keywords: Optimization, Inequality Constraints, Active Damping, Semi-Active Damping.

1 Introduction

Damper systems based on conventional shock absorbers are not able to reach the required performance in many applications, e.g for vehicles such as tractors or harvesters. The reduction of the vehicles speed is the only way to fulfill the requirements of health and safety. The operation of these vehicles at higher working speeds requires an improvement of the damping systems. Therefore, the performance of this system has an important impact on the efficiency of the vehicle. The main tools to achieve the required goal are passive, active and semi-active methods, which allow us to reach different levels of performance, but also at different costs. Especially for applications in farming these costs are an important limiting factor. Additionally, already mounted systems for power and force generation should be used, which are hydraulic systems for farming vehicles. Active hydraulic damping systems are too expensive, because of the necessary active elements, which have a high hardware complexity, see [1]. Also passive systems cannot be improved significantly because of lack of space and the difficulty to adapt them to a wide spectrum of disturbances. Semi-active systems based on hydraulic devices are the way out to reach the required performance taking the costs into account. These devices allow us to control their damping characteristics by a controller, that their behaviour is well adapted to the actual disturbances. This paper is organized as follows. In Section 2 the mathematical model is derived. The adaption of the measured data is treated in Section 3.

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Section 4 is devoted to the derivation of upper limits for the performance, but also for the construction. In Section 5 the results of the optimization is shown. Finally, we conclude in Section 6.

2 Mathematical Model

The vehicle is modeled as a platform A mounted on a platform B, shown in Fig. 1. For the given acceleration a of a platform the position can be calculated by the continuous system

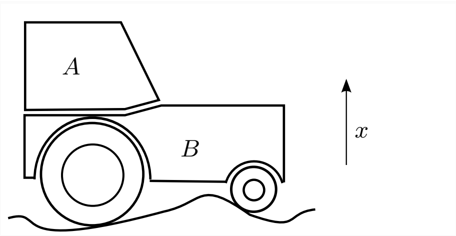

Fig. 1. Simplified picture of a tractor

$$\dot{\mathbf{x}} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} a$$
$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \mathbf{x} \tag{1}$$

with $\mathbf{x}^T = \begin{bmatrix} x & v \end{bmatrix}$ as state, x as position and v as velocity. For efficient calculations the discrete-time system is used. From (1) it can be calculated as

$$\mathbf{x}_{k+1} = \underbrace{\begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix}}_{\mathbf{A}} \mathbf{x}_k + \underbrace{\begin{bmatrix} \frac{T^2}{2} \\ T \end{bmatrix}}_{\mathbf{b}} a_k$$
$$y_k = \underbrace{\begin{bmatrix} 1 & 0 \end{bmatrix}}_{\mathbf{c}^T} \mathbf{x}_k \tag{2}$$

with T as sampling time. With the assumption $\mathbf{x}_0^T = \begin{bmatrix} 0 & 0 \end{bmatrix}$ and the system matrices from (2) the position y_k can be calculated as

$$\begin{bmatrix} y_1 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} \mathbf{c}^T\mathbf{b} & 0 & 0 & 0 \\ \mathbf{c}^T\mathbf{A}\mathbf{b} & \ddots & 0 & 0 \\ \vdots & \ddots & \ddots & 0 \\ \mathbf{c}^T\mathbf{A}^{N-1}\mathbf{b} & \cdots & \mathbf{c}^T\mathbf{A}\mathbf{b} & \mathbf{c}^T\mathbf{b} \end{bmatrix} \begin{bmatrix} a_0 \\ \vdots \\ a_N \end{bmatrix} \tag{3}$$

with the matrix elements

$$\mathbf{c}^T \mathbf{A}^k \mathbf{b} = \begin{bmatrix} 1 \; 0 \end{bmatrix} \begin{bmatrix} 1 & kT \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{T^2}{2} \\ T \end{bmatrix} = \left(k + \frac{1}{2} \right) T^2 . \tag{4}$$

To get the positions x_A and x_B of the two platforms, the system of equations (3) has to be solved with the acceleration a_A of platform A and with the acceleration a_B of platform B.

