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SEMIACTIVE CONTROL STRATEGIES FOR A FULLY SUSPENDED BICYCLE

SUMMARY

The purpose of this work is to present methods for designing semiactive vibration systems, which include mathematical models of vibrating structures. Thus aspects of model building, identification and verification are described in the paper as well as determination of the performance indices, choice of the damping technique, shock absorber modeling and algorithm selection. The article presents a semiactive vibration system analysis of a fully suspended bicycle. For all of the simulation experiments and serving as a reference for the identification experiment a phenomenological model of the bicycle was developed in the Simulink environment. The model was confronted with the real time experiments, which were conducted with the help of an electrical system. The necessity of the discussion of the various performance indices is underlined. Simple control strategy is tested on the bicycle.

***Keywords**: semiactive systems, vibration damping, nonlinear systems, full suspension bicycle, identification*

STRATEGIE STEROWANIA PÓŁAKTYWNYM ZWIESZENIEM W ROWERZE

Artykuł przedstawia metody sterowania układem półaktywnego tłumienia drgań w pełni zawieszonym rowerze Scott G-Zero Fx-2. Zaprojektowano elektryczny układ wspomagający sterowanie tłumikiem MR bazujący na pomiarze przyspieszenia. W celu przetestowania układów regulacji zaprojektowano model fenomenologiczny roweru wyposażonego w tłumiki MR. W artykule zaprezentowano rozważania dotyczące metody identyfikacji modeli nieliniowych zaproponowanych przez autora. Przedstawiono również strategie sterowania zawieszeniem półaktywnym roweru.

1. INTRODUCTION

Although the idea of semiactive suspension has been know and studied in the last decade there are few commercial applications in offer. The reason for that is the control difficulty and still maintenance and resistance problems. One of the first commercial applications of other than passive suspension in the automotive industry was an active pneumatic suspension introduced by Lotus. It is obvious that such suspension requires huge amounts of energy, and is thus economically unjustifiable. In applications were energy amount is crucial and bounded like the automotive industry semi and quarter active suspension systems are being recently developed. One of the known commercial applications is the Delphi MagneRide™ used in Cadillac STS automobiles. MagnetoRheological (MR) suspension is effective, however because of the used MR fluids, which are temperature sensitive and loose their agility under stress, there is still work to be done in the field of their design and the design of the control suspension systems with MR fluids.

Recently most of the work devoted to applications of the MR and ER suspension dampers concentrates on vibration damping in the automotive machines [4, 5, 7, 11] and beam structures such as buildings or bridges for seismic protection [6, 13, 15]. Although some attempts have been made to construct an MR damper for bicycles [2, 11] few applications if any have been developed to yield a complete control system.

Although semiactive suspensions offers low energy operation it is difficult to control because of it's nonlinear nature since the parameters' change serves as a control signal. Furthermore it can only offer vibration damping throughout the control of the energy dissipation. However some of the recent publications state that proper control can provide fully active behavior of the semiactive MR suspension systems [3].

The paper introduces an MR suspension system in a fully suspended Scott G-Zero Fx-2 bicycle (Fig. 1).

The bicycle rear suspension has been replaced by a Lord RD-1005-03 MR damper and a dedicated spring, which can generate a force of 2 kN to 2.5 kN. Lord W-Box is used for current flow setting in the MR damper windings. An electrical circuit has been designed (MTB MRS – Mountain Bike Magnetorheological Suspension System) to control the MR damper current depending on the measurements of the accelerations of primarily 2 and eventually 4 elements of the bicycle. For control tests a simplified phenomenological

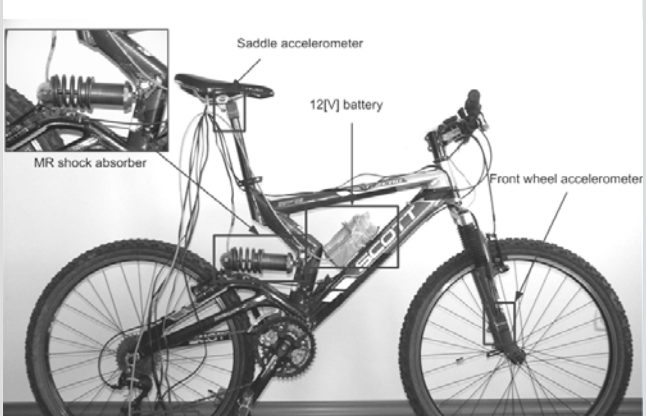

Fig. 1. MR suspension system in a fully suspended bicycle

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model of the bicycle with MR damper [1] has been assembled in the Simulink environment. Since behavior of the most of the plants cannot be approximated by linear models a nonlinear identification is considered with the use of the method described by K. Plaza in [9].

