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RESEARCH ARTICLE / ARAŞTIRMA MAKALESI

Lqr-Fuzzy Logic Control of a Quarter Vehicle Model

Çeyrek Taşıt Modelinin Lqr-Bulanık Mantıklı Kontrolcü ile Kontrolü

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Abstract

In this study, a new control rule was developed using two different control methods, and the results were discussed by applying the developed controller to the quarter vehicle model. A new hybrid controller was designed by considering the advantages of Fuzzy Logic control method and Linear Quadratic Regulator (LQR) control method. Control gain coefficients used in LQR controller were determined by fuzzy logic control method. The developed new controller has been applied to the quarter vehicle model. In the results, control with only Fuzzy Logic controller and developed LQR-Fuzzy Logic controller were compared. It was understood from the results that the developed control method was satisfactory.

Keywords: *Fuzzy Logic Control, LQR Control, Quarter Vehicle Model, Simulation*

Öz

Bu çalışmada iki farklı kontrol yöntemi kullanılarak yeni bir kontrol kuralı geliştirilmiş ve geliştirilen kontrolcü çeyrek taşıt modeline uygulanarak sonuçlar değerlendirilmiştir. Bulanık Mantık kontrol yöntemi ve Lineer Kuadratik Düzenleyici (LQR) kontrol yönteminin avantajları dikkate alınarak yeni bir hibrit denetleyici tasarlanmıştır. LQR denetleyicide kullanılan kontrol kazanç katsayıları bulanık mantık kontrol yöntemi ile belirlenmiştir. Geliştirilen yeni kontrol yasası çeyrek taşıt modeline uygulanmıştır. Sonuçlar kısmında, pasif, sadece bulanık mantıklı kontrolcü ve geliştirilen LQR-Bulanık mantıklı kontrolcü ile elde edilen sonuçlar karşılaştırılmıştır. Geliştirilen kontrol yönteminin tatmin edici olduğu sonuçlardan anlaşılmıştır

Anahtar Kelimeler: *Bulanık Mantıklı Kontrol, LQR Kontrol, Çeyrek Taşıt Modeli, Simulasyon*

1. Introduction

Systems such as robots, vehicles and aircraft are difficult to control due to external disturbances. For this reason, controllers that can absorb both nonlinear behaviors and external disturbances are needed. In recent years, control studies in the field of control generally focus on hybrid controllers developed by using two controllers together. While one controller eliminates nonlinearity in the system, the other controller protects the system against external disturbances. This control method is the result of the development of the classical controller and the newly used controllers. In this study, a new controller was developed by using the LQR and fuzzy logic controllers. Control gain coefficients in the LQR controller are mostly found with the equation in the literature. In this study, gain coefficients in LQR controller were determined by using fuzzy logic controller. Thus, a new control method was obtained by using two different controllers. A quarter vehicle model was used to implement the developed controller. Previous studies were taken as reference for this developed controller.

1.1. Literature review

In this study, a new controller was developed by using two different controllers and this developed controller was applied to a two-degree-of-freedom quarter vehicle model. There are different studies in the literature with Fuzzy Logic controller and LQR controller. These;

Devdutt [1] applied a fuzzy logic controller to a semi-active two-degree-of-freedom quarter vehicle model. In order to see the effectiveness of the study, both time-related and frequency changes of the applied control method were analyzed. Input parameters are designed as passenger seat velocity and secondary suspension system velocity also the output parameter is the controller force. Simulation results showed that the semi-active system using the controller is more effective than passive suspension systems. Palanisamy & Karuppan [2] aimed to design a controller to control the yaw movement of vehicle suspensions. Since active suspension systems are difficult to model, they designed a fuzzy logic controller that can control the unmodeled part of active suspensions by using a fuzzy logic controller. In the fuzzy logic controller, the input parameters are determined as body error and change in error, and the output parameter is determined as control force. They carried out simulations using various road entries and understood that the results were satisfactory. Bhangal & Raj [3] applied fuzzy logic controller to active suspension systems and compared them with passive suspension systems. Also, they applied LQR controller to active suspension systems. The results show that fuzzy logic controller is more effective in reducing the acceleration of sprung mass than LQR controller and passive suspension system. Majdoub et al. [4] focusses on solving the problem of controlling quarter-car semi-active suspension system. To overcome with this problem, they designed an active control system. LQR controller and Lyapunov based control method were used as controllers. Various simulations have been made for the proposed control method.

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And it has been understood that the developed control method is more stable than passive systems. Rao & Kumar [5] presented Linear Quadratic Regulator (LQR) for quarter car semi active suspension system. In this study, the hydraulic damper was replaced with a magneto-rheological damper and a new controller was designed for the suspension system. With the simulations, it has been understood that the developed controller improves ride comfort.

