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Contents

Volume 17
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Research Articles

Foreword

Dr. Mohd Haris, Md Khir 1

Modeling and Layout Design of Resonant Lateral Comb Magnetic Sensor

F. Ahmad, J. O. Dennis, M. H. Md Khir and N. H. Hamid 1

DC Characterization and Post-CMOS Processing of a Microcantilever Sensor

A. Mirza, N. H. Hamid, M. H. Md. Khir, J. O. Dennis, K. Ashraf 13

Enhanced Performances of a Wireless System-on-Chip for MEMS Biomedical Plantar Pressure Sensor

Abdul Hadi Abdul Razak and Yufridin Wahab 22

Simulation of Liquid Material for Microfluidic-based Acoustic Sensor

M. F. A. Rahman, M. R. Arshad and A. A. Manaf 30

Design, Simulation and Fabrication of a Mass Sensitive CMOS-MEMS Resonator

A. Y. Ahmed, J. O. Dennis, M. H. Md Khir, M. N. Mohamad Saad and M. R. Buyong 40

Artificial Neural Network-based Electronic Nose for the Detection of Sulfate-reducing Bacteria

Earn Tzeh Tan, Zaini Abdul Halim, Darah Ibrahim, Rashidah Abdul Rahim, Junita Mohamad Saleh, Umadevi Chandaran 50

Microcontroller Based Neural Network for Landmine Detection Using Magnetic Gradient Data

Mohamed Elkattan, Ahmed Salem, Fouad Solima, Aladin Kamel and Hadia El-Hennawy 60

An Intelligent ANN Based Control of A Quasi Six-Phase Voltage Source Inverter

Mohammad Shahid Jamil, Mohammad Ibrahim Al-Naemi, Mohd. Arif Khan, Atif Iqbal, Shaikh Moinuddin 70

Comparative Study and Analysis of Suspension Systems using Adaptive Fuzzy Control

LAIQ Khan and M. Umair Khan 81

Development of NOx Emission Model Using Particle Swarm Optimized Least-Squared SVR (PSO-LSSVR) Hybrid Algorithm

Elangeshwaran Pathmanathan, Rosdiazli Ibrahim, Vijanth Asirvadam 98

Development and Implementation of Hybrid Controllers for Flow Control Application

M. Iqbal Ab Ghafar, R. Ibrahim, Zulfadhli Mazlan 110

Capability of Optical Approach in Condition Based Monitoring of Lubricant Oil

M. F. M. Idros, Hadzli Hashim, Md. Shabiul Islam, Sawal Hamid Ali 125

Extracting Broadband Tissue Optics Parameters from One Source-Detector CW Diffuse Optical Spectroscopy <i>Aulia Nasution</i>	135
A Low Ripple Charge Pump Using Low-Voltage CMOS Process <i>Lee Fu New, Zulfiqar Ali bin Abdul Aziz and Mun Fook Leong</i>	147
Experimental Study on a Directional Cylindrical Dielectric Resonator Antenna (CDRA) At 5 to 6 GHz <i>M. A. Zakariya, Z. Baharudin, M. H. Md Khir, A. J. Jamali, M. F. Ain, Z. A. Ahmad</i>	158
RF Energy Harvester: Harvesting Power from WiFi Signals for Low Power RFID Application <i>S. S. B. Hong, R. Ibrahim, M. H. Md Khir, M. A Zakariya, H. Daud</i>	168
Analytical Investigation of Frequency Dependence of Average Power of a Vibration Energy Harvester <i>K. Ashraf, M. H. Md. Khir, J. O. Dennis</i>	176
Trapezoidal Electrodes Array for Electret-Based Electrostatic Energy Harvester <i>Mohamad Radzi Ahmad and Mohd Haris Md Khir</i>	186
Power Management for USB2.0 5 V Supply Using Load Resistive and Switch Capacitive Detection Approach <i>Tan Thiam Loong, Dr. Anwar Hasni bin Abu Hassan</i>	199
DSP Sensorless Controller of Switched Reluctance Motor-Generator Approaching to AM Modulation <i>A. Moraveji, A. Siadatan, E. Afjei, M. Rafiee and E. Zarei Ali Abadi</i>	208
Optimal Feedforward Zero Phase Error Tracking Control for High Precision X-Y Table <i>Hashimah Ismail, Norlela Ishak, Mazidah Tajjudin, Mohd Hezri Fazalul Rahiman, Ramli Adnan</i>	217
Implementation and Optimization of Human Tracking System Using ARM Embedded Platform <i>Shen Khang Teoh, Vooi Voon Yap, Chit Siang Soh, Patrick Sebastian</i>	226
Effectiveness of the Polymer Electrolyte Membrane Fuel Cell in High Humidity Climate <i>Z. Jalauddin, N. M. Nor, T. Ibrahim, and Y. T. Sin</i>	234
Permittivity and Conductivity Dispersions of Properly and Non-properly Slaughtered Goat Meat <i>Abdullah MOHIRI, Zainal Arif BURHANUDIN and Idris ISMAIL</i>	247
Utilizing Bi₂Te₃ TE Pellet as the Condenser of Thermal Power Plant <i>M. Rafiee, A. Siadatan, E. Zarei Ali Abadi and E. Afjei</i>	257

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Comparative Study and Analysis of Suspension Systems using Adaptive Fuzzy Control

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Abstract: Conventional passive suspension systems are unable to handle the tradeoff between ride comfort and vehicle stability. Ride comfort can be analyzed by vehicle's body and passenger seat displacement, while vehicle stability can be examined by degree of freedoms (D.O.F) like pitch and roll. Semi-active and Takagi Sugeno Kang (TSK) based active control systems are implemented in MATLAB/SIMULINK, to better deal with this tradeoff. Adaptive TSK controllers consist of different degree of fulfillment (DOF), differentiating control strategies to others. Irregular road surfaces are taken into account to analyze the performance of passive, semi-active and active control systems. For better comparative analysis, optimal performance index is selected to show the most effective suspension system. The result shows that active suspension systems with TSK based control strategies have better pitch, roll and heave displacement; therefore they are able to better handle the tradeoff between vehicle stability and passenger comfort compared to other suspension systems.

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Keywords: Active suspension system, Fuzzy logic control, Takagi Sugeno Kang, Full-car model.

1. Introduction

Suspension system is the crucial part of vehicle's body; its main purpose is to isolate the body of vehicle from wheels and to reduce the vertical accelerations transferred from road to passenger seat, so as to offer better ride comfort. Usually, automotive suspension structures cannot handle the tradeoff between conflicting measures that are road handling and ride comfort of passenger. The suspension system should offer better handling of car and should isolate passenger from any disturbances. Good ride comfort can be offered by suspension with soft stiffness, whereas stiff suspension can facilitate

good road handling of the vehicle. The conventional or passive suspension fails to maintain the tradeoff between these two criteria, the parameters of suspension are in general fixed and they cannot be adapted to road surface. This in return gives very discomfort feeling to passenger if the stiffness is hard or it affects vehicle instability when stiffness is soft. In passive suspension system, spring absorbs all the energy and the damper then dissipates this energy in the form of heat. If damping of the suspension is changed on runtime the suspension is semi-active. Active suspension has advantage over passive suspension that it can introduce external power in the system to dissipate energy. So, it can adapt its parameters with respect to changing road disturbances.

