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Ellipsoidal-Based Robust Control for Vehicle Active Suspension Systems under Load Uncertainties and Network-Induced Interruptions

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ABSTRACT

This paper presents a novel ellipsoidal-based robust control design for vehicle active suspension systems operating under uncertain load conditions and subject to denial-of-service (DoS) cyberattacks. The proposed controller leverages a networked control system (NCS) architecture and employs bilinear matrix inequalities (BMIs) reformulated into linear matrix inequalities (LMIs) to synthesize a secure and robust state-feedback law. The resulting invariant ellipsoidal set ensures stability by minimizing the impact of road-induced disturbances and cyber threats. Simulation results demonstrate the superiority of the proposed control scheme over traditional H ∞ methods in terms of stability and disturbance rejection. The approach enhances both riding comfort and control reliability in intelligent automotive applications.

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1. Introduction

1.1 Survey of the Related Publication

Vehicle suspension systems (VSSs) have garnered significant attention due to their crucial role in an automobile's chassis performance. A decent suspension system for a car should always provide road-holding capabilities, good handling, and favourable comfort (Pan et al., 2018). Many researchers have focused on investigating a range of cutting-edge techniques, including active control, semi-active control, and passive control, to enhance a vehicle's suspension performance. Numerous studies have demonstrated that active control can address the multi-objective control issue in car suspensions. As a result, countless active suspension control techniques have been proposed. The H∞ control is an efficient technique for improving the durability of vehicle suspension performance in terms of road holding, suspension stroke limits, and actuator saturation (Chen & Guo, 2005). Regional pole placement is an additional strategy to improve dynamic performance in terms of the intended damping ratio and settling time (Soliman & Bajabaa, 2013). By forcing the closed-loop poles to lie in a specific area, this technique achieves the required settling time and damping ratio, even when the passenger load varies. Furthermore, Soliman et al. (2016) provide information on actuator saturation. While Soliman et al. (2018) solve the problem for the discrete-time case, Soliman & Bajabaa (2013) and Soliman et al. (2016) solve the problem for the continuous-time situation. Another excellent defense against load uncertainty is sliding mode control (SMC). The conventional SMC is ineffective in eliminating unmatched disturbances. To mitigate the impact of the mismatched disturbance on the system's performance, the SMC utilises the invariant ellipsoid (BAJABA et al., 2024; Chibani et al., 2018; Wang et al., 2017). Many academics have expressed worry about H∞ control in recent years (Gao et al., 2010; Guan et al., 2018; H. Li et al., 2014; P. Li et al., 2014). For example, in Gao et al. (2010), the H∞ control problem of an uncertain active suspension with digital signal sampling was studied. It is worth noting that the majority of active suspension control techniques currently in use are based on the conventional point-to-point control architecture. Unlike traditional active car suspension controls, the majority of modern ones link the controller to the system via a communication network, as shown in Figure 1. Intelligent mechatronic technologies, such as smart cars, have made people's daily lives considerably more convenient than they were with conventional control systems. The stability and comfort of the ride are directly impacted by the automobile suspension system in intelligent vehicles. As more parts, including sensors, actuators, and controllers, are linked together through communication networks in today's smart cars, sensor or actuator failures typically affect these cars, particularly in the suspension systems. The following benefits have led to the widespread usage of networked control systems (NCSs) in recent decades: their low cost, flexibility, ease of installation, and high dependability (Viadero-Monasterio et al., 2022). The NCS is a viable and efficient method of managing active car suspension over network media, enhancing security and reliability from a technical perspective. A wireless communication network is used to inject the supplementary feedback signal into the control channel (Fig. 1). Nonetheless, the NCSs face the following challenges:

(1) its constrained bandwidth. An event-trigger technique is employed to reduce the load of communication (Arumugam & Chen, 2024).

(2) Because the channels of communication are frequently exposed, they are vulnerable to cyberattacks. Time delays (Wang & Zhou, 2019), data tampering (also known as false data injection, FDI, or deception assaults) (Sun et al., 2021), and denial-of-service (DoS) attacks (Ye et al., 2020) are examples of cyberattack threats that can seriously harm a communication network.