Nagarkar et al [6] studied modelling and control of nonlinear quarter vehicle model including with seat and driver. PID and LQR controllers are applied to nonlinear quarter vehicle model as a controller. Genetic Algorithm rule is used to determine the cost functions of LQR and PID controllers in this study. From the simulation results, it is understood that it is advantageous to determine the estimation of the gain coefficients with a different control rule. Gokul & Malar [7] demonstrated an adaptive approach for the vehicle suspension system by using the LQR control method. The gain coefficients of the LQR controller were determined using the particle swarm optimization method. In order to prove the accuracy of the results obtained with the simulation, they created an experimental setup using a shaker table and tested the controller. The results showed that the controller they presented is advantageous in terms of road handling and ride comfort. Uddin [8] designed an LQR controller for the quarter vehicle model. Computer simulation was made according to active and passive suspension system. The results show that the developed controller has improved vertical displacement, vertical velocity, and vertical acceleration of the vehicle. Kaleemullah, Faris & Hasbullah [9] designed active suspension systems for quarter vehicle model. Robust H controller, LQR controller and Fuzzy control are compared with passive suspension system. The results showed that the controllers designed in active suspension systems are more successful in road handling and ride comfort. Wei et al [10] developed a hybrid controller for active suspension systems. The proposed controller consists of LQR and modal decomposition control rules. Modal decomposition method also works with the principle of weighting according to the importance of parameters such as neural network. When the results are compared with the passive system, the efficiency of the hybrid controller is understood. Bharali & Buragohain [11] applied three different controllers to a quarter vehicle model with three degrees of freedom. These controllers are PID controller, Linear Quadratic Controller (LQR) and Fuzzy logic controller. They explained the purpose of the study as increasing the ride comfort. As a result of the study, they observed that the fuzzy logic controller is more effective in stability. Divekar & Mahajar [12] aimed to provide ride comfort and road handling and to eliminate the discomforts caused by external disturbances of a vehicle. So that they developed control laws for quarter vehicle model with seat driver. LQR and Fuzzy logic controller have been adapted to this model and different control inputs have been applied to the model. From the results, they have seen that the LQR controller is more successful than the fuzzy logic controller for the step input. Anh [13] studied active suspension systems using PID control and LQR controllers. In this study, the PID controller supports to optimize the vehicle body acceleration and the LQR controller supports to optimize the vehicle body displacement. Rao & Narayanan [14] applied the sky hook damper model to the half vehicle model and examined the differences between LQR controller. From the simulation results, it has been observed that the displacement and velocity values obtained with the LQR controller are close to the skyhook model.

The summary of similar studies in the literature is as follows. Research shows that hybrid controllers are more advantageous. Therefore, a new hybrid control method has been developed by combining LQR and fuzzy logic controllers in this study by recognizing the deficiency in the literature.

There are two important situations for vehicles. The first one is road handling and the second one is ride comfort. It is very difficult to cure these two conditions at the same time. There are many controllers used to control the active suspension system such as PID controller, LQR controller et al. For this, a new controller was designed by considering two different control methods. A hybrid controller is designed using fuzzy logic controller and LQR controller. The control gain coefficients in the LQR control law were determined using a fuzzy logic controller. The input parameters in the fuzzy logic controller are determined as the vertical displacement error of the vehicle and its change with time. The output parameters are LQR gain coefficients (Q,R). The control rule between input and output parameters was determined by trial-and-error method. The effectiveness of the developed controller was obtained by performing simulations with a step path input with an amplitude of 0.01(m).

2. Materials and Methods

In this study, fuzzy logic controller, one of the most important controllers used in artificial intelligence technology, and LQR controller, which is one of the optimal control methods, are combined. LQR is a feedback control method. The control gain coefficients used in this controller are determined by trial-and-error method. A fuzzy logic controller, on the other hand, is a controller used to make predictions. Therefore, a new controller was designed from the combination of these two control methods. A quarter vehicle model was used to properly examine the results.

In the introduction part of this study, previous studies and the purpose of this study are given. In the materials and methods part, the equations of motion of the quarter vehicle model are mentioned. LQR control and Fuzzy Logic Control methods are explained in detail. In the result and discussion chapter, the results of the simulations are given, and the results are discussed. The last section is the discussion section. The advantages of the developed controller are emphasized by examining the results given in the previous section.

2.1. Quarter vehicle model

In Figure 1, two degree of freedom quarter vehicle model is presented.