To achieve better road handling and ride comfort, numerous researches have been carried out on half-car model and full-car model, involving semi-active and fully active strategies to enhance the suspension systems. In [1], Rahmi used active suspension with PID based controller and applied it on full-car model. The response of vehicle was observed by using four of the controllers in four tires suspensions and one under passenger seat. It was observed that PID active control suspensions provided more ride comfort than passive suspension. In [2], Aws used semi-active suspensions with fuzzy based controller and applied it on half-car model. Aws used fewer rules for fuzzy controller in comparison to fuzzy controller in [3] and still provided better efficiency. The fuzzy based controller was further compared with passive and LQR controller, performing better results than all others. Sinasi [4], has compared active and passive suspensions and gave thorough analysis of active and passive suspension, and discussed their limitations and their advantages. Sinasi, recommended active system as the most efficient system but discussed the high cost of active system, which is the main problem for active system to be placed in normal passenger vehicles. Sara [5], has analyzed quarter-car model and applied different semi-active controls which include fuzzy, optimal and optimal neural network control so as to avoid the critical effect caused by vibrations on human health. It was observed that optimal neural network providing best comfort to human than rest of the controllers. Yahya [6], has used LQR control as active control on quarter-car model and compared the results with passive suspension. Christophe [7], didn't use any model of car and took direct values from physical car with the help of sensors. These values were fed to dampers which provided the required force. Results of this control were physically checked on different test tracks. The formulated controller can be tuned online very efficiently and easily. According to Christophe this model free technique can be applied to any type of suspension, whether it is semi-active or active control. Salah [8], has used neuro fuzzy controller for semi-active suspension and applied it on quarter-car model, incorporating neural and fuzzy logic. It was observed that the fuzzy controller requires less rules and good damping ability was observed for different road profiles. Moreover, suspension working space and tire dynamic load were also improved. Kumar [9], has used PID Controller as an active controller. He compared it with passive suspension, the results of his research have shown active suspension performing better than passive by reducing sprung mass displacement, acceleration and suspension travel.

With the progress in the control technology, electronically controlled suspensions have increased importance. This type of suspension has active elements, which are controlled by microprocessor and better performance in vehicle response can be obtained [10, 11]. Fuzzy logic Control (FLC) has advantage over other strategies that is in this type of control accurate representation of system is not required. Since the system depends on measurements from different sensors, which can be inaccurate so fuzzy control strategy is ideal in this case. Due to these advantages this kind of control strategy is suitable for overcoming the trade-off between the passenger safety and vehicle stability.

For better performance of active suspensions, the controllers should have the ability to provide better adaptation to changing road profiles [12]. TSK controller is designed in this study for active suspension system, so the control parameters should adapt to changing road conditions. In this study suspension system for full-car model is taken into account for varying road disturbances. The suspension system should be proficient enough to not allow large oscillations and to dissipate the oscillations rapidly.

For the active suspension system there are two different strategies. In the first strategy, the suspension system comprises controllers without seat control. In the second strategy, seat is also controlled with suspensions to bring more passenger comfort.

The paper is coordinated into six sections. Section 2, discusses the full-car's model. Semi-active suspension control is discussed in Section 3. Section 4, discusses active suspension techniques (TSK). All the models with full-car suspension model implementation in MATLAB/SIMULINK with result comparisons are discussed in section 5. Section 6 concludes the research.

2. Vehicle's Model

The 8-D.O.Fs full-car model has all likely control actions that are heave, pitch and roll displacements that are taken for proper analysis. The model comprises passenger seat, unsprung mass (mass of wheels assemblage) and sprung mass (mass supported on springs). Sprung mass (vehicle body) is supported on springs and dampers, while unsprung mass (i.e., for tires) only spring is taken in the consideration ignoring dampers. The sprung mass has 3-D.O.Fs i.e., heave, pitch and roll, the seat has 1-D.O.F and rest 4-D.O.Fs are of 4 wheels or unsprung masses. Using the Newton's 2nd law of motion and free body diagram, the equations for the 8-D.O.F motions are inferred [13].

The general class of nonlinear MIMO system is described by:

$$y^{(r)} = A(x) + \sum_{i=1}^p \sum_{j=1}^s B_{ij}(x) u_j + \sum_{i=1}^p \sum_{j=1}^s G_{ij} x z_j, \quad (1)$$

where $x = \left[y_1, \dot{y}_1, \dots, y_1^{(r_1-1)}, \dots, y_p, \dot{y}_p, \dots, y_p^{(r_p-1)} \right]^T \in \mathcal{R}^r$ is the overall state vector, which is assumed available and $r_1 + r_2 + \dots + r_p = r$; $u = [u_1, u_2, \dots, u_s]^T \in \mathcal{R}^s$ is the control input vector, $y = [y_1, y_2, \dots, y_p]^T \in \mathcal{R}^p$ is the output vector and $z = [z_1, \dots, z_s]^T \in \mathcal{R}^s$ is the disturbance vector.

$A_i(x)$, $i=1, \dots, p$ are continuous non-linear functions, $B_{ij}(x)$, $i=1, \dots, p; j=1, \dots, s$ are continuous non-linear control functions and $G_{ij}(x)$, $i=1, \dots, p; j=1, \dots, s$ are continuous non-linear disturbance functions.

The general non-linear function is:

$$A(x) = [A_1(x) \ A_2(x) \ \dots \ A_p(x)]^T \quad (2)$$

The general control matrix $B(x)$ and the disturbance matrix are

$$B(x) = \begin{bmatrix} b_{11}(x) & \dots & b_{1s}(x) \\ \vdots & \ddots & \vdots \\ b_{p1}(x) & \dots & b_{ps}(x) \end{bmatrix}_{p \times s} \quad (3)$$

$$G(x) = \begin{bmatrix} g_{11}(x) & \cdots & g_{1s}(x) \\ \vdots & \ddots & \vdots \\ g_{p1}(x) & \cdots & g_{ps}(x) \end{bmatrix}_{p \times s} \quad (4)$$

The general output of non-linear MIMO system is:

$$y^{(r)} = A(x) + B(x).u + G(x).z, \quad (5)$$

where $A(\bullet) \in \mathbb{R}^{p \times p}$; $B(\bullet) \in \mathbb{R}^{p \times s}$; $G(\bullet) \in \mathbb{R}^{p \times s}$.

The above matrices can be shown in state-space form, with state vector x that is also represented in row matrix form.

The generic non-linear car model is

$$A(x) = [A_1(x) \ A_2(x) \ A_3(x) \ \cdots \ A_{16}(x)] \quad (6)$$

$$x = [x_1 \ x_2 \ x_3 \ \cdots \ x_{16}]^T \quad (7)$$

$A_1(x)$ to $A_8(x)$ are velocity states and $A_9(x)$ to $A_{16}(x)$ are acceleration states of four tires, seat, heave, pitch and roll [1].

The disturbance inputs for each tire individually are represented in the form of z matrix.

$$A(x) \in \mathbb{R}^{(16 \times 16)}, \ B(x) \in \mathbb{R}^{(16 \times 4)}, \ G(x) \in \mathbb{R}^{(16 \times 4)}, \ \text{state vector } x \in \mathbb{R}^{(16 \times 1)}, \ u \in \mathbb{R}^{(4 \times 1)} \ \text{and } z \in \mathbb{R}^{(4 \times 1)}.$$

z_s are s disturbances applied to full-car model. u_s are s control outputs to the full-car model, so to regulate the car model disturbances. y_p are p states of car. r_s are s desire outputs for the controller to achieve.