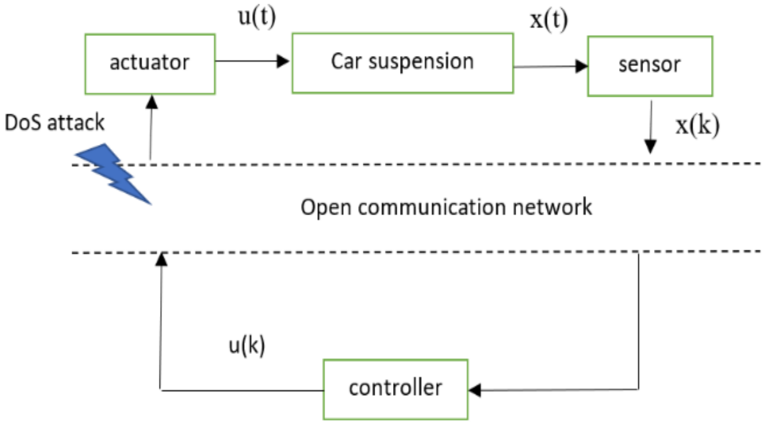

Figure 1: Network-Based Closed-Loop System with DoS Attack

From the perspective of control security, DoS and FDI are the two primary categories of cyberattacks (Mahmoud et al., 2019). Since communication networks are frequently vulnerable to adversaries, the cyber-attack issue has become a significant concern in the design of networked systems. The sensor fault estimate problem for a class of network-based car suspension system with DoS assault, where the attack information is partially unknown or ambiguous, is examined in ref (Ye et al., 2020). based on the comments above. Either the Bernoulli model or the Markov jump model (with the challenge of assuming the attack's transition probability) could be used as the stochastic representation of the DoS attack.

1.2 Main Contributions

The main contributions are:

- This paper addresses the car networked control which is secure under DoS attack.
- The proposed control is also robust control against load variation for linear discrete-time systems.
- It applies an ellipsoidal bound to a robust invariant-set. The most important thing is to keep the system's state within the robust invariant feasible set which is a collection of states that ensures the stability of the suggested control technique. Minimizing the invariant ellipsoid volume improves the system's performance by attenuating the disturbance consequence.
- The development of robust invariant-set is based on quadratic boundedness.

1.3 Structure of the Paper

The paper is organised as follows: The quarter-car active suspension models and issue formulation are presented in Section 2. Section 3 introduces and explains the notion of the invariant-ellipsoid set. The proposed control, which is secure against DoS attacks and resilient against load uncertainty, is presented in Section 4 along with a comparison to H∞ control. The end contains the conclusions.

2. Quarter Car Modelling and Problem Formulation

2.1 Notations and Facts

All the notation used is standard. Scalars are represented by small Greek letters, vectors by small letters, and matrices by capital letters. (.)' denotes transposition for matrices or vectors. If X > 0 (≥ 0) for symmetric matrices, then X is positive definite (nonnegative definite). R stands for sets of real numbers. To simplify the notation of partitioned symmetric matrices, the symbol (*) generically indicates each of its symmetric blocks, whereas trace (X) indicates the trace function of X for square matrices. In the sequel, the following mathematical inequality is used.

Fact 1-Bounding inequality (Poznyak, 2024):

For any real matrices X_1, X_2 and X_3 with appropriate dimensions and $X_3'X_3 \le$ I, it follows that

$$X_1X_3X_2 + * \le \varepsilon X_1X_1' + \varepsilon^{-1}X_2'X_2, \forall scalar\ \varepsilon > 0$$

Fact 2-Schur complement (Poznyak, 2024):