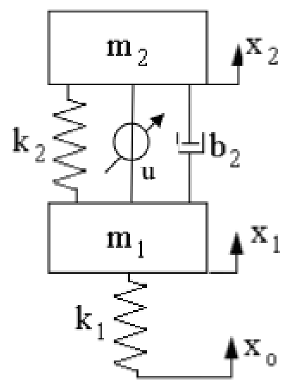

Figure 1. Quarter vehicle model

The equations of motions of the quarter vehicle model demonstrated in Equation 1 and Equation 2. [5]

$$m_1\ddot{x}_1 - b_2(\dot{x}_2 - \dot{x}_1) + k_1(x_1 - x_0) - k_2(x_2 - x_1) = -u \quad (1)$$

$$m_2\ddot{x}_2 + b_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) = u \quad (2)$$

In Equation (1) and Equation (2) m_1 represents the unsprung mass of the vehicle, m_2 represents the sprung mass of the vehicle, and b, k are the damping and stiffness parameters respectively. The numerical parameters of the quarter vehicle model are given in Table 1.

Table 1. Numerical parameters. [14]

Parameter	Unit	Values
m_1	kg	36
m_2	kg	240
b_2	Nsm^{-1}	980
k_1	Nm^{-1}	160 000
k_2	Nm^{-1}	16000

The state space model of the quarter vehicle model is given below.

$$z_1 = x_1, \quad z_2 = \dot{x}_1, \quad z_3 = x_2, \quad z_4 = \dot{x}_2 \quad (3)$$

If Equation 1 and Equation 2 are rewritten using Equation 3;

$$\dot{z}_1 = z_2$$

$$\dot{z}_2 = \frac{1}{m_1}[b_2(z_4 - z_2) - k_1(z_1 - x_0) + k_2(z_3 - z_1) - u]$$

$$\dot{z}_3 = z_4$$

$$\dot{z}_4 = \frac{1}{m_2}[-b_2(z_4 - z_2) - k_2(z_3 - z_1) + u] \quad (4)$$

Using Equation 3, the state space model Equation 5 is obtained.

$$\dot{z} = [A]\, z + [B]\, u + L[x_0]$$

$$y = C[z] \quad (5)$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{-(k_1 + k_2)}{m_1} & \frac{-b_2}{m_1} & \frac{k_2}{m_1} & \frac{b_2}{m_1} \\ 0 & 0 & 0 & 1 \\ \frac{k_2}{m_2} & \frac{b_2}{m_2} & \frac{-k_2}{m_2} & \frac{-b_2}{m_2} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ \frac{-1}{m_1} \\ 0 \\ \frac{1}{m_1} \end{bmatrix} \quad L = \begin{bmatrix} 0 \\ \frac{k_1}{m_1} \\ 0 \\ 0 \end{bmatrix} \quad C = [0\ 0\ 1\ 0] \quad (6)$$

2.2. LQR controller

LQR control method is one of the traditional, optimal control methods like PID controller. Unlike the PID controller, it works on the principle of multiple inputs and multiple outputs. Since it is a feedback control method, most of the control laws currently consider the working principle of the LQR controller.

$$u = K * x \quad (7)$$

In Equation (7), the K is represented as control gain coefficient. In order to optimize the coefficient K in Equation (7), the cost function must be minimized. And the cost function is represented as in Equation (8);

$$J = \int_0^{\infty} \{x(t)'Qx(t) + u(t)'Ru(t)\}\, dt \quad (8)$$

If Equation 7 substitutes in Equation (8)

$$J = \int_0^{\infty} x^T(Q + K^T R K)x\, dt \quad (9)$$

In Equation 8, Q and R are the gain coefficients and they should be positive. There are no specific rules for obtaining these coefficients. It's all about trial and error. Therefore, in this study, a fuzzy logic controller that works according to the trial-error principle was used to determine these coefficients. To determine K, assume that there is a constant P;

$$\frac{d}{dt}(x^T P x) = -x^T(Q + K^T R K)x \quad (10)$$

The P value in Equation 6 is determined by the Ricatti equation.

$$PA + A^T - PBR^{-1}P + Q = 0 \quad (11)$$

In Equation 11, A and B represents the state spaces variables of the system.

$$\dot{x} = Ax + Bu \quad (12)$$

The optimum control signal in the LQR controller should be as in Equation 13.

$$u(t) = -R^{-1}B^T P(t)\, x(t) = -Kx(t) \quad (13)$$

The most important part in the LQR controller is to determine the Q and R coefficients. The Q and R coefficients both have specific meanings. While the Q coefficient is adjusted for the response speed of the system, the R coefficient represents the energy consumed in the system.[15] Although there are several methods used to determine the Q and R coefficients, these coefficients are also determined by trial-and-error method.[16] In this study, Q and R coefficients were found with fuzzy logic controller, which is another control method.

