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Comparison of Two Fuzzy Skyhook Control Strategies Applied to an Active Suspension

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ABSTRACT

This work focuses on simulation and comparison of two control skyhook techniques applied to a quarter-car of the active suspension. The objective is to provide comfort to the driver. The main idea of skyhook control is to imagine a damper connected to an imaginary sky, thus, the feedback is performed with the resultant force between the imaginary and the suspension damper. The first control technique is the Mandani fuzzy skyhook and the second control technique is a Takagi-Sugeno fuzzy skyhook controller, in both controllers the inputs are the relative velocity between the two masses and the vehicle body velocity, the output of the Mandani fuzzy skyhook is the coefficient of imaginary damper viscous-friction and the Takagi-Sugeno fuzzy skyhook is the force. Finally, we compared the techniques. The Mandani fuzzy skyhook showed a more comfortable response to the driver, followed closely by the Takagi- Sugeno fuzzy skyhook.

Keywords: *Active suspension, Mandani, Quarter-car, Skyhook, Takagi-Sugeno.*

1. INTRODUCTION

The automobile industry is growing up and innovating in order to reduce the cost of production and provide products with the highest technology [1]. A good example of this innovation is the suspension system, which is essential for a professional driver because isolates the vibrations of the vehicle body. According to [2] and [3] these vibrations are the cause of many health problems in the human body, especially back pain. With the advent of new suspensions, they became to be classified as: passive, active and semi-active suspensions. Passive systems are composed by a spring and a damper. Their operation is given by the fact that the damping force is not constant. This variable force depends on the intensity of the suspension compression. When the car undergoes an unexpected obstacle, the suspension has a damping force that increases while the spring and damper are compressed. According to [4], active suspensions are characterized by having an actuator between the tire and the vehicle body. The system is capable to insert or remove energy through the efforts that are variable. The actuator requires sensors to measure the displacement and acceleration of the vehicle body and the tire, which are used as input signals. The force applied between the tire and the vehicle body does not only depend on relative displacement, but also on other variables, as example the position of the vehicle body and the tire and acceleration of the vehicle body. The semi-active suspension is not capable to inject energy into the system, it is just capable to store or dissipate the energy of the system. Therefore, semi active suspensions are not able to achieve the same levels of comfort and stability of an active suspension, but feature a higher robustness and lower cost than active suspension system. They are considered as a “middle ground” between the active and passive suspension [5]. The actuator is often a damper, which is generally constituted by electromechanical valves [6] or valves that use magneto rheological fluid (MR). In the literature, controllers used in semi-active suspensions are skyhook and fuzzy type combined with some optimal control (in this case semi-active suspension with MR fluid) [7]. Therefore, in this article is proposed the design a Takagi- Sugeno fuzzy (TS-F) skyhook, Mandani fuzzy (M-F) skyhook. All controllers were simulated and compared with each other.

In all results, the vibration of the vehicle body was analyzed, because according to [8] when the suspension is designed to give priority to driver comfort, the oscillation in the vehicle body must be as small as possible, regardless the oscillation in the tire. The oscillation can be measured by analyzing the acceleration of the vehicle body.

This article is organized as follows: in Section 2 the modeling of the plant; in Section 4 the M-F skyhook controller; in Section 5 the TS-F skyhook controller; in Section 6 the results obtained in this work and in Section 7 the conclusions are presented.

2. SYSTEM MODEL

The quarter-car model was obtained by isolating a quarter of the vehicle. This model can only be applied in vehicles that have the weight evenly distributed. The model can be observed in Fig. 1. One of the masses represents a quarter of vehicle body (Ms) and the other represents the tire (Mus). Between the masses, there is the active suspension, which is represented by a spring, an actuator (a servo motor) and a damper. The tire stiffness in contact with the ground was simulated using a spring and a damper positioned parallel one to another [9]. For the force representation in each element of the suspension, it was used the relative displacement where the spring constant (Ks), multiplied by the relative displacement between the vehicle body (Zs) and the tire (Zus) represents the spring force; the damper viscous-friction coefficient (Bs) multiplied by the difference between the relative velocity of vehicle body (Zs) and tire (Zus) represents the damper force. The tire force representation was obtained using a system like the passive suspension, a passive damper (Bus) plus a spring (Kus). Thus,