Given a matrix X composed of constant matrices X_1, X_2, X_3, where $X_1 = X_1'$ and $0 < X_2 = X_2'$ as follows

$$X = \begin{bmatrix} X_1 & X_3 \\ * & X_2 \end{bmatrix},$$

we have the following result: $X > 0$ if and only if

$$X_2 > 0, X_1 - X_3X_2^{-1}X_3' > 0,$$

An effective way to improve suspension performance is accomplished through the addition of an active damper in parallel with the conventional passive system. Active suspension control utilises pneumatic or hydraulic actuators that create the desired forces within the suspension system. To quantify the motion of the body and suspension system, the technology requires the placement of sensors at various locations throughout the vehicle. An online controller uses this information to instruct the actuator to deliver the precise force required. By forcing pressure-controlled oil into the jack, the impact of road disturbance is rejected. Fig. 2 (Chen & Guo, 2005) depicts an active suspension system for a quarter-vehicle.

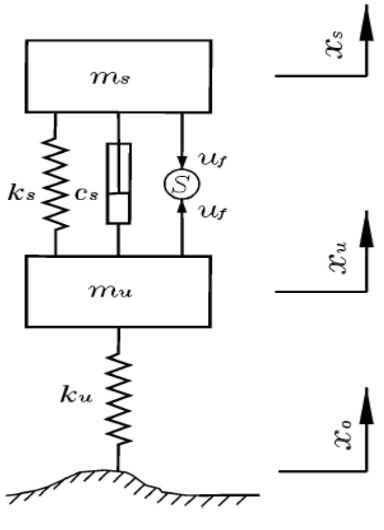

Figure 2: Two-DOF Quarter-Car Model with an Active Suspension

Because it provides adequate precision in practice, the quarter car model was chosen. The tire stiffness is denoted by $k_u$in Figure 2, while the sprung and unsprung masses are represented by m_s and m_u , respectively. Furthermore, u_f is the scalar active force produced by a hydraulic actuator, whereas $x_s -,\ x_u - x_0\ and\ x_0$ are the suspension stroke, tyre deflection, and vertical ground displacement brought on by uneven roads, respectively. Utilising a collection of state variables.

$$\begin{gathered} x_1 = x_s - x_u \\ x_2 = \dot{x}_s \\ x_3 = x_u - x_0 \\ x_4 = \dot{x}_u \end{gathered} \tag{1}$$

The continuous-time state-space model linearized around an operating point, of the suspension shown in Figure 2 is given by

$$\dot{x} = A_c x + B_c u + D_c w, y = Cx, z = Cx \tag{2}$$

Where A_c , B_c, D_c, are respectively

$$\begin{bmatrix} 0 & 1 & 0 & -1 \\ -\frac{k_s}{m_s} & -\frac{c_s}{m_s} & 0 & \frac{c_s}{m_s} \\ 0 & 0 & 0 & 1 \\ \frac{k_s}{m_u} & \frac{c_s}{m_u} & -\frac{k_u}{m_u} & -\frac{c_s}{m_u} \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ \frac{u_s}{m_s} \\ 0 \\ -\frac{u_s}{m_u} \end{bmatrix} \tag{3}$$

where the normalized active force $u = u_f/u_s$ is the control input and $w = \dot{x}_0$ represents the disturbance caused by road roughness.

-Active suspension stochastic discrete-time model under DoS attack.

In the car industry, digital computers are used intensively. To use digital computer control directly, the system dynamics must be discretised. The quarter car dynamics with cyber-attack (2) is discretized with a suitable sampling time T_s $(\mathit{selected\ as\ one\ \ tenth\ of\ the\ time\ constant\ of\ the\ fastet\ mode})$ as linear time-invariant LTI.

$$\left.\begin{gathered} x(k+1)=Ax(k)+Bu(k)+Dw(k), \\ y(k)=Cx(k),z(k)=Cx(k) \end{gathered}\right\} \tag{4}$$