2.3. Fuzzy logic controller

Zadeh was the first to come up with this control rule [17]. There are not only clear definitions in this developed control method. While describing any situation, definitions such as true-false, yes-no or 1-0 are made. In fuzzy logic, this is not the case. Intermediate values are also included. For example, when describing a situation, intermediate values other than 1-0 are also included. By means of fuzzy logic, intermediate values are expressed with membership functions. Membership functions can be expressed with geometric shapes such as triangles, trapezoids (Figure 2).

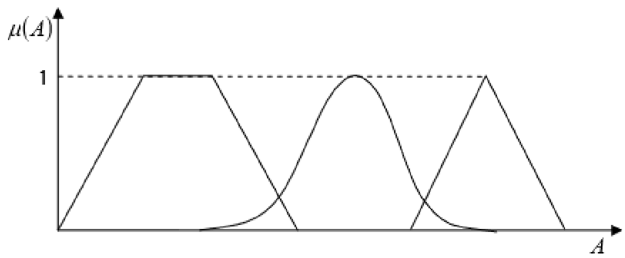

Figure 2. Geometric shapes of membership functions. [18]

Fuzzy Logic Controller consists of fuzzification, rule evaluation and defuzzification steps. First in the fuzzification part, membership functions are defined for the input variables. In the second part, rule table is created along the decision of the relationship between input and output variables. And final part is the fuzzification which the output membership function is converted from fuzzy values to exact values.

The most disadvantage of the LQR controller is that there isn't any clear method for determining the gain coefficients (Q and R) used in the controller. Therefore, in this study, control gain coefficients were determined by fuzzy logic controller. (Figure 3)

In the fuzzy logic controller, first the input and output parameters are determined. Any parameter in the model can be selected as input and output parameters. Rules are written to establish a connection between input and output parameters. These rules can be created by taking reference from previous studies or by trial and error. The trial-and-error method is to obtain the closest desired result according to the simulation results obtained with the membership functions and rules. Membership functions can take different forms. Rules can be created in different ways. These may vary depending on the closeness of the results obtained to the expected results.

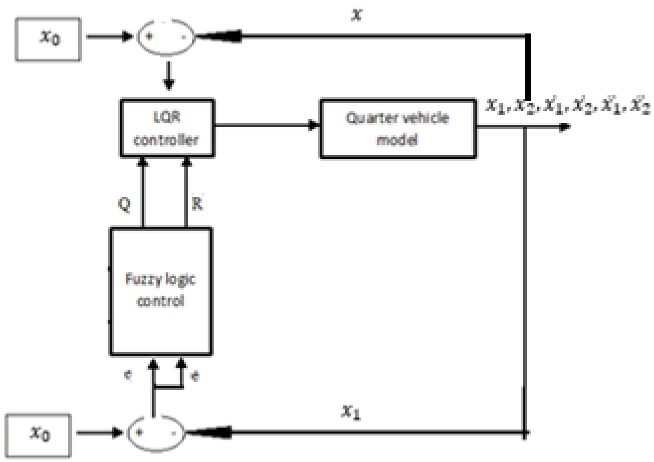

Figure 3. Block diagram of developed control system.

The purpose of the controller is to determine the Q and R gain dynamics in the LQR controller with a fuzzy logic controller. Therefore, system error and its derivative are selected as input. (Figure 4 and Figure 5)

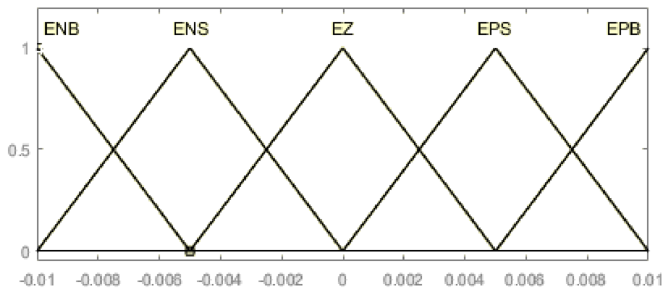

Figure 4. Membership functions of inputs (e).

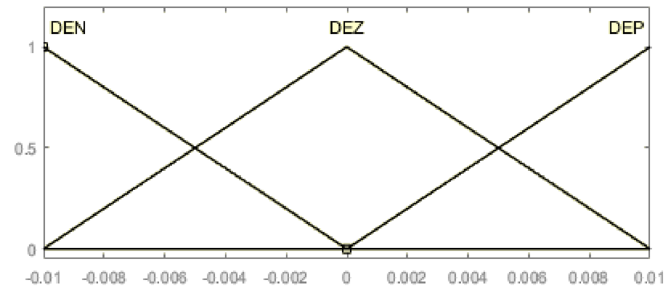

Figure 5. Membership functions of inputs (ė).

