Reducing Off-road Vehicle Seat Vibrations Using Hydraulic Piston and Fuzzy Logic Controller

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Abstract - This paper examines the capabilities of fuzzy logic based controllers in the process of active suspension of a heavy vehicle seat vibrations. The hydraulic cylinder is used as an active element, while the damper and the air spring are used as passive elements for reducing vibrations. MATLAB and Simulink are used as tools for developing the simulation model of the driver seat. The mathematical model was created according to the physical setup of the vehicle seat at the testing laboratory. Description of the seat, including its mechanical characteristics and mathematical model, is given in the paper. Control system description and implementation on the experimental setup using dSPACE module, is also explained. The SEAT value is used for the validation of control quality. The obtained simulations show that the developed suspension controllers provide superior passenger comfort for different types of road.

Keywords - SEAT value; active suspension; reducing vibrations; hydraulic cylinder; air spring; damper; fuzzy logic; fuzzy controller

I. INTRODUCTION

It is proven that driving a heavy vehicle for a long time period can cause health disorders on a driver's body [1,2]. Some medical studies indicate that the low frequency is responsible for these health disorders, such as, a low back pain, fatigue and stress. According to the ISO 2631 standard, the human body is most sensitive to vibrations' frequencies from 1 Hz to 80 Hz [1].

Classical control theory was usually used for reducing vibrations of the heavy vehicle seat. These approaches are based on an explicit mathematical model description [3-5]. But, the difficulty to mathematically describe some physical phenomenon appeared to be the main limitation in the traditional control methods. Either the user is unable to collect all the needed informations about the system, or the mathematical equations are too complex. With the development of soft computing techniques, a great progress was made in solving the mentioned problems. Seat vibrations were reduced using neural networks [6-8], fuzzy logic [9] and hybrid modes [10] to control passive and semi-active elements in the under-seat construction. This paper introduces the hydraulic cylinder as an active element, that can achieve higher levels of suspension performance. Two parameters describe the performances of the control system: acceleration of the seat and the deflection. Active elements allow design of the suspension controllers that focus on minimizing the accelerations of the seat (hence, the forces on the driver), in a broader range of the deflection.

In order to develop a control system for vibrations reduction, a physical setup of the vehicle seat is assembled in the laboratory. In order to simulate the behaviour of the system, it was necessary to create a mathematical model. Then, a control concept which minimizes the impact of the vibrations on a driver's body is obtained. The experiments are conducted by acting on a vehicle seat (both simulated and real model) with the test signals that represents a bumpy road.

The main goal of this project was to discuss the results of vibrations reduction that can be achieved for very difficult types of road, using a fuzzy logic based controller, and the combination of active and passive control elements. There are several advantages of the used approach. In order to design the fuzzy controller, the exact dynamics of the whole system does not need to be known, which is not the case in [3-5]. With the usage of the hydraulic cylinder as an active element, it is possible to generate forces in both directions, which is a great progress comparing to the passive and semi-active elements previously used [6-10]. It will be shown that the designed controller gives superior results, even for the most difficult types of road.

The paper is organized as follows. In Section II the model of the vehicle seat is presented. The limitation for the control concept and the design of road adaptive suspension controllers are the subject of Section III. Implementation of the control algorithm in the experimental setup is briefly discussed in Section IV. Concluding remarks are found in Section V.

II. MODEL DESCRIPTION

A physical model of the heavy vehicle seat is given in Fig.1. It consists of the seat, its suspension system and 75 kg dummy, which represents the driver's body. The suspension system, which consists of three elements, the hydraulic cylinder (piston), the damper and an air spring, is fixed to the vehicle's cabin floor.