A stochastic model can be used to model the dynamics under a DoS attack. The Bernoulli model for the following LTI system is:

$$x(k+1) = Ax(k) + \beta(k)Bu(k) + Dw(k) \tag{5}$$

where x(k) ∈ R^n, u(k) ∈ R^m are the state variables and control input, respectively. In our study system, n = 4, m = 1. The Bernoulli distribution *β(k)* independent, identically distributed (i.i.d) sequence. (the Bernoulli distribution is the discrete probability distribution of a random variable which takes the value 1 with probability *p* and the value *0* with probability *q=1−p*.) In other words, $\beta(k)$ switches between two values, 0, and 1). Hence, the input matrix under DoS attack switches between two values $0_{n.m}, B_{n.m}$. This can be modelled as

$$\begin{gathered} x(k+1) = A\mathrm{x}(k) + (B + \Delta B)u(k) + Dw(k) \\ \Delta B = -B.diag(\beta_1(k) \ldots \beta_m(k)) = -B.\Delta(k).I, \|\Delta(k)\| \leq 1 \end{gathered} \tag{6}$$

-Active suspension uncertain stochastic discrete-time model under DoS attack. The Bernoulli model representing the DoS attack (6), adding parameters uncertainty, system (6) becomes:

$$x(k+1) = (A + \Delta A)x(k) + (B + \Delta B)u(k) + (D + \Delta D)w(k) \tag{7}$$

Where $\|\Delta_{\boldsymbol{A}}\| \leq 1, \|\Delta_{\boldsymbol{B}}\| \leq 1, \|\Delta_{\boldsymbol{D}}\| \leq 1$. Note that the uncertainty in (6) is modelled in the norm-bounded form. It is required to design robust state feedback

$$u(k) = Kx(k) \tag{8}$$

to stabilize the uncertain system (7).

3. Ellipsoidal Design of Secure Active Suspension Control

3.1 The Proposed Control

Given an LTI norm-bounded uncertain system

$$\left.\begin{gathered} x(k+1)=(A+\Delta A)x(k)+(B+\Delta B)u(k)+(D+\Delta D)w(k),y(k)=Cx(k) \\ \|\Delta_A\|\leq 1,\|\Delta_B\|\leq 1,\|\Delta_D\|\leq 1 \end{gathered}\right\} \tag{9}$$

The idea of the ellipsoidal control design is to force the state trajectory x(k) to be attracted into a small region around the origin (ellipsoid, centered the origin)

$$E = x'_a(k)P^{-1}x_a(k) \leq 1, P > 0 \tag{10}$$

Once the state trajectory enters the ellipsoid, x(k) will not leave E when the time evolves (time-invariant ellipsoid). Hence, ellipsoid E is termed attractive or invariant. To attenuate the impact of the external disturbance on system performance, the ellipsoid volume, in terms of the linear function trace (P), must be minimised. The following theorem solves this problem.

3.1.1 Theorem 1 (Khlebnikov et al., 2011): Consider the minimization problem

$$minimize \ \mathrm{tr}\ [CPC']$$

subject to the following constraints

$$\begin{bmatrix} -\alpha P & (AP+BY)' & 0 & PH_A' & (H_BY)' & 0 \\ * & \Psi & D & 0 & 0 & 0 \\ * & * & -(1-\alpha)I & 0 & 0 & H_D' \\ * & * & * & -\varepsilon_1 I & 0 & 0 \\ * & * & * & * & -\varepsilon_2 I & 0 \\ * & * & * & * & * & -\varepsilon_3 I \end{bmatrix} \leq 0,$$
$$P > 0,$$
$$and\ the\ scalars\ \ 0 < \alpha < 1, \varepsilon_1 > 0, \varepsilon_2 > 0, \varepsilon_3 > 0$$

Where,

$$\Psi = -P + \varepsilon_1 F_A F_A' + \varepsilon_2 F_B F_B' + \varepsilon_3 F_D F_D'$$

$$with\ \ F_B = -B, H_B = I \ \ , \|\Delta_A\| \leq 1, \|\Delta_B\| \leq 1, \|\Delta_D\| \leq 1$$

Note in (10) is also modelled in the norm-bounded form. The above problem can be solved using the following theorem.