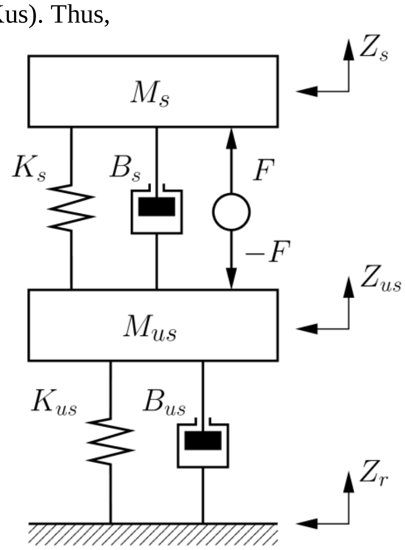

Fig. 1. Model of quarter-car suspension [9].

the representation of the force due to the tire stiffness is given by the difference between the displacement of the ground (Zr) and the irregularities velocity of it (Zr) and the tire. Then, the representation by states space:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \\ \mathbf{y} = \mathbf{Cx} + \mathbf{Du} \end{cases} \quad (1)$$

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & -1 \\ \frac{-Ks}{Ms} & \frac{-Bs}{Ms} & 0 & \frac{Bs}{Ms} \\ 0 & 0 & 0 & 1 \\ \frac{Ks}{Mus} & \frac{Bs}{Mus} & \frac{-Ks}{Mus} & \frac{-(Bs+Bus)}{Mus} \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{Ms} \\ -1 & 0 \\ \frac{Bus}{Mus} & \frac{-1}{Mus} \end{bmatrix}, \mathbf{u} = \begin{bmatrix} \dot{Zr} \\ F \end{bmatrix},$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \frac{-Ks}{Ms} & \frac{-Bs}{Ms} & 0 & \frac{Bs}{Ms} \end{bmatrix}, \mathbf{x} = \begin{bmatrix} Zs - Zus \\ \dot{Zr} \\ Zus - Zs \\ \dot{Zus} \end{bmatrix},$$

$$\mathbf{D} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{Ms} \end{bmatrix}, \mathbf{Y} = \begin{bmatrix} Zs - Zus \\ \ddot{Zs} \end{bmatrix}$$

2.1 Ground Displacement

The simulation of the controllers was chosen a waveform sinusoidal so that the frequency varies from 0 to 100 Hertz, as can be seen (2),

$$Zr = 0,0015\sin(freq \cdot t) \quad (2)$$

where *freq* is a waveform type ramp, with range 0 to 100 Hz and t is the time, 0 to 10 seconds. The Zr waveform can be seen in Fig. 2. This waveform was chosen because according to [10] the main frequency band that the human body is exposed at the maximum varies until 100 Hz. To analyze the acceleration response of the vehicle body was used rms (root mean square) values, which can be calculated with (3),

$$rms = \sqrt{\sum a^2}. \quad (3)$$

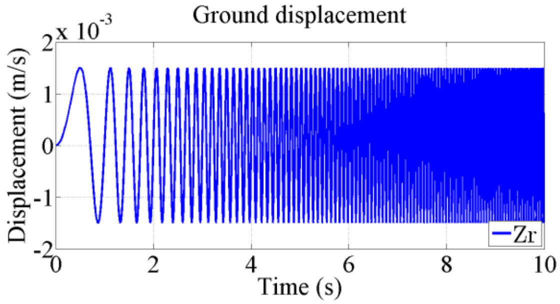

Fig. 2. The Zr waveform, to simulate the ground displacement.

The open loop simulation can be seen in Fig. 3, the vehicle body response showed a maximum rms acceleration (2.07 m/s^2) in the frequency equals 6.31 Hz. In 2.63 Hz, starts increasing the acceleration and in 6.84 Hz decreasing.

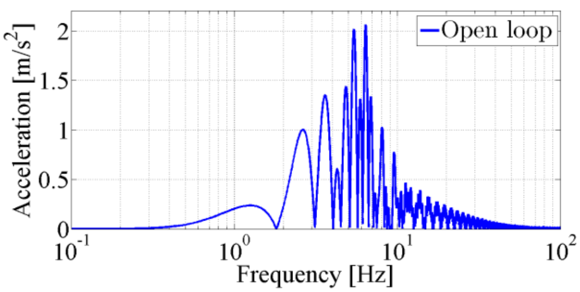

Fig. 3. Response of the vehicle body in rms acceleration, open loop.