3. Semi-Active Suspension

Semi-Active control is used by using Skyhook control. When unsprung mass and sprung mass moves in opposite direction, the damper is on and force of the damper is applied. The damper is switched off when both masses move in the same direction. Semi-active control has advantage compared to passive suspension that it adapts to variable road profile. Furthermore, if semi-active control is failed due to any reason, the suspension acts like a passive suspension. So risk of failure in this suspension type is low.

$$F_{\text{damper}} = C_{\text{sky}} \times A_{\text{sprung}} \ \text{if } (A_{\text{sprung}} \times (A_{\text{sprung}} - A_{\text{unsprung}})) > 0 \quad (8)$$

$$F_{\text{damper}} = 0 \ \text{if } (A_{\text{sprung}} \times (A_{\text{sprung}} - A_{\text{unsprung}})) < 0, \quad (9)$$

where F_{damper} is the required force needed by damper; A_{unsprung} is the velocity of unsprung mass; A_{sprung} is the velocity of sprung mass; A_{sprung} for four tires can be derived out from the four equations:

$$A_{\text{sprung1}} = Z + a \sin \theta - c \sin \phi \quad (10)$$

$$A_{\text{sprung2}} = Z + a \sin \theta + d \sin \phi \quad (11)$$

$$A_{\text{sprung3}} = Z - b \sin \theta - c \sin \phi \quad (12)$$

$$A_{\text{sprung4}} = Z - b \sin \theta + d \sin \phi \quad (13)$$

where Z , θ and ϕ are the heave, pitch and roll displacement. A_{sprung1} to A_{sprung4} are sprung mass velocity of four tires.

Fig. 1 shows working of semi-active suspension.

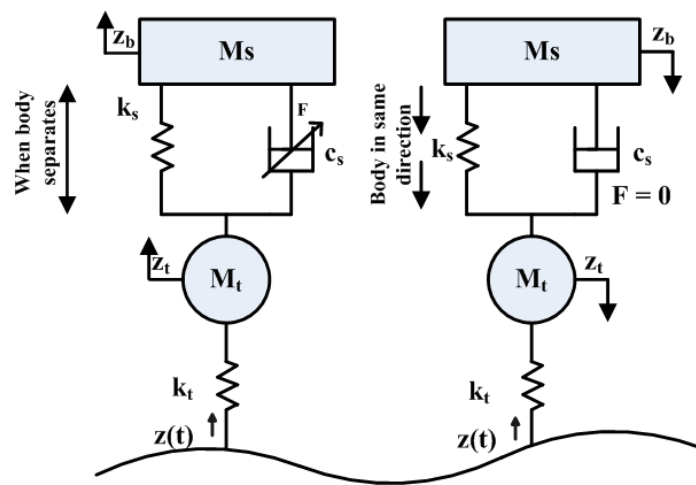


Fig. 1. Semi-active Suspension Control.

4. TSK Fuzzy Model

Takagi Sugeno Kang (TSK) fuzzy model is proposed in 1985 by Takagi-Sugeno, it is defined by fuzzy IF-THEN rules that represent relation (input-output) of a nonlinear system [14, 15]. The TSK reasoning method is a rule based association, which is different from linguistic model (L.M), as it uses functional type consequent instead of fuzzy type consequent used in linguistic model. Geometrically, the rules of the TSK reasoning model correspond to an approximation of mapping by a piecewise linear function. Complex non-linear systems in TSK can be defined in terms of fuzzy sets, and fuzzy reasoning is then applied to linear sub-model regions. Each local rule in TSK is represented by linear system models. TSK can be used as a controller of active suspension strategy, for significant vehicle comfort and stability.

The general form of TSK is given below, with antecedent part as Gaussian function, and output as linear function:

$$F = \frac{\sum_{i=1}^m w_i (a_{i0} + a_{i1}x_1 + \dots + a_{ir}x_r)}{\sum_{i=1}^m w_i} \quad (14)$$

$$F = \frac{\sum_{i=1}^R y_i^* w_i}{\sum_{i=1}^R w_i} \quad (15)$$

Here $w_i = \left[\exp - \left(\frac{1}{2} \sum_{j=1}^r \left(\frac{x_i - m_{ij}^*}{\sigma_{ij}} \right)^2 \right) \right]$ is the DOF, $y_i^* = (a_{i0} + a_{i1}x_1 + \dots + a_{ir}x_r)$ is the consequent output of desire DOF; x is the input, m and σ are the mean and variance of Gaussian membership function respectively.

$$F = \sum_{i=1}^m v_i y_i^* \quad (16)$$

Here, $v_i = \frac{\sum_{i=1}^m \left[\exp - \left(\frac{1}{2} \sum_{j=1}^r \left(\frac{x_i - m_{ij}^*}{\sigma_{ij}} \right)^2 \right) \right]}{\sum_{i=1}^m \left[\exp - \left(\frac{1}{2} \sum_{j=1}^r \left(\frac{x_i - m_{ij}^*}{\sigma_{ij}} \right)^2 \right) \right]}$ is the normalized DOF.

4.1 Update Equations for TSK

In TSK algorithm, the parameters which are to be updated are antecedent means, antecedent variances and consequent constants of linear equations. To find these update parameters, minimization of square of instantaneous errors between output of actual fuzzy model and current output with respect to unknown parameters is considered. These update equations will help in minimizing the error between the desired and actual output.

$$E_k = \frac{1}{2} (r_k - F_k)^2 = \frac{1}{2} e^2 \quad (17)$$

Update equation for the coefficients of consequent part, by gradient descent method using equation (14) and equation (17) is

$$a_{io}(k+1) = a_{io}(k) - \alpha \frac{\partial E_k}{\partial a_{io}} = a_{io}(k) - \alpha v_i e \quad (18)$$

Update equation for the variable of consequent part, using equation (14) and equation (17) is

$$a_{ij}(k+1) = a_{ij}(k) - \alpha \frac{\partial E_k}{\partial a_{ij}} = a_{ij}(k) - \alpha v_i e x_j \quad (19)$$

Update equation for the mean of antecedent part

$$m_{ij}^*(k+1) = m_{ij}^*(k) - \alpha \frac{\partial E_k}{\partial m_{ij}^*} = m_{ij}^*(k) - \alpha v_i (a_{i0} + a_{i1}x_1 + \dots + a_{ir}x_r - F) e \frac{x_j - m_{ij}^*(k)}{\sigma_{ij}^2} \quad (20)$$

Update equation for the variance of antecedent part

$$\sigma_{ij}(k+1) = \sigma_{ij}(k) - \alpha \frac{\partial E_k}{\partial \sigma_{ij}} = \sigma_{ij}(k) - \alpha v_i (a_{i0} + a_{i1}x_1 + \dots + a_{ir}x_r - F) e \frac{(x_j - m_{ij}^*(k))^2}{\sigma_{ij}^3}, \quad (21)$$

where α is learning rate and a 's are TSK consequent variables for update.

4.2. Takagi Sugeno Kang 1

The antecedent and consequent part is same in TSK 1 as in TSK, antecedent and consequent parameters update equations are also same as in TSK, but only the DOF is changed. T-norm 1 is used for DOF, in place of product in TSK. T-norm 1 is

$$T(\mu_A, \mu_B) = w_i = \min(\mu_A, \mu_B) (\mu_A + \mu_B - \mu_A \cdot \mu_B)^{p_i}, \quad (22)$$

where μ_A and μ_B are the two membership functions. There is only one parameter in this T-norm i.e. p_i , this brings low complexity compared to two T-norms that will be discussed later. The update equation of this parameter i.e. p_i is evaluated in next sub-section.