3.1.2 Theorem 2: Consider the Minimization Problem

$$minimize\ tr\ [CPC']$$

subject to the following constraints

$$\begin{bmatrix} -\alpha P & (AP+BY)' & 0 & PH_A' & Y' & 0 \\ * & \Psi & D & 0 & 0 & 0 \\ * & * & -(1-\alpha)I & 0 & 0 & H_D' \\ * & * & * & -\varepsilon_1 I & 0 & 0 \\ * & * & * & * & -\varepsilon_2 I & 0 \\ * & * & * & * & * & -\varepsilon_3 I \end{bmatrix} \leq 0,$$
$$P > 0,$$
$$and\ the\ scalars\ \ 0 < \alpha < 1, \varepsilon_1 > 0, \varepsilon_2 > 0, \varepsilon_3 > 0$$

Where,

$$\Psi = -P + \varepsilon_1 F_A F_A' + \varepsilon_2 BB' + \varepsilon_3 F_D F_D'$$

and the minimization is carried out concerning the matrix variables $P = P'$, scalar variables $\varepsilon_1, \varepsilon_2, \varepsilon_3$, and the scalar parameter α. The solution P, Y of this problem defines the matrix CPC' of the output bounding ellipsoid and the secure (against cyber- attack), robust (against load uncertainty) state regulator is

$$K = YP^{-1} \tag{11}$$

Note that the optimization problem in theorem 2 is nonlinear matrix inequality due to the product term αP. This difficulty can be overcome by an iterative algorithm as follows. The scalar α is fixed in an outer loop and the resulting LMIs are solved in the inner loop.

3.2 Comparison with H_∞Control

The H_∞control can be obtained as follows

$$minimize\ \gamma$$

Subject to

$$\begin{bmatrix} P & AP-BY & D & 0 \\ * & P & 0 & PC' \\ * & * & \gamma I & 0 \\ * & * & * & \gamma I \end{bmatrix} > 0, P > 0, \gamma > 0$$

The resulting controller is

$$K_\infty = YP^{-1} \tag{12}$$

4. Simulation Verification

In this section, an illustrative example is given to show the effectiveness of the proposed design. The system parameters and nominal values are shown in Table 1 (Chen & Guo, 2005).

Table 1: Quarter-Car Active Suspension Parameters

Parameter	Value
I. m_s	II. 320 kg
III. m_u	IV. 40 kg
V. k_s	VI. 18 kN/m
VII. k_u	VIII. 200 kN/m
IX. c_s	X. 1 kN.s/m
XI. u_s	XII. 1.5 kN

Substituting the values in Table 1, the continuous-time state equation (3) is obtained. To implement digital computer control directly, the system is discretised using a zero-order hold. The sampling time T_s is selected as nearly one tenth of the time constant of the fastest pole. Therefore, $T_s = 0.01\ s$.

4.1 Robustness Against Load Uncertainties

Assuming the load varies between 250 kg to 390 kg. the average model between such extremities is

$$\hat{A} = A + \Delta A, \quad \Delta A = F_A \Delta H_A$$

Where,

$$A = \begin{bmatrix} 0.97771 & 0.0086841 & 0.21787 & -0.0079273 \\ -0.51262 & 0.96884 & -0.75936 & 0.028569 \\ 0.019608 & 0.0011574 & 0.77953 & 0.0080791 \\ 3.5673 & 0.21779 & -40.395 & 0.56175 \end{bmatrix},$$

$$F_A = [-0.0019605 \quad -0.52825 \quad -0.00014917 \quad -0.050103]'$$

$$H_A = [-0.20947 \quad -0.012741 \quad -0.31081 \quad 0.011674]$$

Also, $\hat{B} = B + \Delta B, \quad \Delta B = F_B \Delta H_B$

Where,

$$B = [0.0018579 \quad 0.042719 \quad -0.001634 \quad -0.29727]'$$

$$F_B = [-0.00054977 \quad -0.11362 \quad -4.9417\text{e}-05 \quad -0.01396]', H_B = 0.080943$$

The external disturbance is $D = [0 \quad 0 \quad -0.01 \quad 0]'$. The above norm-bounded form is obtained using the singular value decomposition (Werner et al., 2003). Table 2 show the proposed and the H_∞ control (11), and (12) respectively, obtained using the MATLAB-LMI toolbox, yalmip interface, and sedumi solvers.