3. GENERAL SKYHOOK

The skyhook controller is one of classical semi-active control, but it also can be applied to an active system. The main idea is to imagine a damper connected between the vehicle body and an "imaginary sky". The skyhook can be classified as continuous skyhook and on-off skyhook [11]. The continuous skyhook is designed so that the feedback of the system is the resultant force between the imaginary and the suspension damper [12]. The on-off skyhook is implemented with the control law like the following expression,

$$B_{sky} = \begin{cases} B_{\max} & if \quad \dot{Z}s(\dot{Z}s - \dot{Z}us) \geq 0 \\ 0 & if \quad \dot{Z}s(\dot{Z}s - \dot{Z}us) < 0 \end{cases} \quad (4)$$

where Zs is the velocity of the vehicle body and (Zs - Zus) is the relative velocity of the tire and the vehicle body. To applied this control strategy in a active suspension which the input control is the force, thus, the force generated by skyhook damper (Fsky) is related to velocity of the vehicle body (Zs), as follows,

$$F_{sky} = B_{sky}\dot{Z}s. \quad (5)$$

The continuous skyhook strategy consists in calculating an imaginary coefficient of damper viscous-friction from the critical damping coefficient, as follows, the damping factor of the skyhook damper, that way, (5) can be rewritten as follows,

$$B_{cr} = 2\sqrt{KsMs}, \quad (6)$$

thus, the damping factor of the skyhook damper,

$$\xi_{sky} = \frac{B_{sky}}{B_{cr}} \rightarrow B_{sky} = \xi_{sky} B_{cr}, \quad (7)$$

that way, (5) can be rewritten as follows,

$$F_{sky} = 2\xi_{sky}\sqrt{(KsMs)}\dot{Z}s. \quad (8)$$

In [11] and [13] is used this technique as semi-active controller, with a variable damping coefficient, which depends only on the velocity of the vehicle body and the tire. In [12] is used the force of the skyhook damper equal of the suspension damper, and with that, it obtained a variable damping coefficient that depends only on the velocity of the vehicle body and the tire, it becomes a semi-active controller. The purpose on this article is design an active controller. Thus the resultant force obtained from the difference between the two dampers, skyhook and suspension, was used as the feedback of system,

$$F = bs(\dot{Z}us - \dot{Z}s) - 2\xi_{sky}\sqrt{(KsMs)}\dot{Z}s. \quad (9)$$

4. MANDANI FUZZY SKYHOOK

According to [7], the most common method used in fuzzy control is the Mandani with the connective **AND**. This method is more intuitive, and the specialist knowledge can be applied directly in the controller. In simplified form the fuzzy controller can be divided into three blocks: fuzzification, rule inference and defuzzification. The fuzzification changes numerical values of the fuzzy inputs into membership functions. The rule inference determines how the rules are interpreted, for example, the kind of Mandani with connective **AND** can be interpreted as follows: **IF** [vehicle body velocity is zero] **AND** [relative velocity between the masses is zero] **THEN** [force is zero]. The defuzzification is the opposite of the fuzzification, but with the fuzzy output, i.e., changes the membership function into fuzzy output.

The fuzzy input one is the vehicle body velocity and the other one is the relative velocity between the two masses. This variables were used because the plant outputs are relative displacements between the two masses and the acceleration of the vehicle body, thus differentiating (instead of it, was used a differentiation filter) and integrating the output of the plant, respectively. The imaginary coefficient of damper viscous-friction (B_{sky}) was chosen as fuzzy output. Simulating the open-loop system with the maximum force (39,2 N) and with the minimum force (-39,2 N), the range of the vehicle body velocity was —0,65 to 0,70 m/s and the range of the relative displacement between the two masses was —1,5 to 1,0 m/s. The output range was —66,0 to 00,0 Ns/m (negative sinal comes the (9), but according to [14] when the gain module (Bsky) increasing the damper is little compressed and this gives better ride comfort. After some simulation, the output range is —110,0 to 00,0Ns/m. The fuzzy inputs and output were evenly divided into three triangular membership functions, each one received a name (linguistic variable) which are: Negative (N), Zero(Z) and Positive (P) to inputs, Fig. 4 and 5, the output Bsky (B), Medium Bsky (MB) and Zero (Z), Fig. 6.

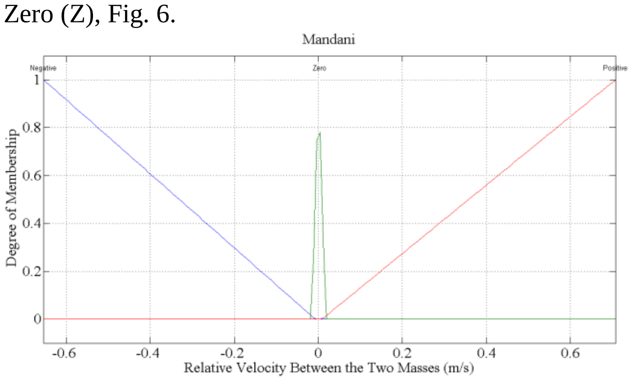

Fig. 4. Membership function of input, the relative velocity between the two masses (m/s).