4.2.1. Update Parameters of TSK 1

Parameter updates are derived by gradient descent rule, the error minimization is the basic goal. New update parameter will be.

$$p_i(t+1) = p_i(t) - \Delta p_i \quad (23)$$

$$p_i(t+1) = p_i(t) - \eta_i \frac{\partial E_k}{\partial p_i} \quad (24)$$

For finding a new parameter p_i , using equation (17) and (14).

$$\Delta p_i = -\eta_i \frac{\partial E_k}{\partial p_i} = \eta_i e \frac{\partial F}{\partial p_i}, \quad (25)$$

where η is the learning factor; e is the error, and $\frac{\partial E_k}{\partial p_i}$ is the partial derivative of sensitivity with respect to p_i .

$$\Delta p_i = \eta_i e \frac{\partial F}{\partial w_i} \frac{\partial w_i}{\partial p_i} \quad (26)$$

Taking partial derivative of equation (22) w.r.t p_i .

$$\frac{\partial w_i}{\partial p_i} = w_i \ln(\mu_A + \mu_B - \mu_A \cdot \mu_B) \quad (27)$$

Taking partial derivative of output F , (14) w.r.t first T-norm:

$$\frac{\partial F}{\partial w_i} = \left(\frac{y_i^* - F}{\sum_{j=1}^R w_j} \right). \quad (28)$$

The learning factor used in here is

$$\eta = \frac{w_i}{\sum_{j=1}^R w_j} \quad (29)$$

Putting equations (27), (28) and (29) in equation (25):

$$\Delta p_i = \frac{w_i}{\sum_{j=1}^R w_j} \left(\frac{y_i^* - F}{\sum_{j=1}^R w_j} \right) w_i \ln(\mu_A + \mu_B - \mu_A \cdot \mu_B) e \quad (30)$$

The new update parameter from equation (23) is

$$\Delta p_i(t+1) = p_i(t) - \frac{w_i}{\sum_{j=1}^R w_j} \left(\frac{y_i^* - F}{\sum_{j=1}^R w_j} \right) w_i \ln(\mu_A + \mu_B - \mu_A \cdot \mu_B) e \quad (31)$$

4.3. Takagi Sugeno Kang 2

Like TSK 1, the antecedent and consequent part is same in TSK 2 as in TSK. Only difference is T-norm 2 used in TSK 2 as DOF is

$$T(\mu_A, \mu_B) = w_i = (\mu_A \cdot \mu_B)^{p_i} (\mu_A + \mu_B - \mu_A \cdot \mu_B)^{q_i} \quad (32)$$

Here, p_i and q_i are the two update parameters. These two parameters are also adapted along with antecedent and consequent parameters. This brings in more complexity but it helps in finding exact contribution of membership function in respective rule, so it improves the output result. The update equations of these two parameters i.e. p_i and q_i are,

$$p_i(t+1) = p_i(t) - \frac{w_i}{\sum_{j=1}^R w_j} (\mu_A \cdot \mu_B)^{p_i} \ln(\mu_A \cdot \mu_B) e (\mu_A + \mu_B - \mu_A \cdot \mu_B)^{q_i} \quad (33)$$

$$q_i(t+1) = q_i(t) - \frac{w_i}{\sum_{j=1}^R w_j} (\mu_A + \mu_B - \mu_A \cdot \mu_B)^{q_i} \ln(\mu_A + \mu_B - \mu_A \cdot \mu_B) e (\mu_A \cdot \mu_B)^{p_i} \quad (34)$$

4.4. Takagi Sugeno Kang 3

T-norm 3 used as DOF in TSK 3 is

$$T(\mu_A, \mu_B) = w_i = \mu_A^{p_i} \mu_B^{q_i}, \quad (35)$$

where μ_A and μ_B are two membership functions, and p_i and q_i are two update parameters. These two parameters are also adapted along with antecedent and consequent. The update equations of these two parameters i.e. p_i and q_i are,

$$p_i(t+1) = p_i(t) - \frac{w_i}{\sum_{j=1}^R w_j} (\mu_A)^{p_i} (\mu_B)^{q_i} \ln(\mu_A) e^{\left(\frac{y_i^* - F}{\sum_{j=1}^R w_j} \right)} \quad (36)$$

$$q_i(t+1) = q_i(t) - \frac{w_i}{\sum_{j=1}^R w_j} (\mu_A)^{p_i} (\mu_B)^{q_i} \ln(\mu_B) e^{\left(\frac{y_i^* - F}{\sum_{j=1}^R w_j} \right)} \quad (37)$$

4.5. Algorithm: Back-Propagation Learning Based Adaptive TSK Controllers

- 1) Set the input-output, t_{ref} and F of the system.
- 2) In forward pass the current DOF of the rules, the w_i 's and the estimated output of fuzzy model F are calculated; current estimates $y_i^*(k)$, $m_{ij}^*(k)$ and $\sigma_{ij}(k)$ of unknown parameters $y_i^*(k)$, $m_{ij}^*(k)$ and $\sigma_{ij}(k)$ are used. Where, y_i^* 's consequent parameters consisting of constant and variable parameters as discussed above.
- 3) In the backward pass the current parameter estimates $y_i^*(k)$, $m_{ij}^*(k)$ and $\sigma_{ij}(k)$ are updated according to the learning rules equation (18-21). p_i is updated according to the learning rule equation (31) for TSK 1. p_i and q_i are updated according to the learning rules equation (33-34) for TSK 2. p_i and q_i are updated according to the learning rules equation (36-37) for TSK 3.
- 4) Finally, output of the controller added with disturbance is given to the system.
- 5) Repeat steps (2-4) until system converges.

5. Simulation

Fig. 2 shows structure of adaptive active suspension control strategy.

Four controllers are used to control four suspension components placed between tires and car body, and one another to control suspension component under passenger seat. Each adaptive fuzzy based controller has two inputs.

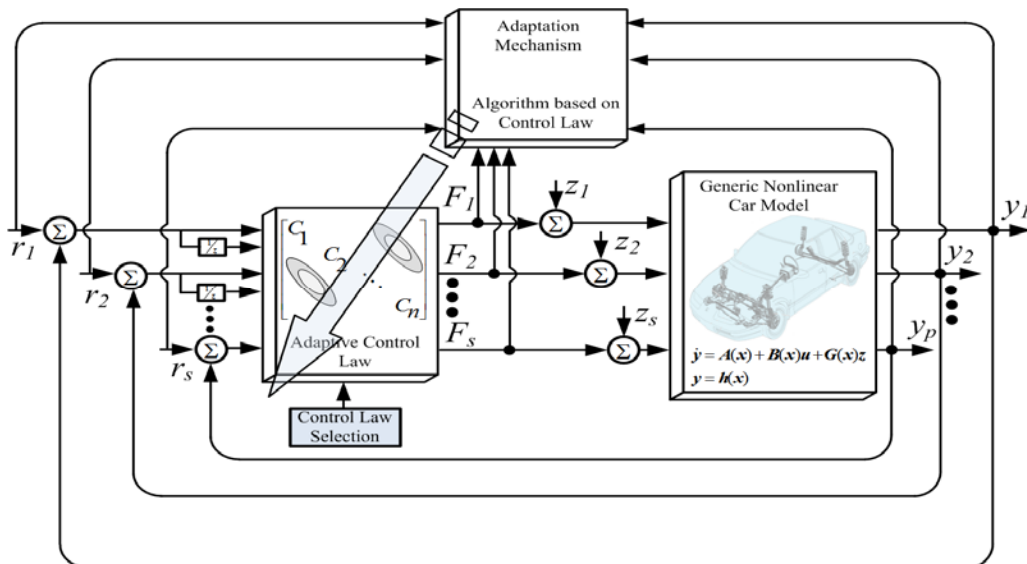


Fig. 2. Active Suspension Control.