Determining the control index in the automotive machines is more complicated than it is in 1-D simulations. Behavior of the suspension should be adjusted depending on the road situation. That aspect is considered in the paper.

A few of the control algorithms, which are mentioned in the publications [3, 4, 10] are discussed for the bicycle suspension control.

2. BICYCLE AND MTB MRS DESCRIPTION

The fully suspended Scott G-Zero Fx-2 has been upgraded by substituting its oil damper with an MR damper in the rear suspension (Fig. 1). A 3.4 Ah, 12 V Panasonic Battery has been attached to the bicycle to provide the power supply for the Lord W-Box™ and the MTB MRS electrical system. The acceleration/orientation sensors have been attached to the front fork and under the saddle. Eventually 4 measurements in 2 axis will be used, additionally on the handlebars and the rear wheel axis.

2.1. MTB MRS system

MTB MRS is an electrical circuit of the elements and features (Tab. 1).

Table 1. MTB MRS parts description

Element name	Features
RCM3000 core module	Core module with Rabbit processor, 3.3V Supply, 512kB Flash, Ethernet, I/O, Low Power, Timers…
ADS8345	16 bits, 8 channels, SPI…
DAC7513N	8 bits, 1 channel, SPI...
Atmel DataFlash	8MB Flash memory
Power Circuit	12V input, 5V,3.3V output
LCD Display	Low power
Keyboard	4 buttons for communication
Lord W-Box™	12V supply, 0-5V control, 0-2 A output
MEMSIC accelerometers	2 orthogonal outputs, ± 2g range

The above described circuit allows for MR suspension control and data acquisition.

3. BICYCLE PHENOMENOLOGICAL MODEL

To completely model bicycle's behavior on the road an enormous amount of factors would have to be taken into account as it has been done in [8]. However for the purpose of the suspension system design such model can be simplified greatly just as it has been done in [3, 4, 10]. For the first phenomenological model only vertical bicycle parts movement is taken into account. With that assumption the model presented in Figure 2 has been constructed.

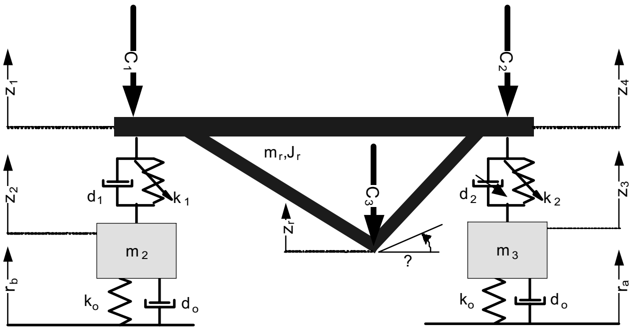

Fig. 2. Bicycle phenomenological model

The forces assigned by C_1, C_2, C_3, represent vertical forces generated by the bicycle rider respectively on the handlebars, saddle and pedals. According to that mechanical model the equations describing the bicycle's vertical movement on the road were derived:

$$m_r\ddot{z}_r = -k_1(z_1 - z_2) - d_1(\dot{z}_1 - \dot{z}_2) - m_r g - C_1 - \\ - C_2 - C_3 - k_2(z_4 - z_3) - d_2(\dot{z}_4 - \dot{z}_3) \tag{1}$$

$$m_2\ddot{z}_2 = k_1(z_1 - z_2) + d_1(\dot{z}_1 - \dot{z}_2) - \\ - m_2 g - k_o(z_2 - r_b) - d_o(\dot{z}_2 - \dot{r}_b) \tag{2}$$