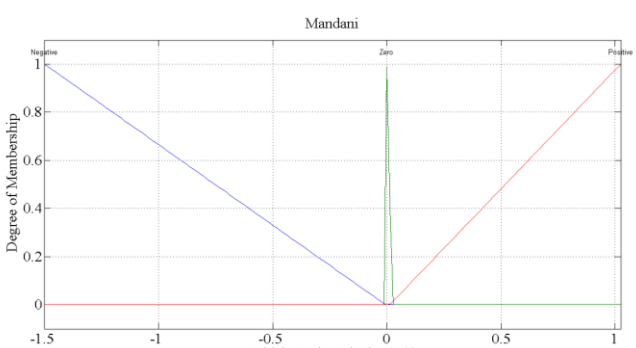

Fig. 5. Membership function of input, the vehicle body velocity (m/s).

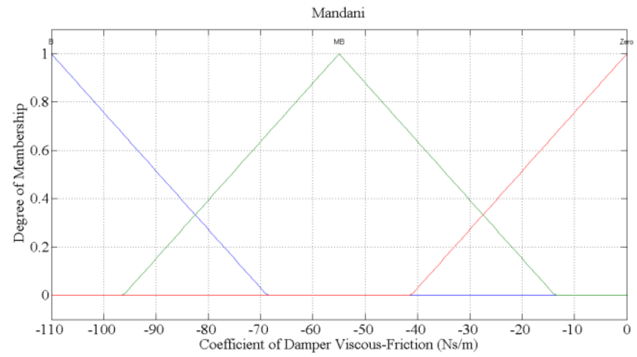

Fig. 6. Membership function of output, coefficient of damper viscous-friction (Ns/m).

Table 1: Fuzzy rules.

		$(\dot{Z}_s - \dot{Z}_{us})$		
		N	**Z**	**P**
$\dot{Z}_s$	**N**	**B**	**MB**	**Z**
	Z	**MB**	**Z**	**MB**
	P	**Z**	**MB**	**B**

Then the table was constructed with the fuzzy rules, Table I. The strategy of the defuzzification is the center area, which calculates the centroid (division of the area into two equal parts) of the composite area by the union of all the rules to generate the fuzzy output. The surface generated with the controller M-F skyhook, can be seen in the Fig. 7, is almost discontinuous, this way the coefficient will have a large variation with a small variation in inputs velocities.

The vehicle body response, Fig. 8, showed a maximum rms acceleration (1,44 m/s2) in the frequency equals 5,37 Hz. In 2,51 Hz starts increasing the acceleration and in 6,31 Hz.

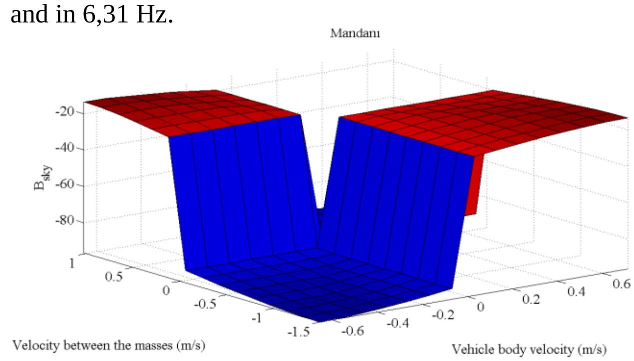

Fig. 7. Surface generated with the controller M-F Skyhook.

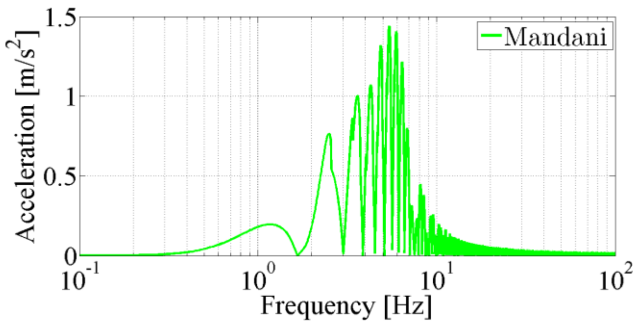

Fig. 8. Response of the vehicle body in rms acceleration, with M-F Skyhook.