One of that inputs is r_j and the second input is delayed value of r_j , where, $j=1,2,\dots,s$. r is the desired target for the controller to achieve. The output y_p states are fed as an error to the controllers, so to adapt the adaptation mechanism for the desire regulation. This error plays the critical role in establishment of adaptation law, which is entirely based on algorithm that is discussed in previous section. The controller is trained by this algorithm to achieve the desired level of performance. In the proposed work, for full-car model four states of tires are used by the four controllers to adapt the adaptation law. The four disturbances z_1, z_2, z_3 and z_4 from the rough road through tires traverse into the suspension system. There are two cases, which are to be considered as discussed before. In the first case, four controllers are to control four suspension components placed between tires and car body, so only the states of the four tires y_1, y_2, y_3 and y_4 displacements are used as an error to the controller, which develops the control law according to that error. These control inputs F_1, F_2, F_3 and F_4 are provided to the plant from each controller for accomplishing the desired performance of the non-linear full-car model i.e. both better passenger comfort (better seat and heave displacement) and better vehicle stability (better heave, pitch and roll displacement). In the second case, one another controller is deployed to control suspension components under passenger seat. So, another state y_5 is used as an error to the controller. The control law is developed on the basis of error. The outputs of controllers are controlled inputs of full-car model, so to bring in additional passenger safety. The TSK controllers have two inputs with inference mechanism containing two rules having two membership functions each. The learning rates for TSK front left, front right, rear left and rear right controllers are 0.02, 0.01, 0.0097 and 0.01 respectively. For TSK: 0.3015, 0.3015, 0.02345 and 0.02345 respectively. For TSK 2: 0.04, 0.04, 0.03 and 0.028 respectively. For TSK 3: 0.04, 0.013, 0.02 and 0.02 respectively.

To compare and elaborate the performances of all the controllers in terms of vehicle's stability and passenger's safety, two types of road profiles are taken into account.

- Road profile 1 contains potholes only. Each tire has different disturbances acting on it. This case is considered, if the vehicle is traveling on very rough road and vehicle's stability as well as passenger safety has high risk on these kinds of roads. This road profile is efficient enough to analyze the pitch and roll of the vehicle.
- Road profile 2 comprises random road bumps and potholes. Front tires are considered to have same disturbances, similarly rear tires have same disturbances. This kind of road profile is efficient to analyze the heave of the vehicle.

On the basis of these road profiles performances of all the suspension systems are compared and performance indices are evaluated to determine the best suspension system control strategy from the controllers implemented i.e., passive, semi-active or active control (TSK).

5.1. Results Comparison

Fig. 3 shows case 1: seat displacement due to road profile without any controller under passenger seat. Passive control has many unwanted oscillations as elaborated by figure, semi-active control has reduced some oscillations and is somehow performing better than passive suspension. TSK and TSK 1 have higher settling time compared to TSK 2 and TSK 3, showing the learning of TSK and TSK 1 is slower compared to TSK 2 and TSK 3, when an abrupt change occurs. Overall, active suspensions with TSK controllers have reduced unwanted oscillations. As it is clear by results, TSK controllers have reduced passenger seat displacement, hence showing more passenger comfort compared to semi-active and passive suspensions. Fig. 7 shows case 2: seat displacement due to road profile with a controller under passenger seat. The result clearly elaborates that with the inclusion of an additional controller under passenger seat, the oscillations are further reduced as compared to oscillations without controlling seat. TSK and TSK 3 transient response is not as good as of other TSK strategies but overall steady state response of all the TSK controllers are better. Figs. 4-6 show heave, pitch and roll displacement due to road profile. With comparison to passive and semi-active suspension, active suspensions with TSK controllers have reduced oscillations showing that vehicle weight balance is better with TSK controllers, hence vehicle stability is much ensured. TSK has worse transient and settling response compared to other TSK controllers, showing the importance of proper DOF in choosing accurate learning rules and hence providing proper adaptation of controllers with respect to irregular road changes. Fig. 8 shows control efforts of four controllers of active suspension system. These are control efforts of front left tire (FL), front right (FR) tire, rear left (RL) tire and rear right (RR) tire. Since in road profile, disturbances on all the tires were different so weight shift on tires were not uniform. That makes pitch and roll poor for passive suspension control but active control strategy has shown better vehicle stability. To further show the superiority of TSK based controllers compared to passive and semi-active suspensions, simulation results are showed for road profile 2 in Fig. 9-13. Fig. 9 shows case 1: seat displacement due to road profile 2 without any controller under passenger seat. TSK based controllers are much better than passive and semi-active control. Similarly, Fig. 13, shows case 2: seat displacement due to road profile 2 with a controller under passenger seat. Active control strategies ensured more passenger safety due to an extra controller under seat as elaborated by results. Fig. 10-12 show heave, pitch and roll displacement due to road profile 2. Fig. 14 shows control efforts of four controllers of suspension system.

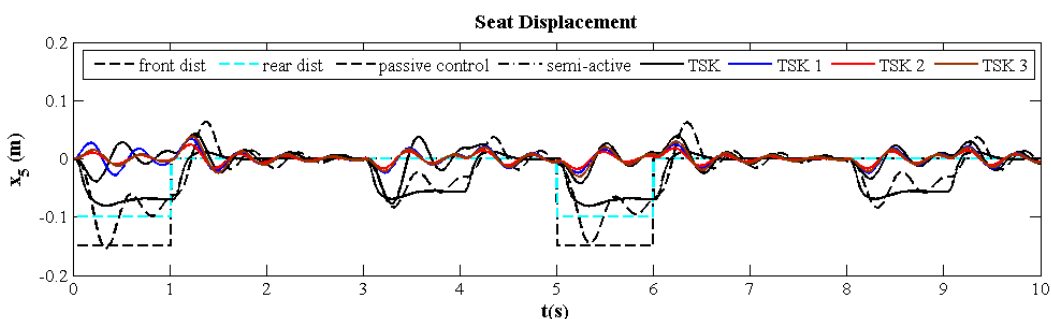


Fig. 3. Case 1: Seat Displacement due to Road Profile 1.

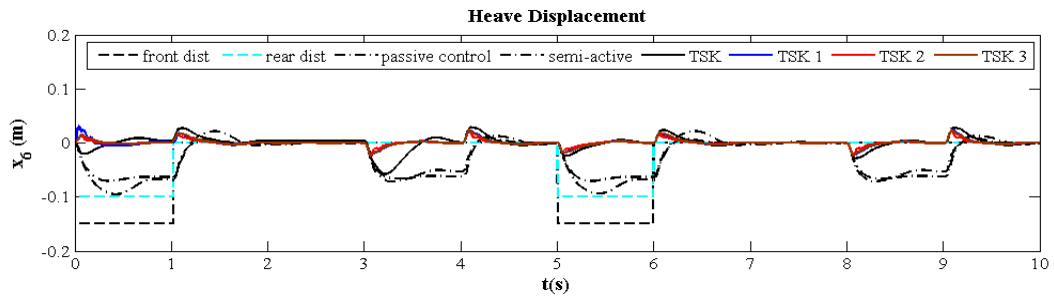


Fig. 4. Heave Displacement due to Road Profile 1.