$$m_3\ddot{z}_3 = k_2(z_4 - z_3) + d_2(\dot{z}_4 - \dot{z}_3) - \\ - m_3 g - k_o(z_3 - r_a) - d_o(\dot{z}_3 - \dot{r}_a) \tag{3}$$

$$J_r\ddot{\varphi} = r_1\cos(\alpha_{C_1} - \varphi)\cdot C_1 - r_3\sin(\alpha_{C_2} - \varphi)\cdot C_2 - \\ - r_1\cos(\alpha_{C_1} - \varphi)\cdot F_{T_1} + \\ + r_3\sin(\alpha_{C_2} - \varphi)\cdot F_{T_2} + r_{mg}\sin(\alpha_{mg} - \varphi)\cdot m_r g \tag{4}$$

where:

$$F_{T_1} = -k_1(z_1 - z_2) - d_1(\dot{z}_1 - \dot{z}_2) \tag{5}$$

$$F_{T_2} = -k_2(z_4 - z_3) - d_2(\dot{z}_4 - \dot{z}_3) \tag{6}$$

$$z_1 = z_{1,0} - r_1\sin(\alpha_{1r}) - \\ - (z_{r,0} - z_r) + r_1\sin(\alpha_{1r} + \varphi) \tag{7}$$

$$z_4 = z_{4,0} - r_3\sin(\alpha_{2r}) - \\ - (z_{r,0} - z_r) + r_3\sin(\alpha_{2r} + \varphi) \tag{8}$$

All of the parameters, which are not shown for the sake of clarity in Figure 2 are the geometrical parameters of the tested bicycle (r_1, r_3, r_{mg}, α_{C1}, α_{C2}, α_{mg}, α_{1r}, α_{2r}).

Assuming that the rear shock absorber includes an RD-1005-03 MR damper the following equations given by B.F. Spencer Jr., S.J. Dyke, M.K. Sain, J.D. Carlson in [1], can be included in the phenomenological model description:

$$f = c_1 \dot{y} + k_{MR}(x - x_o) \tag{9}$$

$$\dot{z} = -\gamma |\dot{x} - \dot{y}| z |z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \tag{10}$$

$$\dot{y} = \frac{1}{c_1 + c_0}\left[\alpha z + c_0 \dot{x} + k_0 (x - y)\right] \tag{11}$$

$$\alpha(u) = \alpha_a + \alpha_b u \tag{12}$$

$$c_1(u) = c_{1a} + c_{1b} u \tag{13}$$

$$c_0(u) = c_{0a} + c_{0b} u \tag{14}$$

$$\dot{u} = -\eta(u - v) \tag{15}$$

The explanation of what each equation represents and the parameters values of the MR model are presented in [1]. What is important for the bicycle phenomenological model is the generated force by the MR damper, which is assigned by f and the control voltage of the W-Box™ assigned as v. The model described by the above equation was assembled in the Simulink environment.

4. CONTROL STRATEGIES

Last 50 years of achievement in the field of semiactive control algorithms are shortly described by D. Hrovat [4]. In the recent years due to the growth of the application possibilities semiactive control has been developed further. Benefits of such approach are strongly underlined however the control difficulties due to inherited nonlinear dynamics still make it challenging to apply. Automotive machines force higher level algorithms use for satisfactory riding performance. In automotive suspension system analysis the car models where simplified throughout quarter or semi car models and neglect the bounds of possible displacement of suspension parts, which stand an additional nonlinearity. That also forces the performance indexes to be verified. Several control strategies for a fully suspended bicycle are mentioned in the following paragraphs.

4.1. First principle control

Assuming that the performance index trying to be minimized is the mean value of the acceleration of the saddle, a simple first principle control algorithm can be designed. Simplifying the behavior of the MR damper to an on-off device the damping can be switched on or off depending on the z_4 acceleration reading. In Figure 3 results of the simulation of such control scheme of the fully suspended bicycle are presented.