5. TAKAGI-SUGENO FUZZY SKYHOOK

The Takagi-Sugeno-Kang or Sugeno method of fuzzy infer-ence is very similar to the Mandani, the difference is that the Sugeno are two kind of output membership functions, linear or constant. The Sugeno can be interpreted as follows:
IF [Input 1 = x] **AND** [Input 2 = y] **THEN** [Output is z = ax + by + c].
For a zero order, the output z is constant (that means a = b = 0) [15]. To design the TS-F skyhook was used the same inputs of the M-F skyhook and the same rules, just the output membership function was modified, in the Table I the linguistic variables B and MB were changed to F and MF respectively. Equation (9) is a linear equation, thus the membership function was interpreted as two linear function (F and MF) and one constant (Z), where F is (9), MF is (10) and Z is constant and equal to zero.

$$MF = Bs(\dot{Z}us - \dot{Z}s) - \xi_{sky}\sqrt{(KsMs)}\dot{Z}s. \quad (10)$$

The Mandani uses as output a linguistic variable, as the Takagi-Sugeno output uses a linear equation, that way, the final output of the TS is the weighted average of all outputs level, Z_i, with the firing strength of the rule, W_i. An example, consider the [Input 1 = x] and [Input 2 = y], the final output with **AND** rule [15], as follows,

$$\text{Final Output} = \frac{\sum_{i=1}^{N} W_i Z_i}{\sum_{i=1}^{N} W_i}, \quad (11)$$

where N is the number of rule.

The surface generated with the controller TS-F skyhook, can be seen in the Fig. 9, this surface will have a small force variation with a large variation in inputs velocities.

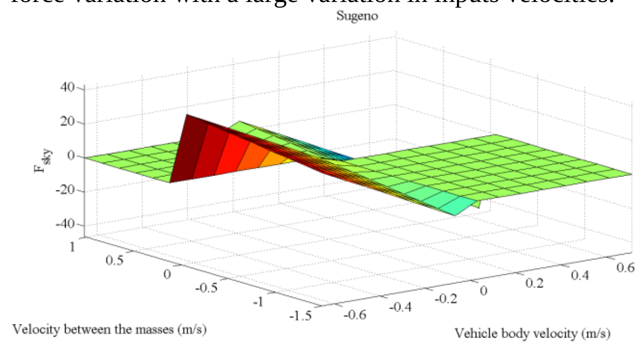

Fig. 9. Surface generated with the controller TS-F Skyhook.

The transition is softer than the M-F skyhook. The vehicle body response, Fig. 10, showed a maximum rms acceleration (1,56 m/s2) in the frequency equals the M-F skyhook (5,37 Hz). The acceleration starts increasing in 2,00 Hz and in 6,31 Hz decreasing.

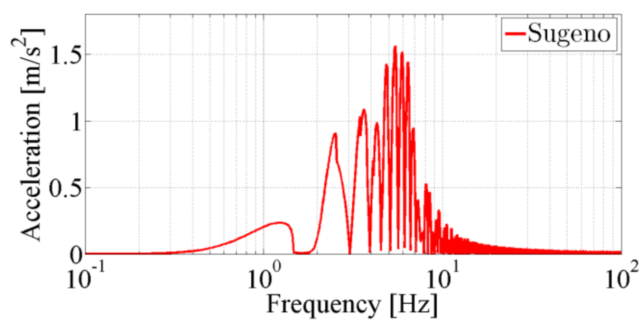

Fig. 9. Response of the vehicle body in rms acceleration, with TS-F Skyhook.

6. RESULTS

In Fig. 8 and 10 is shown the rms acceleration responses of the vehicle body. The controller M-F skyhook has showed the lowest acceleration amplitude compared with the TS-F skyhook and the frequency range was smaller than the TS- F skyhook.
This difference is due to the fact that the variation of the output of TS-F skyhook controller to be slower than the M- F skyhook controller for the same variation of the input. As consequence of this increase, in the vehicle body simulation the controller TS-F skyhook presented a biggest frequency range and acceleration amplitude. The controllers managed to decrease the acceleration around of 5-6 Hz, as showed in the Figs. (8), (10) and (3).

7. CONCLUSIONS

The M-F skyhook controller is more comfortable to the driver, isolating the vibrations of the vehicle body and decreasing the risk of fractures in the human body [16]. The M- F skyhook obtained the lowest values of the rms acceleration of the TS-F skyhook in the vehicle body. According [10] the arousal frequency more harmful to the human body is between 4 and 8 HZ and the both controllers managed to decrease the acceleration amplitude in this frequency range.

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