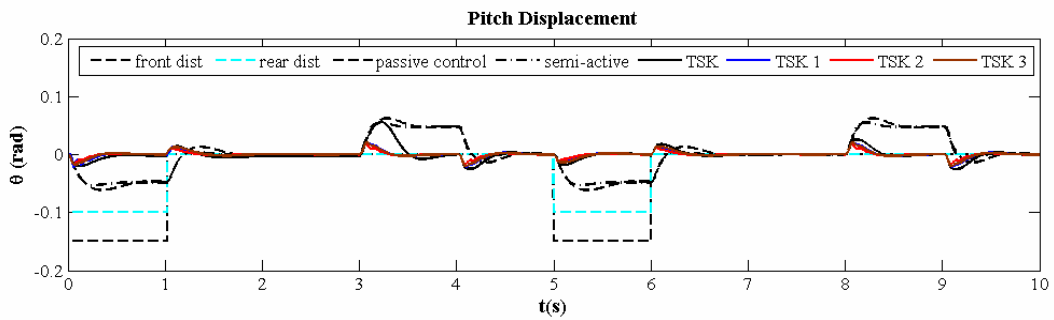


Fig. 5. Pitch Displacement due to Road Profile 1.

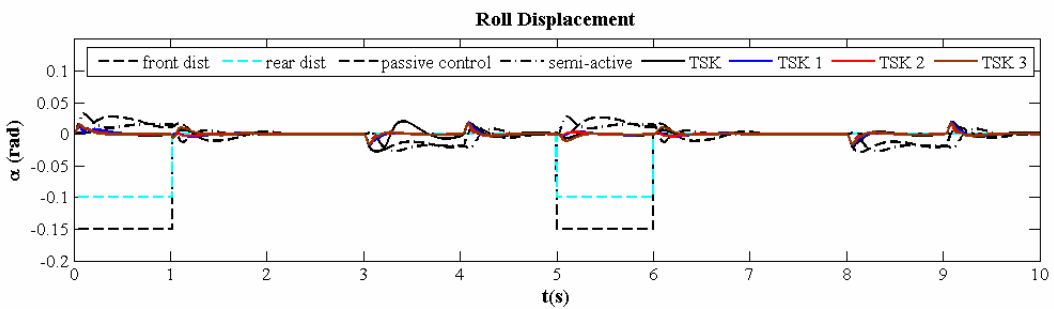


Fig. 6. Roll Displacement due to Road Profile 1.

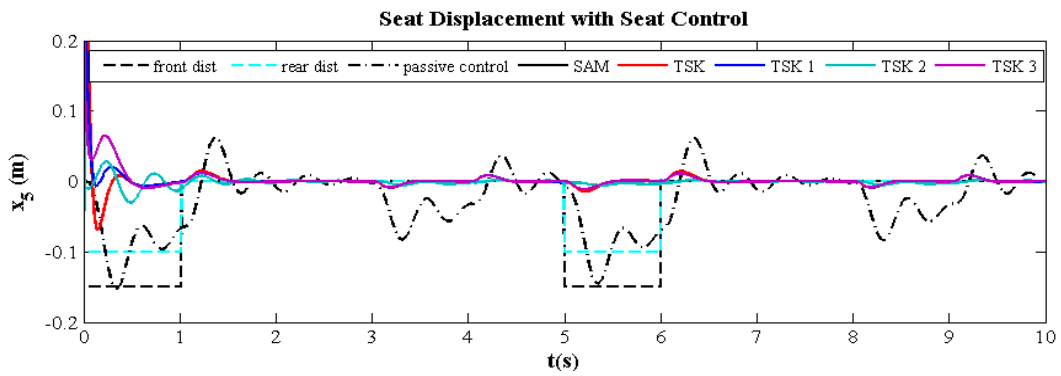


Fig. 7. Case 2: Seat Displacement due to Road Profile 1.

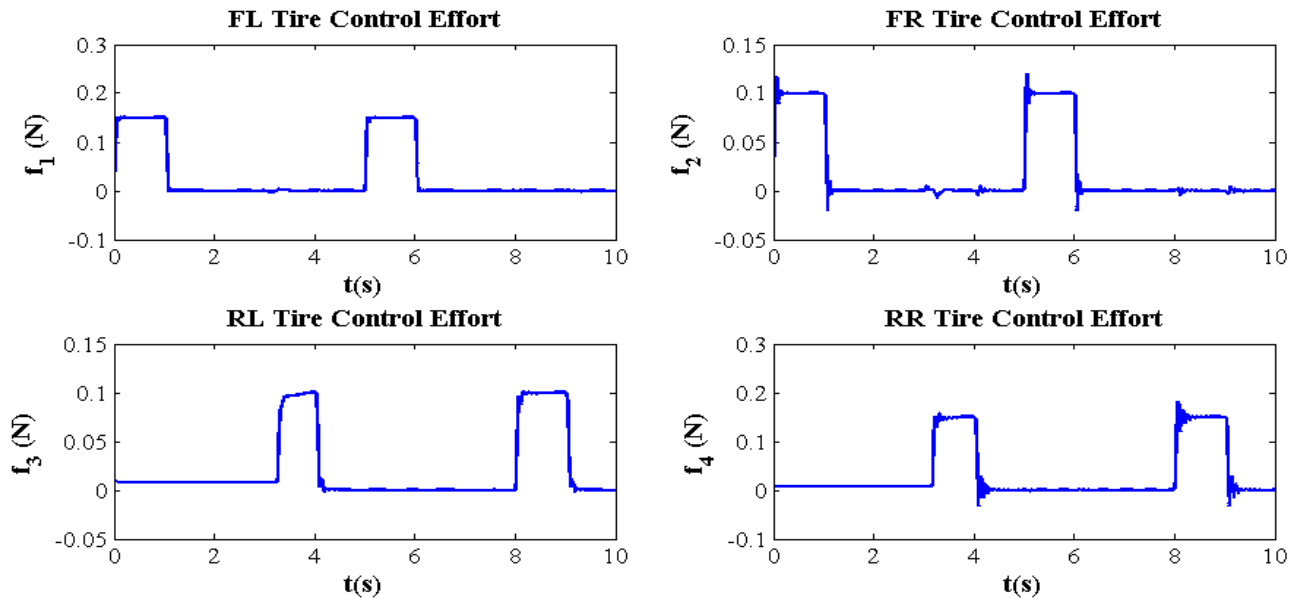


Fig. 8. Control Efforts for Road Profile 1.