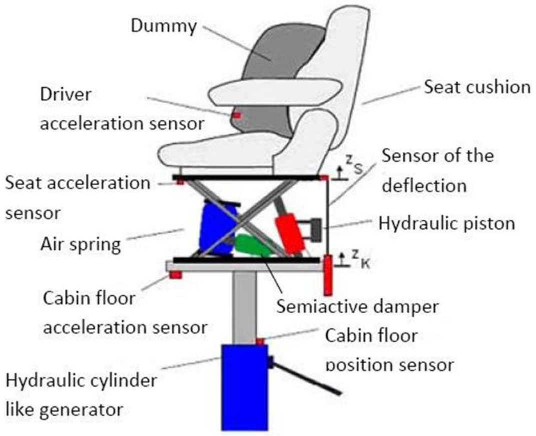

Figure 1. Model of the seat

A simulation of the cabin floor movements is done using a hydraulic cylinder, which generates the vibrations. The vibrations need to be isolated in the under-seat area, so they should not be transferred to the driver. It can be seen in Fig. 1 that the seat is equipped with 5 sensors, which enable collecting all the needed data.

It is possible to describe the mathematical model of the seat by a second order differential equation:

$$m_s\ddot{z}_s = F_{LF,V} + F_{D,V} + F_S - F_{R,S} - m_S g; \qquad (1)$$

Where:

- $\ddot{z}_s$ - the acceleration of the seat,
- m_s - the total mass of the seat, including the mass of the seating area, the mass of the cushion and the mass of the dummy,
- F_S - the hydraulic cylinder force,
- $F_{R,S}$ - friction force in the under-seat construction,
- $F_{LF,V}$ - force that represents the influence of the air-spring at the seat,
- $F_{D,V}$ - the oil damper force.

Considering that this paper deals only with a hydraulic cylinder as an active element, it will be described in more detail. The cylinder consists of two chambers, A and B, as it is shown at Fig. 2. These two chambers are connected through a valve. The openness of the valve is controlled by an external energy source, and can vary from fully open to completely closed. An external energy source allows us to generate the force needed to move a piston. The valve allows changing the flow diameter. Pressure difference between two chambers depends of the flow diameter, and it corresponds to the cylinder force.

When the piston is moving forward, the oil from the front chamber is squeezed out and sucked in the back chamber, and vice versa. Due to existence of the auxiliary pressure sources, P_T - tank pressure, and P_0 - permanent pressure source, it is possible to generate a force in both directions, independently of the piston's movement direction [13].

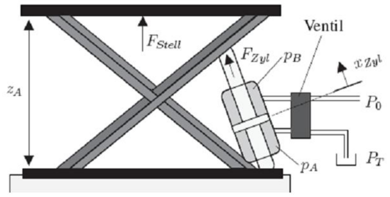

Figure 1. Hydraulic cylinder model

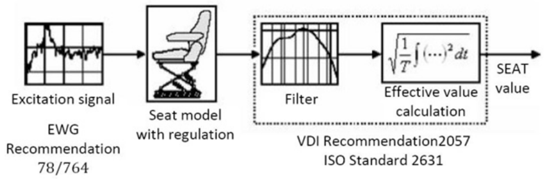

Figure 3. SEAT value evaluation scheme

It should be noticed that the complete and detailed mathematical model of the seat (including the model of the damper, air spring and other physical processes) is far more complex [11-13] then the presented one, and it is not included in this paper for the sake of simplicity.

III. CONTROL SYSTEM DESCRIPTION

A. A limitation and validation for the control concept

Two important measures of quality for the control system to be developed are: deflection and SEAT value [11-13].

Deflection is defined as the relative movement of the seat to the cabin floor, which is evaluated as a difference between the movement of the seat z_S, and the movement of the cabin floor z_k:

$$z_A = z_S - z_K; \qquad (2)$$

The allowed deflection of the seat is less than 5 cm: $|z_A| < 5$ cm. Excessing this value would result in damage to the under-seat construction.