In the fuzzy logic controller, the input parameters are determined as the error and its derivative. Error is the difference between the vertical displacement of the vehicle and the road input. Membership functions are determined in a triangular shape between -0.01 and 0.01. Five different membership functions are defined for the error. Also the second input of the fuzzy logic controller is the derivative of the error. Three different membership functions for the derivative of the error are defined. Membership functions are determined in a triangular shape between -0.01 and 0.01.

In this study, the rule table was created by trial and error method. This table can also be created taking into account the literature. But since there isn't any similar study, it was created by trial and error method. (Table 2 and Table 3) The trial and error method proceeds as follows. A random rule was written among the specified inputs. For example, if the error is ENB and the derivative of the error is DEN, the output parameter is selected as QN4. This means that if the error and the time derivative of the error are chosen to be small values, the output Q will also be small. This is directly proportional to the intuition and the knowledge of the expert. The other part of the table was created using this assumption. This rule table was simulated and the results were obtained. Then, a different rule table was created and the results were obtained. The results were obtained by creating this and many similar rule tables, and finally the most desired result was taken into account.

Table 2. Fam table for Q.

e\ ė	DEN	DEZ	DEP
ENB	QN4	QN3	QN2
ENS	QN2	QN2	QN1
EZ	QNZ	QNZ	QNZ
EPS	QP1	QP2	QP2
EPB	QP3	QP3	QP4

Table 3. Fam table for R.

e\ ė	DEN	DEZ	DEP
ENB	RN4	RN3	RN2
ENS	RN2	RN2	RN1
EZ	RNZ	RNZ	RNZ
EPS	RP1	RP2	RP2
EPB	RP3	RP3	RP4

And also output membership functions are shown in Figure 6 and Figure 7.

Figures 6 and 7 show the membership functions of the output parameters Q and R. It is defined as nine triangular membership functions in the range of -1000 and 1000.

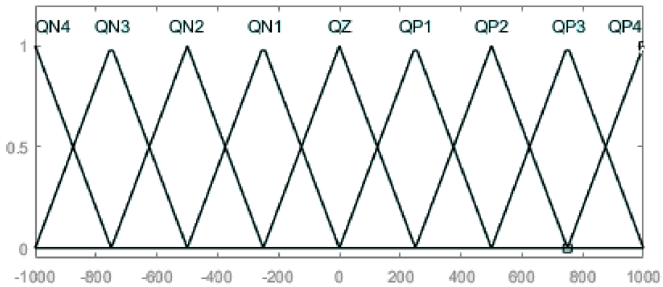

Figure 6. Membership functions of output. (Q)

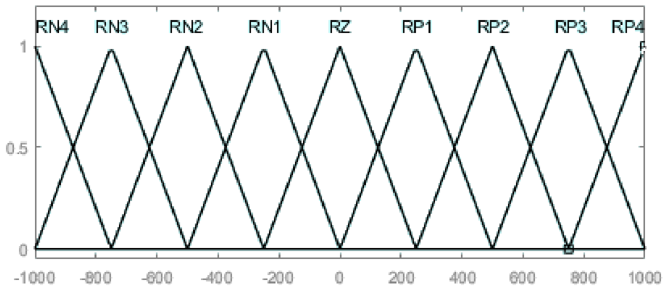

Figure 7. Membership functions of output. (R)

In fuzzy logic control, variables can be defined as anyway. The expression defined as ENB in Figure 4 means E symbolizes error N is negative and B means large. Generally, S (Small), Z (zero), P stands for (positive). The example in Figure 4 is EPS named (Error-Positive-Small). These definitions are completely user's definitions. DE, expressed in Figure 5, represents the derivative of the second input, the error. DEN, DEZ, DEP means derrivative of error small-zero-positive, respectively.

The same is valid for output functions. In Figures 6 and 7, there is a situation where the output membership functions are expressed linguistically. The letter Q at the beginning of the membership functions in Figure 6 represents the Q gain coefficient, and the letter R in Figure 7 represents the R gain coefficient.

In the 2nd and 3rd tables, a relationship has been established between the input and output membership functions. This is called the FAM table. Table 2 is for Q, and Table 3 is for R. For example, if the error (e) is (ENB) in the 2nd table and the derivative of the error ($\dot{\mathbf{e}}$) is DEN, then the gain coefficient Q takes the value of QN4. Or, if the error specified in Table 3 is e (ENS) and the error derivative ($\dot{\mathbf{e}}$) is DEZ, the gain coefficient R takes the value RN2.