3 Measured Data

As a result of the bad surroundings the measured data contains high noise. Due to the high sampling frequency $f_a = 2\,\text{kHz}$, the measured signal can be filtered by a second-order low pass filter. In frequency range it is called Tustin transfer funcion and is defined as

$$F(q) = \frac{1}{1 + 2\,\zeta\,\frac{q}{\Omega_0} + \left(\frac{q}{\Omega_0}\right)^2}$$

with the sampling time $T = 0.5\,\text{ms}$, the damping factor $\xi = 0.7$ and the time constant $\Omega_0 = 50\,\pi\frac{1}{\text{s}}$. Afterwards the data is downsampled from $T = 0.5\,\text{ms}$ to $T = 20\,\text{ms}$, where the Nyquist-Shannon sampling theorem, $f_a > 2\,f_{max}$ with f_a as sampling frequency and f_{max} as maximum frequency of the signal see [2], has to be fulfilled. In order to reduce the computing time, only every fortieth value is used. For a defined time interval the original data of acceleration is shown in Fig. 2, the filtered and downsampled data is displayed in Fig. 3.

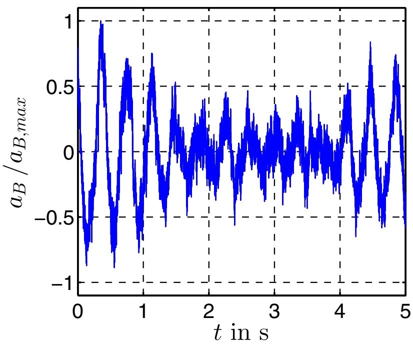

Fig. 2. Original acceleration

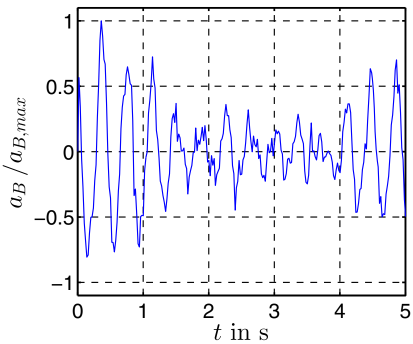

Fig. 3. Filtered acceleration

Due to reasons of confidentiality, all values here and in the following are normalized.

4 Optimization

One chooses an acceleration of platform B for example by measurement a_B and tries to move platform A in such a way that certain conditions are kept. The acceleration a_A has to be found in a way that ε reaches a minimum. Furthermore the inequality constraints have to be kept. In Fig. 4 the simplified model of the two platforms is illustrated. The optimization problem is now defined as (5) where $a_{A,i}$ is the acceleration and $x_{A,i}$ is the position of platform A, $x_{B,i}$ is the

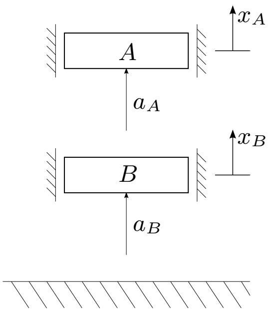

Fig. 4. Simplified model

$$\begin{aligned} &\min_{a_{A,i}} \ \varepsilon \\ |a_{A,i}| &\leq \varepsilon \\ |x_{A,i} - x_{B,i}| &\leq s_{max} \end{aligned} \tag{5}$$

position of platform B at the timestep i, i runs over all measurements, and s_{max} is the maximum of displacement. The initialvalue of $\mathbf{x}_0$ is assumed to be $\mathbf{x}_0 = \mathbf{0}$. With (4) the second constraint of (5), can also be written as

$$\left| \sum_{k=0}^{i-1} \left(i - k - \frac{1}{2} \right) T^2 \left(a_{A,k} - a_{B,k} \right) \right| \leq s_{max} \, .$$

The minimization of ε, see (5), is a linear program. To be able to expand it to nonlinear dampers in the future, the software package NLOpt is used. The optimization is solved with GNU Octave [3], where an algorithm of the NLOpt package [4] of the Massachusetts Institute of Technology is used. Following code shows a pseudocode of the programming with the NLOpt package in GNU Octave:

```
opt.min_objective = @myfunc;
opt.fc = cell(1,2*N);

for i=1:1:N
    opt.fc(i) = {(@(x)myconstraint1(x,i))};
    opt.fc(i+N) = {(@(x)myconstraint2(x,i))};
end

[xopt,fmin,retcode] = nlopt_optimize(opt,[max(abs(g)) g']);
```