The second criterion that is used to measure the control quality in this paper is the SEAT value. Smaller SEAT value means that more unwanted vibrations are isolated. SEAT value is calculated as the ratio between the values of the effective seat acceleration, and effective cabin floor acceleration:

$$SEAT = d^2 z_{S_{ef}} / d^2 z_{K_{ef}}. \qquad (3)$$

Fig. 3 presents a scheme that is used to calculate the SEAT value. Before the SEAT value evaluation, the measured values of the accelerations (seat and cabin floor) are filtered. The filtering is done using the VDI 2057 German engineers' recommendations and ISO standard 2631 [1]. The filter is designed with sensitiveness of a human body to specific frequency of the vibrations in mind.

Driving heavy vehicles is usually done at very bumpy roads. As a result, high vertical vibrations occur. These vibrations are carried to a driver through the seat construction. These signals are the representation of a bumpy road. The examinations were done using ISO *em3* signal, because it is the one that simulates the toughest conditions of the road.

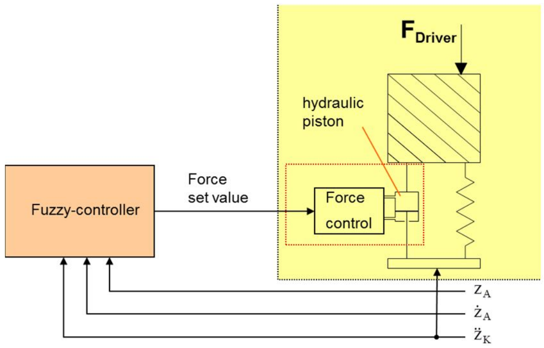

Figure 2. Fuzzy controller design

B. Fuzzy controller design

In this paper, a Sugeno fuzzy controller was used. It uses less processing time, and shows better performance when used in a real-time applications.

Designed fuzzy controller use three input variables, which are the deflection of the seat (z_A), the velocity of the deflection ($\dot{z}_A$) and an acceleration of the cabin floor ($\ddot{z}_K$) [11-13] (see Fig. 4). A force of the hydraulic cylinder is used as an output variable of the fuzzy controller. It was also necessary to compensate the influence of an oil damper and an air spring to the system, in the process of generating force intensities of the fuzzy controller.

Triangular and trapezoidal membership functions are used to describe input variables of the controller. The best response of the system was achieved using these two types of membership functions

While designing the rules for the fuzzy controller, it was noticed that the rules which had good control performance concerning the SEAT value had a negative impact on the values of the seat deflection. So, writing the appropriate set of rules was actually equal to finding the balance between decreasing the SEAT value and assuring that the deflection stays in the allowed range of $\pm$5cm. This is one of the contributions of this paper.

IV. IMPLEMENTATION ON THE EXPERIMENTAL SETUP

The designed controller is created and adjusted using MATLAB/Simulink. After getting and improving the results in the simulation environment, the testing was done at the experimental setup, installed in the laboratory.

The dSPACE card is used as an interface between the experimental setup and the computer. As shown in Fig. 5, the signals that are acquired from the sensors are transmitted to the dSPACE card, through a series of the amplifiers and signal conditioners. Likewise, output signals of the dSPACE card are through amplifiers transferred to the under-seat construction.

MATLAB is used as a sofware interface between dSPACE module and the seat model.

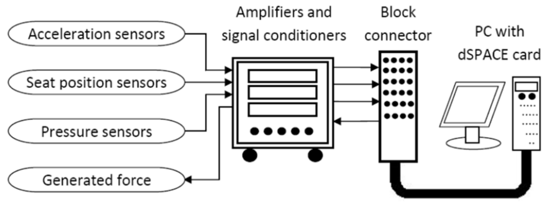

Figure 3. Schematic view of the experimental equipment

V. SIMULATION AND EXPERIMENTAL RESULTS

A MATLAB/Simulink model according to section II was developed for simulation. All simulations, and experiments on the physical model, were conducted in a duration of 25 s, what is considered to be enough time for the unwanted transients to subside.