3. Results and Dicussion

In order to measure the effectiveness of the developed controller, the proposed controller was applied to the quarter vehicle model and the results were discussed. The most important reason for choosing the quarter vehicle model is that it is possible to make more comfortable comments about the results. The values of the quarter vehicle model are given in Table 1. In Figure 8, the road input is given.

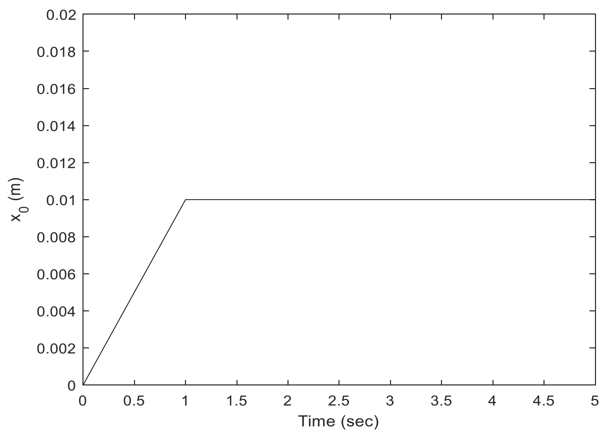

Figure 8. Road input.

The model is simulated for 3 different situations. These are passive Fuzzy Logic controller and LQR-Fuzzy Logic controls. In the fuzzy logic controller, the input membership functions are selected as in Figures 4 and 5. The output function is the controller force. In Figure 9, the displacement of the sprung mass over time is given. With fuzzy logic controller, sprung mass gives better results than passive system. The displacement reaches to the desired position in approximately 2 seconds. And the system oscillates less. LQR-Fuzzy Logic control shows a better result than fuzzy logic controller. With the developed controller, the system reaches the desired position almost without any oscillation.

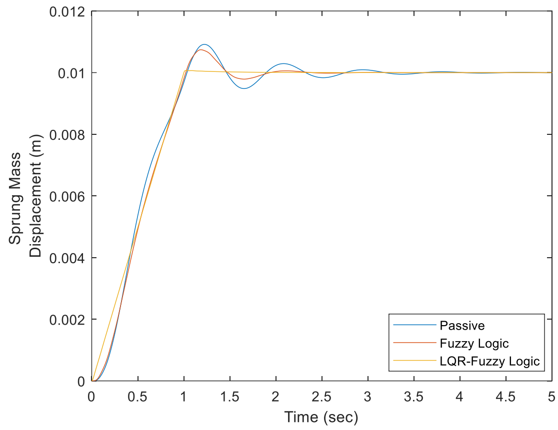

Figure 9. Displacement of the sprung mass over time.

In Figure 10, the displacement error of the sprung mass over time is given. This is the explanatory version of the graph in Figure 9. As can be seen from the figure, the fuzzy logic controller minimized the error faster than the passive system. The error in the developed controller seems to be around $0.1\text{x}10^{-3}$. This is an indication that a successful result has been achieved.

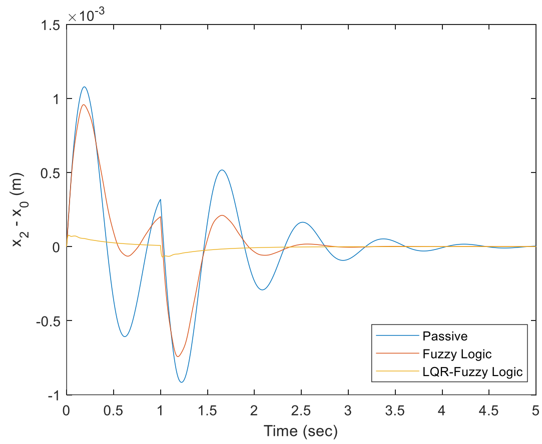

Figure 10. Displacement error of the sprung mass over time.

Figure 11 shows the acceleration of the sprung mass. Acceleration is an important criterion for vehicles, because the more acceleration effect on the vehicle or the later this effect is damped, the more likely it is that the controller has failed. When the figure is examined, it is seen that while the passive system is damped in 4 seconds, the fuzzy logic controller is damped in 2.5 seconds, and the LQR-Fuzzy logic controller is damped in 1.5 seconds. It is understood that while chattering occurs in the fuzzy logic controller, there isn't any chattering in the developed controller and the peak point of the maximum amplitude is 0.02 ms^{-2}.