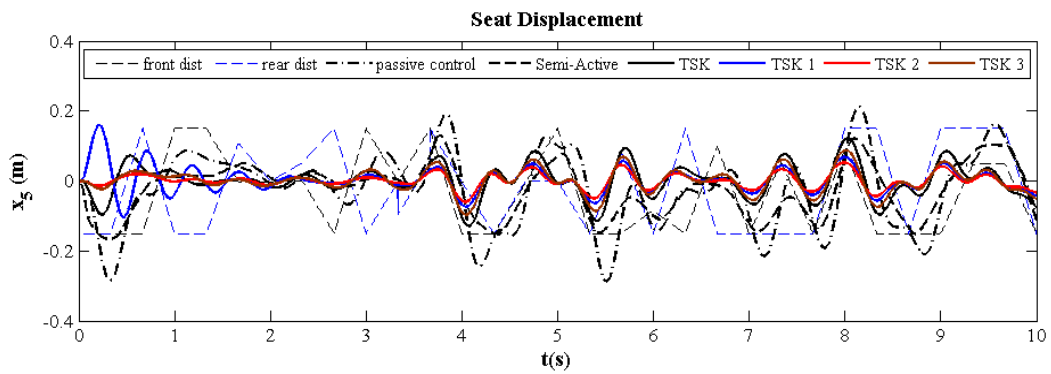


Fig. 9. Case 1: Seat Displacement due to Road Profile 2.

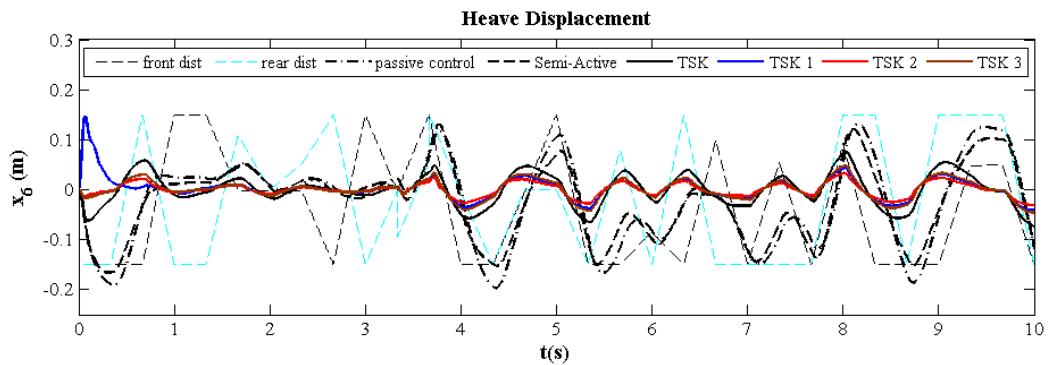


Fig. 10. Heave Displacement due to Road Profile 2.

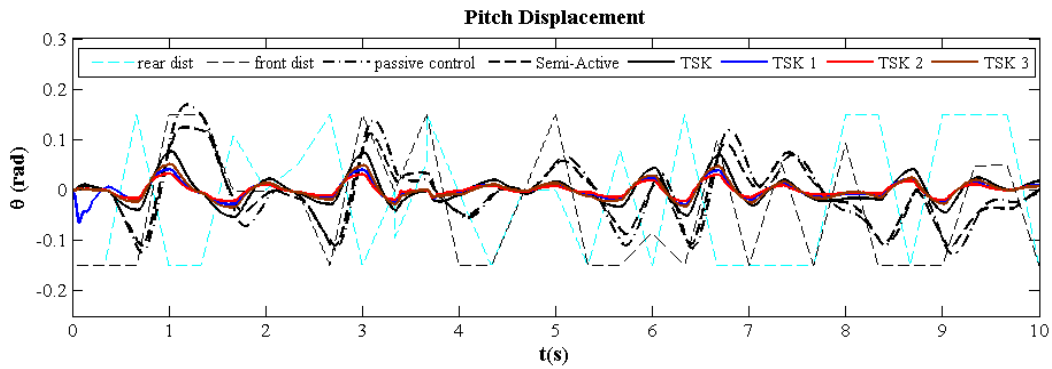


Fig. 11. Pitch Displacement due to Road Profile 2.

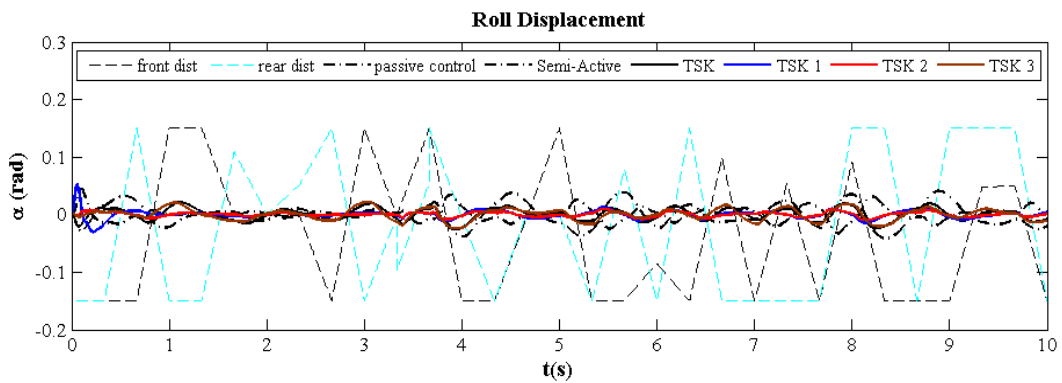


Fig. 12. Roll Displacement due to Road Profile 2.

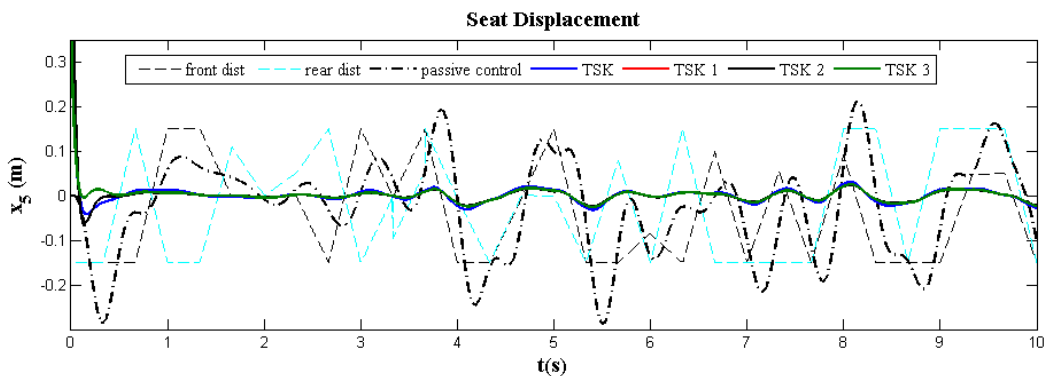


Fig. 13. Case 2: Seat Displacement due to Road Profile 2.

To show the effectiveness of active and semi-active suspensions compared to the passive suspension system, heave displacement and heave acceleration of vehicle's model are taken as performance evaluation parameters. Heave of vehicle plays an important role in vehicle's stability and safety. Performance indices with respect to heave displacement, heave acceleration and overall performance indices are shown in Table 1 and Table 2. The performance parameters used in the tables are,

$$z_{heave}^{rms} = \sqrt{\frac{1}{T} \int_{t=0}^T [h(t)]^2} \quad (38)$$

where, T is total time of simulation. $h(t)$ is heave displacement. \ddot{z}_{heave}^{rms} is suspension deflection (RMS).