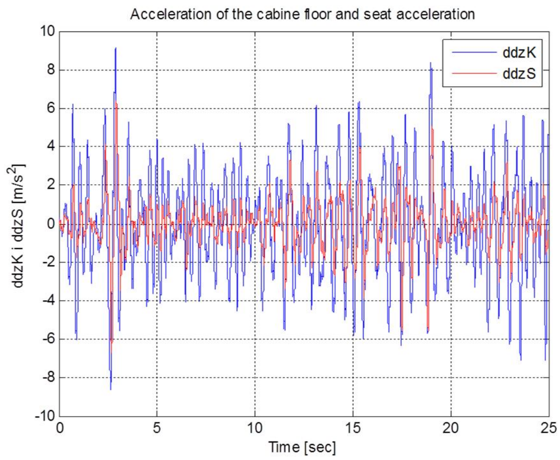

Figure 4. Acceleration of the seat and cabin floor

The best result of the simulation was SEAT = 0.41, with satisfied limitation of the seat deflection, and *em3* as test signal. Fig. 6 shows a diagram of the cabin floor acceleration and acceleration of the seat. It is easy to notice that most of the time the acceleration of the seat is much lower than the acceleration of the cabin floor, which means that designed control is quite good. The main characteristic of the system is its high sensitivity, and small changes in external force tend to augment deflection out of its limits. With the designed fuzzy controller the deflection is in the allowed range, as visible from Fig. 7. The highest value of the seat deflection is 4.8 cm. The forces that are implemented at the hydraulic cylinder are shown in the Fig. 8. It can be seen at the figure that the forces change rapidly. Most of the time the generated forces do not have high intensity. In those situations, when the deflection is not threatened, the main goal was to reduce the acceleration of the seat as close to zero as possible. This means that the resulting forces are small. But in the critical situations, high intensity of the force had to be chosen to contain the deflection value within its range, which had a negative impact at the SEAT value.

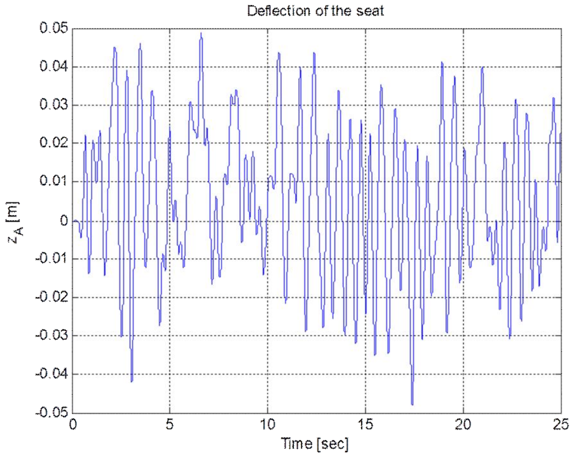

Figure 5. Deflection of the seat

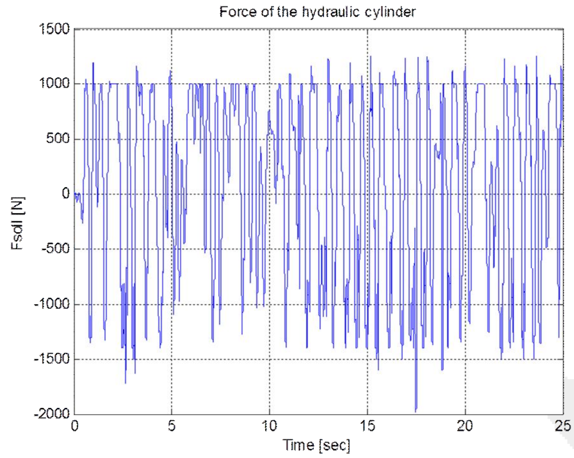

Figure 6. The hydraulic cylinder force

The results of the control algorithm on the physical setup were not as good as in the simulation, as expectable. The results differs mostly because of the innacurate model (e.g. friction very difficult to model exactly as it is), and noise. Hence, the seat value SEAT = 0.52 is obtained.