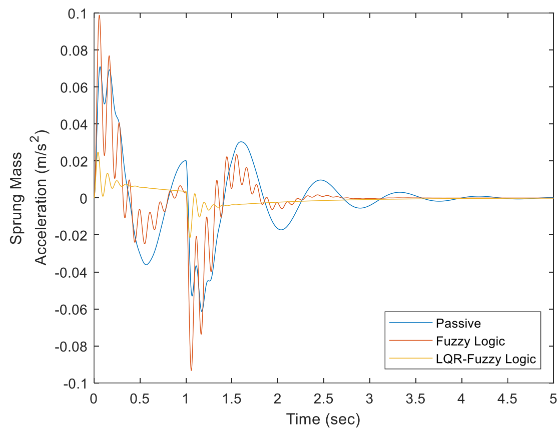

Figure 11. Acceleration of the sprung mass over time.

In Figure 12, tire deflection of the vehicle is given. Tire deflection is an important indicator for road handling. It is seen that the tire deflection is minimized quickly in the developed controller. In passive and fuzzy logic controller, it is understood that the system is minimized later.

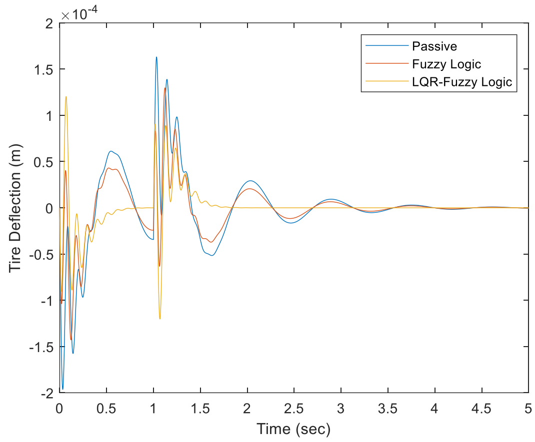

Figure 12. Acceleration of the sprung mass over time.

In the Figure 13 the control forces over time is shown. It is understood that the results are obtained in the expected force range for the quarter vehicle model. It is seen from the figure that the developed controller is more effective with less force.

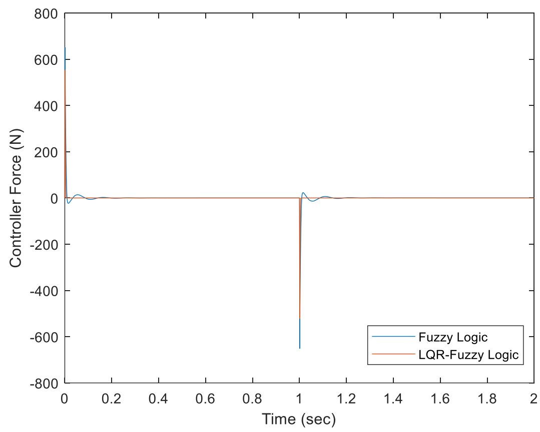

Figure 13. Controller force.

When performing the analytical calculation of frequency analysis, the transfer function of the system is taken into account. In order to find the transfer function of the system, it is necessary to use the equations of the model. Assuming zero initial conditions, The Laplace transform of the system is;

$$(m_1 s^2 + b_2 s + (k_1 + k_2))\, x_1(s) - (b_2 s + k_2)\, x_2(s) = k_1 x_0(s) - u(s) \tag{14}$$

$$(m_2 s^2 + b_2 s + k_2)\, x_2(s) - (b_2 s + k_2)\, x_1(s) = u(s) \tag{15}$$

$$\begin{bmatrix} (m_1 s^2 + b_2 s + (k_1 + k_2)) & -(b_2 s + k_2) \\ -(b_2 s + k_2) & (m_2 s^2 + b_2 s + k_2) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} k_1 x_0(s) - u(s) \\ u(s) \end{bmatrix} \tag{16}$$

$$\Delta = \det \begin{bmatrix} (m_1 s^2 + b_2 s + (k_1 + k_2)) & -(b_2 s + k_2) \\ -(b_2 s + k_2) & (m_2 s^2 + b_2 s + k_2) \end{bmatrix} \tag{17}$$

From Equation (16) and Equation (17), the transfer function of the system is;

$$G_1(s) = \frac{x_1(s) - x_2(s)}{x_0(s)} = \frac{m_2 k_1 s^2}{\Delta} \tag{18}$$

$$G_2(s) = \frac{x_1(s) - x_2(s)}{u(s)} = \frac{(m_1 - m_2)s^2 + k_2}{\Delta} \tag{19}$$

In this direction, when the frequency response of the system is simulated, Figure 14 and Figure 15 are obtained.