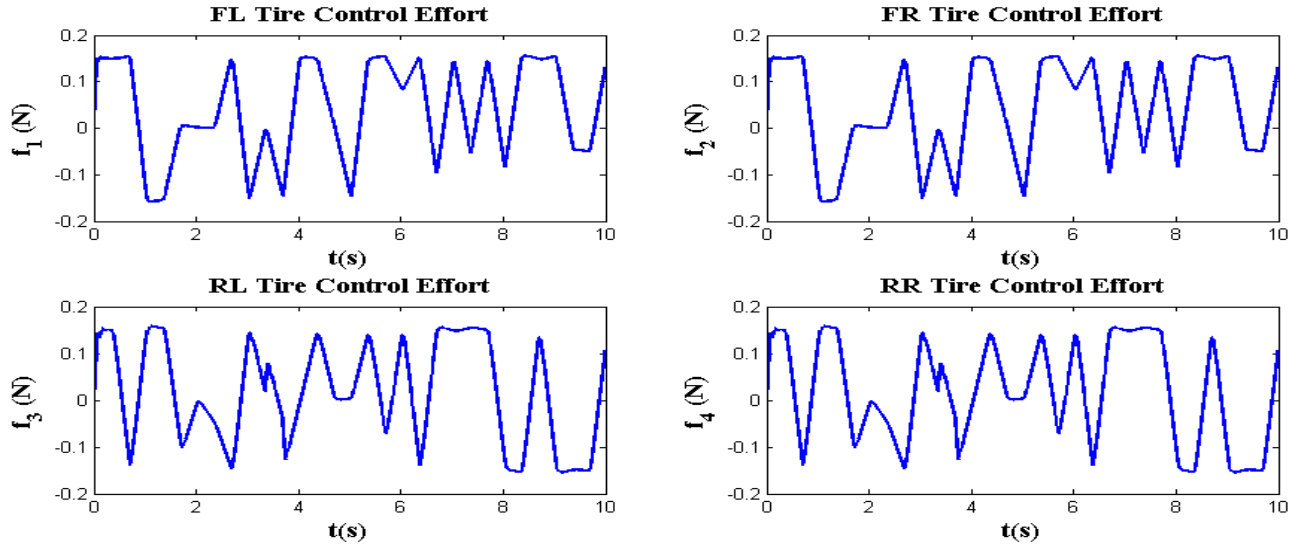


Fig. 14. Control Efforts for Road Profile 2.

Table 1. Performance Index for Road Profile 1.

Road Profile	Control	$\sqrt{\frac{1}{T} \int_{t=0}^T [h(t)]^2}$	$\sqrt{\frac{1}{T} \int_{t=0}^T [\ddot{h}(t)]^2}$	$\frac{1}{2} \int_{t=0}^T (Z_p^T Q Z_p) dt$
Road Profile 1	TSK	0.0129	5.6020	15.6913
	TSK 1	0.0059	4.7600	11.3288
	TSK 2	0.0046	4.2193	8.9013
	TSK 3	0.0062	4.8005	11.5224
	Semi-Active	0.0402	8.231	33.8755
	Passive	0.0431	14.586	106.38

Table 2. Performance Index for Road Profile 2.

Road Profile	Control	$\sqrt{\frac{1}{T} \int_{t=0}^T [h(t)]^2}$	$\sqrt{\frac{1}{T} \int_{t=0}^T [\ddot{h}(t)]^2}$	$\frac{1}{2} \int_{t=0}^T (Z_p^T Q Z_p) dt$
Road Profile 2	TSK	0.0311	4.0684	8.2764
	TSK 1	0.0179	2.7580	3.8034
	TSK 2	0.0131	2.3147	2.679
	TSK 3	0.0191	2.8629	4.0983
	Semi-Active	0.0778	4.3941	9.6571
	Passive	0.0887	8.769	28.44

$$\ddot{z}_{heave}^{rms} = \sqrt{\frac{1}{T} \int_{t=0}^T [\ddot{h}(t)]^2} \quad (39)$$

where, $\ddot{h}(t)$ is heave acceleration. \ddot{z}_{heave}^{rms} is heave acceleration (RMS).

$$J = \frac{1}{2} \int_{t=0}^T (Z_p^T Q Z_p) dt \quad (40)$$

where, $Z_p = [h \quad \dot{h}]^T$ and Q is positive constant matrix. J is overall performance index. Table 1 shows performance indices against road profile 1. With comparison to passive suspension system, semi-active suspension has shown 6.7 %, TSK has shown 70 %, TSK 1 has shown 86 %, TSK 2 has shown 89 %, and TSK 3 has shown 85.6 % improvement. Table 2 shows performance indices against road profile 2. With comparison to passive suspension system, semi-active suspension has shown 12.2 %, TSK has shown 64.9 %, TSK 1 has shown 79.8 %, TSK 2 has shown 85.2 %, and TSK 3 has shown 78.5 % improvement. Thus performance indices also showing active suspension with TSK based control giving better vehicle stability and passenger comfort compared to passive and semi-active suspension. Furthermore, TSK 2 is the better control strategy compared to other TSK based strategies, hence showing the importance of choosing strong DOF in selection of proper rules.

6. Conclusion

In this work, full-car model's suspension control is implemented with the help of passive, semi-active and active control. It was observed that, passive suspension systems cannot handle the tradeoff between vehicle's stability and passenger safety. Semi-active suspension with skyhook control reduces the disturbances and was efficient than passive suspension system. Active suspension systems are able to deal with this tradeoff better than other suspension systems. Full-car vehicle model was used, because it can depict the necessary performance parameters such as body displacement, wheel displacement, seat displacement and other rotational displacements like heave, pitch and roll displacements. Different active controllers based on adaptive Takagi Sugeno Kang (TSK) are developed and are simulated on full-car vehicle's model suspension in MATLAB/SIMULINK. Irregular road surfaces are taken into account, so to check the performances of semi-active control and TSK based active control. The result shows active suspension system with TSK control strategies have better pitch, roll and heave displacement and so is able to better handle the tradeoff between vehicle's stability and passenger comfort compared to other suspension systems. By taking into account all the performance parameters that are seat, heave, pitch, and roll displacement; TSK 2 based active suspension system gave efficient results, thus showing the importance of strong DOF in finding out the right contribution of membership functions.

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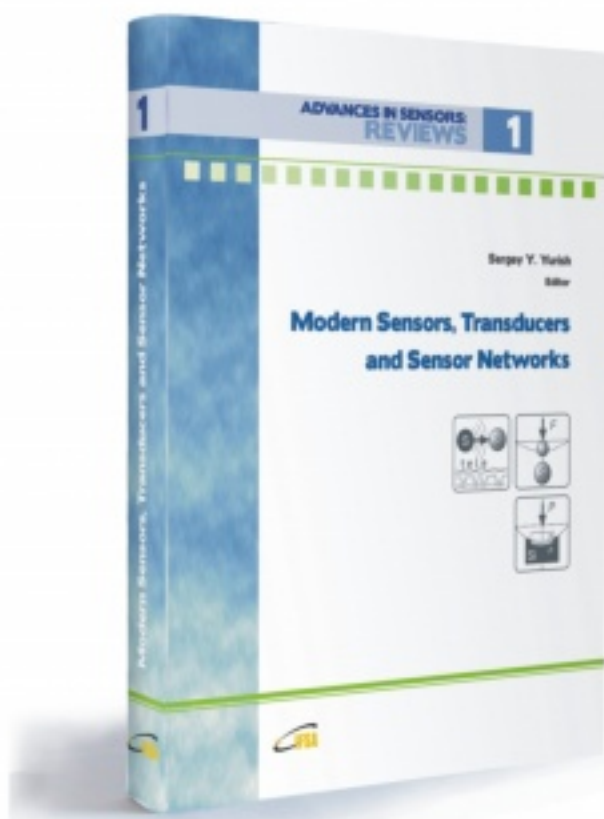
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