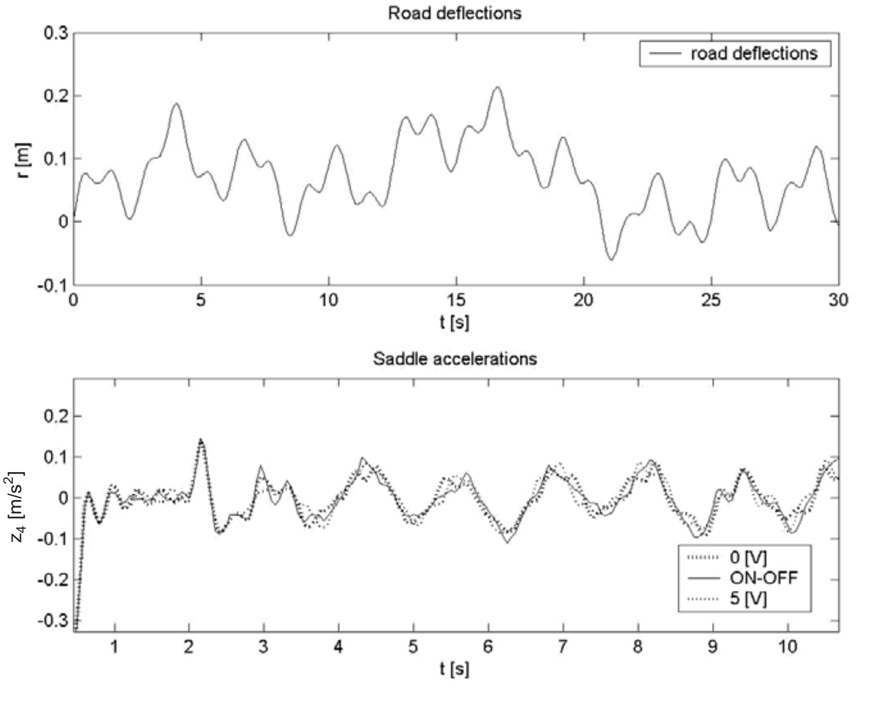

Fig. 3. On-off control results

4.2. Optimal control

Assuming a following linear description of the bicycle can be given:

$$\dot{x} = Ax + Bu \tag{16}$$

$$y = Cx \tag{17}$$

and constraints put on the control signal are known, throughout a chosen index optimization another control law can be derived [14]. To obtain linear state space description of the bicycle behavior the plant could be linearized assuming the damping coefficient of the MR damper is constant, maximal and that hysteresis is omitted. The difficulty however in the problem of optimal semiactive bicycle suspension control lies in the fact that the number of states is very high and finding optimal control $u(t)$ through conjugate equations solving might be very sophisticated.

4.3. Frequency response shaping

Solving control problems with classical approach requires linear model identification. Since the voltage $u(t)$ applied to the W-Box controller kit is the input of our system and acceleration of the saddle is the output the following ‘black box’ model identification can be done (Fig. 4).

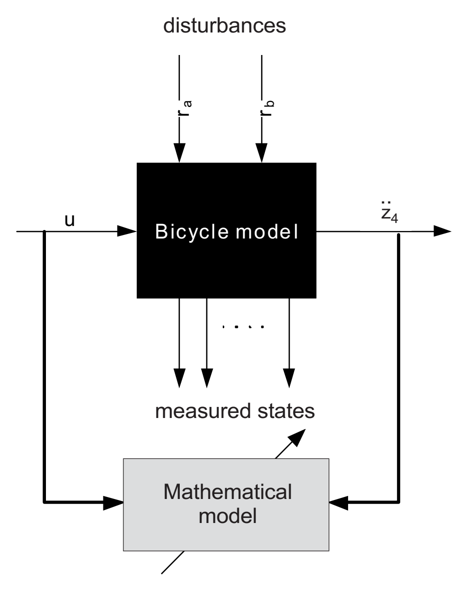

Fig. 4. Black box identification approach

With a mathematical model identified as a transfer function $K(s)$ a controller $C(s)$ can be designed forming the amplitude response of the transfer function $T(s)$ representing disturbance rejection to be minimal in the desired frequency band

$$T(s) = \frac{1}{1 + K(s) \cdot C(s)} \to 0, \text{ for } s = j\omega,\ \omega \in \langle \omega_1, \omega_2 \rangle \tag{18}$$

Depending on the number and values of the $C(s)$ controller parameters the disturbance rejection of the system could be adjusted throughout optimization. The problem could be set as follows: find such a set of $C(s)$ parameters, for which $T(j\omega)$ is for all ω is smaller than a desired value. The whole ω band could be divided into segments with corresponding weights. Additional constraints could be put on some $C(s)$ parameters if necessary. Optimization process with high probability would be nonlinear, concave and with constraints. Robust control optimization methods could be applied.