Table 2: Proposed and H_∞ Controls

Controller	Values	Comments
Proposed controller	$K = [10.954 \quad -15.318 \quad 44.532 \quad -0.4994]$	α =0.~~61535~~
H_∞ Control	$K_\infty = [-530.92 \quad -4.6733 \quad -117.27 \quad 4.2659]$	γ_{opt} =0.001~~6873~~

The above Table 2 shows that the inf-norm of the H_∞ control, 530.92, is much larger than that of the proposed one, 44.532 . This may result in a larger control effort that may damage the suspension's mechanical parts.

4.2 Dos Cyber-Attack

The DoS is modelled by a Bernoulli stochastic variable, as shown in Fig. 3.

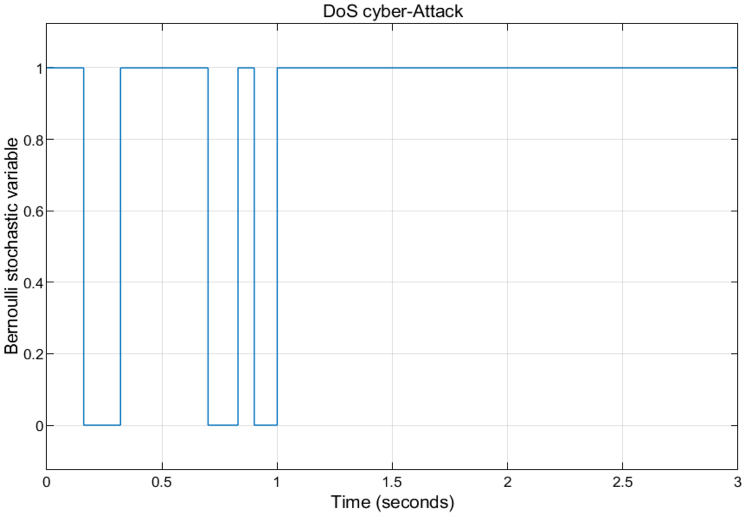

Figure 3: Dos-Attack Modelled by Bernoulli Stochastic Variable

In this work, the DoS attack is assumed to start at t = 0.16 s and end at 1 s. Note that the dos attack is random, unlike the deterministic case.

4.3 Cyber-Security Testing

The security of the proposed control against DoS cyber-attack is tested for step road of 0.015 m. Comparison with H_∞ is also given.