In line one the NLOpt-algorithm is set to an SQP-solver (sequential quadratic programming), see [5] and [6]. In the second line the objective function *myfun* is defined, where ε is minimized with the chosen algorithm. The length of the vector for the constraints is defined in line number 3. We have two constraints, so the length of the vector for the constraints is two times the number of the optimization variables N. Furthermore in line six and seven the inequality constraints are specified as a cell array of function handles, which have to be kept in every point in time i. The last line, number ten, shows the call of the optimization routine, that returns amongst others the outputs $\mathbf{x}_{opt}^T = \left[\, \varepsilon \; \mathbf{a}_A \,\right]$. Here the vector $\left[\, \max(\text{abs}(\mathbf{g})) \; \mathbf{g}' \,\right]$ shows the initial values for the optimization, where $\mathbf{g}$ is the filtered measured data of platform B. The SQP-solver is a gradient-based algorithm, so the function *myfun* but also the function for the constraints *myconstraint1* and *myconstraint2* have to contain the gradient.

5 Optimization Results

In absence of constraints the optimization with active damping and acausal control would yield a lower limit for the acceleration of the platform A equal to zero, but due to the specified constraints, the optimal acceleration $a_{A,opt}$ is not zero. The results for the displacement is shown in Fig. 5. In Fig. 6 the measured data a_A of platform A is shown for comparisons to the optimized acceleration of platform A, which is displayed in Fig. 7.

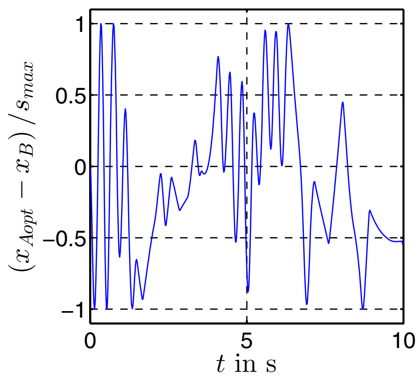

Fig. 5. Inequality Constraints

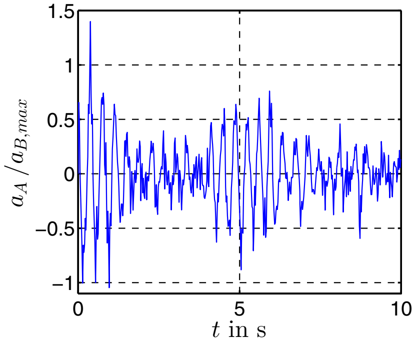

Fig. 6. Measured data of platform A

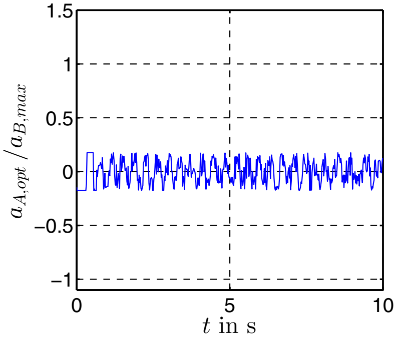

Fig. 7. Optimized acceleration of platform A

5.1 Overview of Acceleration

The acceleration of the tractor was measured in three points. The following tablet contains the measured data and the corresponding optimization results. In Tab. 1 you can find the minima, the maxima and the Euclidean norm of the measured and of the optimized data. The maximum norm of the acceleration of platform A can be reduced by a factor of 4 to 8 compared to the system without active damping.

Table 1. Optimization results

		B	A	
		MD filt.	MD filt.	OPT
1	max a	+1.00	+1.50	+0.23
	min a	−0.95	−1.26	−0.23
2	max a	+1.00	+1.42	+0.18
	min a	−0.81	−1.05	−0.18
3	max a	+1.00	+0.68	+0.14
	min a	−0.85	−0.61	−0.14

		A	
		MD filt.	OPT
1	$\|a\|_2$	8.53	3.34
2	$\|a\|_2$	6.71	2.42
3	$\|a\|_2$	4.27	2.06

6 Conclusions and Outlook

The next step is to optimize the parameters of the semi-active system, where the damping characteristic of the hydraulic device is adjustable. For solving the parametric optimization problem, several typical acceleration profiles will be taken into account. For the implementation of the semi-active damper, the following scenario has to be adapted: Find an optimal choice of the damping parameter, which should be adaptable to the recent damping behavior.

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