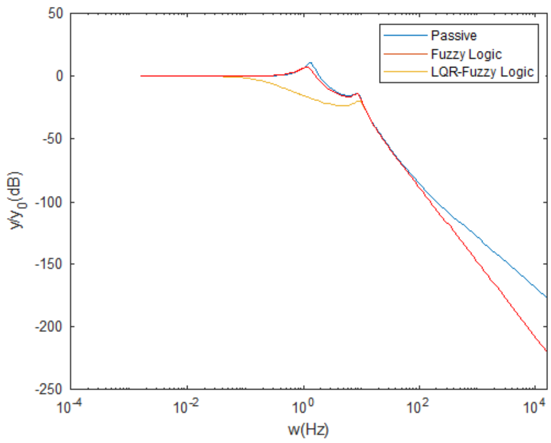

Figure 14. Frequency response of the vertical displacement.

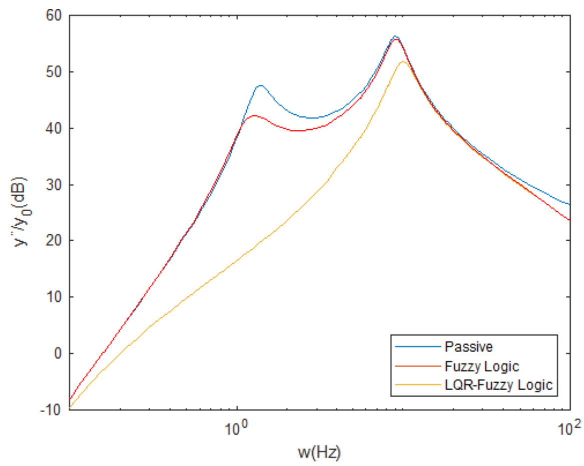

Figure 15. Frequency response of the vertical acceleration.

Figure 14 and Figure 15 show the frequency response of the vertical displacement and acceleration of the vehicle. Frequency response is an important indicator in vehicles in terms of ride comfort. In Figures 14 and 15, the road input was defined as an constant input because frequency is independent of the input parameter. And the systems output is defined as the vertical displacement and vertical acceleration.

The first peak in Figure 14 and Figure 15 shows the frequency response of the vehicle body, and the second peak shows the frequency response of the axle mass. The resonance of the first mass, namely the sprung mass, is around 1 hertz, and the resonance occurs around 10 Hertz, indicate the resonance of the unsprung mass. These frequency values are safe for the proper operation of the vehicle. It is important in terms of ride comfort that the first resonance is suppressed, and the second resonance not increased too much. This indicates that the controller works properly. The frequency responses of the passive system and the fuzzy logic controller system were close to each other. It seems that the fuzzy logic controller has a slight effect on the frequency response. It is understood from Figures 14 and Figure 15 that the developed controller is effective in damping both the body displacement frequency and the peak in the frequency response of acceleration.

4. Conclusions

The most important aim of this study is to design a new hybrid controller using two different controllers. For this, studies in the literature were examined and the most common used controllers in mechanical system design were selected. These are LQR controller and fuzzy logic controller. In the study, the two control gain coefficients Q and R used in the LQR control rule were determined with a fuzzy logic controller. There are different perspectives in the literature on determining the Q and R numbers in the LQR controller. The distinguishing feature of this study comes into play here. With the popularity of artificial intelligence in recent years, fuzzy logic control method has become one of the most used systems. The success of the fuzzy logic controller has been guaranteed by the studies. In this study, the LQR gain coefficients were determined by fuzzy logic control method. In order to determine the efficiency of the developed controller, a quarter vehicle model was selected. When the simulation results are examined, it is understood that an effective controller has been developed. The most important point in the developed controller in this study is the vertical displacement and acceleration of the vehicle. The vehicles displacement reaches to the desired position in approximately 2 seconds in Fuzzy logic controller, however, it is seen that the Lqr-Fuzzy logic controller reaches a steady state immediately. And the system oscillates less in LQR-Fuzzy Logic controller. And the other important point in the study is the acceleration of the sprung mass. When the figure is examined, it is understood that the passive system is damped in 4 seconds, the fuzzy logic controller is damped in 2.5 seconds, and the LQR-Fuzzy logic controller is damped in 1.5 seconds. And It is seen that while chattering occurs in the fuzzy logic controller, there isn't any chattering in the developed controller and the peak point of the maximum amplitude is 0.02 ms^{-2}.

It has been a good reference work for future studies. And in future studies, the effectiveness of the developed controller in this study can be supported by experimental studies. The performance of hybrid controllers developed with different controllers or in different models can be supported by different studies.

Ethics committee approval and conflict of interest statement

This article does not require ethics committee approval. This article has no conflicts of interest with any individual or institution.

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