4.4. Nonlinear control approach

4.4.1. Nonlinear model identification method proposal

Nonlinear models of the fully suspended bicycle with the MR damper could serve their purpose in nonlinear algorithms, which use models for their reference. Accurate model could be also used for state approximation. A phenomenological model, which assembly was depicted above, describes the behavior of a plant model which is of course only an approximation of the full phenomenological description. Furthermore very often exact parameter value determination might be of a problem. Thus the method presented in [9] could be used for identification of some of the parameters’ values or be used for model tuning. The strength of the method, which utilizes system’s structure information, lies in the fact that structure and parameters’ bounds can be predefined with a great certainty especially for mechanical models.

For the full suspension bicycle with MR model identification the above phenomenological model structure could be used. According to [9] parameters’ values bounds could be determined. For the identification purpose during the identification experiment the accelerations of 4 points could be measured. The wheels’ axis accelerations would be used as inputs, since the road displacement cannot be measured, and the acceleration of the saddle would be the output. Additional measurements of the accelerations z_1, z_4, z_r could be used as additional information. With the use of the gradient methods the model of the bicycle, under the parameters’ and signals’ constraints, could be identified. The presented identification algorithm can also be used for MR damper model tuning.

4.4.2. Nonlinear model use for control

The above identified nonlinear model could be used for the purpose of control. One of the algorithms is the IMC control scheme, which would require the use of inverse model of the bicycle with MR suspension. The group of predictive algorithms referring to nonlinear models can also be used along with Lyapunov theory based controllers. An example of nonlinear predictive control schemes is presented by Z. Ogonowski in [12]. Nonlinear model could be used for states observation and state feedback controllers building. Due to the nature of semiactive systems the linearization through feedback scheme is only possible locally.

4.5. Disturbance compensation

Assuming that most of the times the bicycle is riding forward and the front wheel axis measurement is available a classical disturbance compensator can be designed, since the front wheel disturbance will be present after a delay of τ as a disturbance of the rear wheel Figure 5.

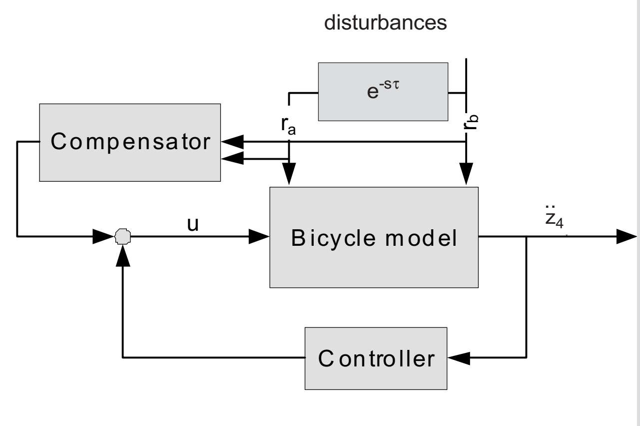

Fig. 5. Road deflections compensation

5. CONCLUSIONS

A fully suspended bicycle allows for the tests of advanced algorithms. Similar problems as faced in cars' suspension control systems are present, thus tested on the bicycle can be developed to be used in automobiles. Still some of the situations are unique for the bicycle like braking on a steep downhill section or the so called 'bobbing action' during pedaling. The movement of the rider can influence the bicycles behavior to a great extent and could also be the topic of identification, modeling and control. Also the fact that while the suspension is softened a lot of energy put to accelerate the bicycle through pedaling might be lost. All of these situations make the bicycle an exceptional object to control and justify the need for study of its behavior with various control algorithms.

The magnetorheological suspension system in a fully suspended bicycle is still being developed. Mechanical and electrical improvements have been made. The above mentioned methods of identification and control are currently tested and their results will be presented in the future.

Including the fact of the suspension travel bound the performance indexes should be verified. This would have an impact on the control algorithms but could prevent from the suspension free travel shortage in case of another shock.

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