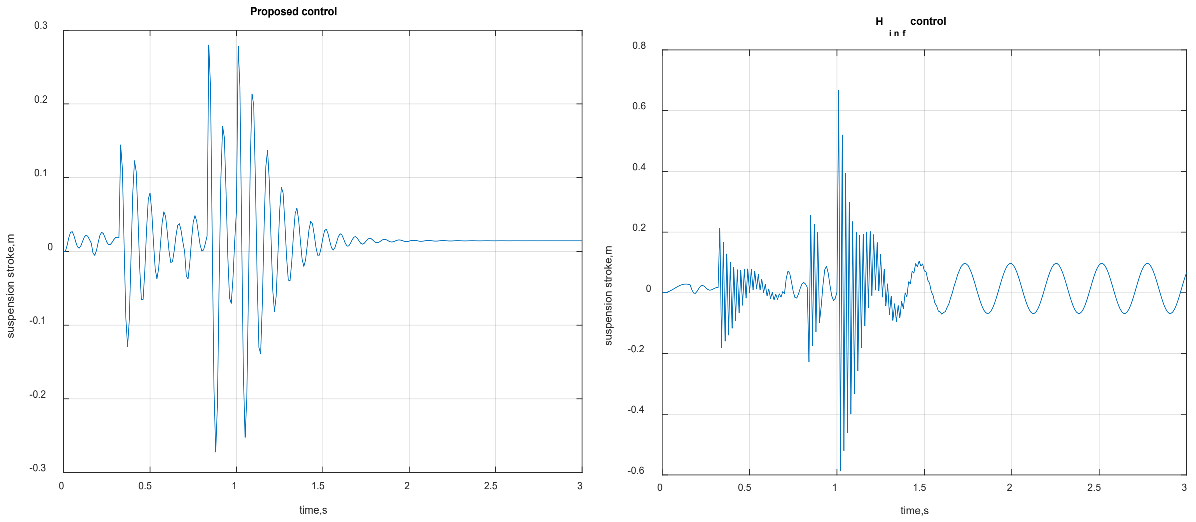

Figure 4: Response under DoS Attack Using the Proposed in Comparison with

The response using the H_∞ is unstable. It is evident that the proposed control outperforms the H_∞.

4.4 Robustness Test for Uncertain Loads

The proposed control is tested for a 0.015 m step road, assuming the passenger load varies between 250 kg and 390 kg (Fig. 5). The proposed control successfully damps the oscillations within the recommended settling time for different passenger load variations.

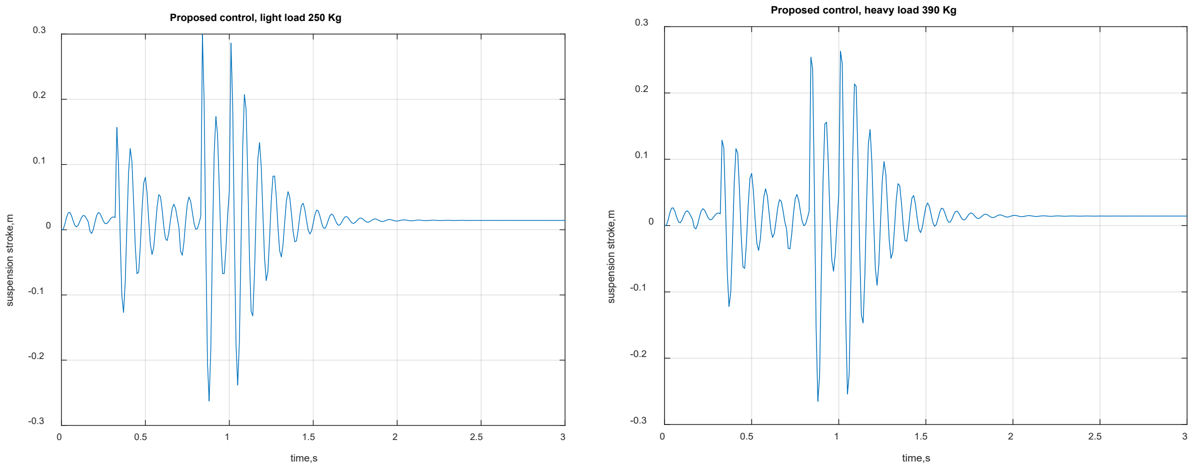

Figure 5: Response under DoS Attack Using the Proposed Control for Heavy and Light Loads

5. Conclusions

In this study, we developed a robust ellipsoidal-based control strategy for vehicle active suspension systems subjected to load uncertainties and network-induced DoS attacks. By modeling the cyber-attacks using a Bernoulli process and formulating the control design through Linear Matrix Inequalities (LMIs), the proposed method ensures closed-loop stability. It enhances ride comfort despite communication interruptions and parameter variations. Simulation results confirm that the proposed controller significantly outperforms traditional H∞ control in terms of resilience, stability, and performance under both nominal and adverse conditions. The ellipsoidal invariant set framework provides an efficient and scalable design technique for real-time automotive control applications. This research contributes to the field of secure and robust control in cyber-physical vehicle systems, particularly under unpredictable load and network conditions. Future work may extend this approach to more complex full-car suspension models and investigate resilience against other types of cyber-attacks such as replay or false data injection attacks. Practical implementation and real-time validation on hardware-in-the-loop platforms can further establish the feasibility of the proposed scheme.

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