Conclusion and Future Work

The advantage of using the fuzzy logic controller is that the exact dynamics of the system does not need to be known, which is often the case. Also, as it can be seen from the presented results, fuzzy logic based controllers with active suspension are capable to reduce about 60% of the unwanted vibrations of the seat. With active element in the under-seat construction we can maintain the soft setting (forces with less intensity) for a large portion of the deflection range. It is recommended to switch to the stiff setting (higher forces intensity) as the critical deflection limit is reached. In this work, deflection is always in the predefined limits, even at the real model. Also, in order to maintain the deflection in its limits, in [4-8] SEAT value is sligthly increased, which is not an issue for the control system described in this paper.

Acknowledgment

All the experimental work was conducted at the Department for Automatic Control of the Friedrich Alexander University in Erlangen – Nürnberg, and supported by DAAD.

References

[1] International Organization for Standardization, ISO 2631-1: Mechanical vibration and shock – Evaluation of human exposure to whole body vibration – Part 1. General requirement, 1997.

[2] International Organization for Standardization, ISO 7096: Earth-moving machinery – Laboratory evaluation of operator seat vibration, 2000.

[3] I. Fialho, and G. J. Balas, "Road Adaptive Active Suspension Design Using Linear Parameter-Varying Gain-Scheduling," IEEE Transactions on Control Systems Technology, vol. 10, no. 1, pp. 43 – 54, January 2002.

[4] C. H. Chuang, and Q. Wang, "Active Controllers for Reducing Vibration Amplitude," American Control Conference, pp. 1611 – 1615, June 1992.

[5] A. J. Connolly, M. Green, J. F. Chicharo, and R. R. Bitmead, "The design of LQG and H_∞ controllers for use in active vibration control and narrow band disturbance rejection," IEEE Conference on Decision and Control, pp 2982 – 2987, vol. 3, December 1995.

[6] Z. Avdagic, S. Cernica, and S. Konjicija, "Reducing Vibration of the Seat with Semi-active Damper by Using the Artificial Neural Networks," International Joint Conference on Neural Networks, pp. 125 – 130, August 2007.

[7] Z. Avdagic, S. Konjicija, and S. Ruhotina, "Use of artificial neural networks in different approaches for reducing vibration of driver's seat," IEEE International Conference on Industrial Informatics, pp. 313 – 318, June 2009.

[8] O. Tanovic, and S. Huseinbegovic, and B. Lacevic, "Road Type Recognition Using Neural Networks for Vehicle Seat Vibration Damping," IEEE International Symposium on Signal Processing and Information Technology, pp. 320 – 323, December 2008.

[9] S. Huseinbegovic, and O. Tanovic, "Adjusting stiffness of air spring and damping of oil damper using fuzzy controller for vehicle seat vibration isolation," International Siberian Conference on Control and Communications, pp. 83 – 92, March 2009.

[10] O. Tanovic, and S. Huseinbegovic, "Hybrid fuzzy-neural network structure for vehicle seat vibration isolation," IEEE International Conference on Control and Automation, pp. 2354 – 2359, 2009.

[11] G. Meier, G. Roppenecker, and Ch. Wurmthaler, "Regelungskonzepte für Fahrzeugsitze mit semi-aktiver Dämpfung," VDI-Berichte Nr. 1672, pp. 53 – 59, 2002.

[12] A. Kühnlein, and Ch. Wurmthaler, "Aktive Federung eines Fahrersitzes mittels Idealmodell," VDI-Berichte Nr. 1971, pp. 785 – 792, 2007.

[13] A. Kühnlein, "Regelung eines aktiven Nutzfahrerzeugsitzes mittels Idealmodell, " VDI-Berichte Nr. 2002, pp. 521 – 535, 2007.