BACHELOR

Influence of varying shape and size on maximal suction force produced by individual soft suction cups

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Fault Isolation in CACC through Model-based Residual Generators

Final report

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Contents

1 Introduction

Cooperative Adaptive Cruise Control (CACC) is an autonomous control technology which allows multiple vehicles to closely drive together in a highway setting. There are 2 types of CACC, one bases on vehicle-vehicle cooperation in which information is exchanged between 2 or more vehicles and one based on infrastructure-vehicle cooperation in which information or guidance is provided by the infrastructure [1]. This use of communication with either other vehicles or the infrastructure is what sets CACC apart from Adaptive Cruise Control (ACC) which just uses onboard sensors. CACC allows for a shorter vehicle-following gap compared to ACC, which when used on heavy duty vehicles, causes a significant reduction of the drag force, thus decreasing fuel consumption [2].

However this use of communication between vehicles and infrastructure and onboard sensors comes with some safety concerns. If the information gathered by the onboard sensors or inter-vehicle or vehicle-infrastructure communication is not accurate due to a faulty sensor for example this can lead to poor performance or even crashes. Therefore there is a real need for algorithms that allow us to detect and isolate such faults in the inter-vehicle communication and onboard sensors for CACC systems.

In this project such an algorithm will be built in the form of a model-based isolation scheme based on residual generators, i.e, transfer matrices that decouple the effect of faults at different parts of the system. This will be done by first modelling the faulty longitudinal dynamics of a platoon based on a one-vehicle look-ahead CACC developed and validated in [3]. This CACC system uses onboard sensors to detect distance and difference in velocity between vehicles and the velocity and acceleration of individual vehicles. Beyond sensors, this CACC system uses inter-vehicle wireless communication to exchange acceleration data from leader to follower. There is no infrastructure-vehicle communication in this system. The modelled faulty longitudinal dynamics will then be used to design residual generators in the frequency domain. These residual generators will be used to isolate faults in the onboard sensors and the inter-vehicle communication. From these, one residual generator will be selected and tested for inaccuracies in the dynamics.

2 Dynamics

2.1 Model

Before the faulty dynamics can be modelled, the model of the normal dynamics of a platoon needs to be understood. The strategy used is a one-vehicle look-ahead CACC developed and validated in [3]. A model of the uncontrolled dynamics of this CACC strategy with m vehicles is shown in Equation 1 [4].This model uses both onboard sensors and inter-vehicle communication and does not use vehicle-infrastructure communication.

$$\begin{aligned} \begin{pmatrix} \dot{v}_1 \\ \dot{a}_1 \end{pmatrix} &= \begin{pmatrix} a \\ -\frac{1}{\tau}a_1 + \frac{1}{\tau}u_1 \end{pmatrix}, \\ \begin{pmatrix} \dot{d}_i \\ \dot{v}_i \\ \dot{a}_i \end{pmatrix} &= \begin{pmatrix} v_{i-1} - v_i \\ a_i \\ -\frac{1}{\tau}a_i + \frac{1}{\tau}u_i \end{pmatrix}, \quad i \in S_m \backslash \{1\} \end{aligned} \tag{1}$$

Here, vehicle 1 is the leading vehicle, d_i is the distance between vehicles i and $i-1$, defined as $d_i = q_{i-1} - q_i - L_i$, where q_i is the rear bumper position and L_i is the length of vehicle i. Moreover v_i, a_i and u_i are the velocity, acceleration and vehicle input of vehicle i. The vehicle input can be best interpreted as the desired acceleration. Constant τ represents the drive train dynamics of the vehicle. A policy for inter-vehicle spacing is set. This policy is shown in Equation 2.

$$d_{r,i}(t) = r_i + hv_i(t), \quad i \in S_m \backslash \{1\} \tag{2}$$

Here, $d_{r,i}$ is the desired amount of space between 2 vehicles, r_i is the standstill distance and h is the time gap. This spacing policy is used to regulate the error in the distance between 2 vehicles. This error is defined in Equation 3.

$$e_i(t) = d_i(t) - d_{r,i}(t), \quad i \in S_m \backslash \{1\} \tag{3}$$

When this error is equal to zero, this means the distance between 2 vehicles is equal to the desired distance. The objective of the controller is to regulate this error to zero. In [3], it is proved that this objective is achieved with the dynamic controller shown in Equation 4.

$$\dot{u}_i = -\frac{1}{h}u_i + \frac{1}{h}(k_p e_i + k_d \dot{e}_i + k_{dd} \ddot{e}_i) + \frac{1}{h}u_{i-1}, \quad i \in S_m \backslash \{1\} \tag{4}$$

Here, k_p, k_d and k_{dd} are the controller coefficients.

2.2 Numeric validation

This model is tested in a Simulink setting with 2 vehicles, a leader and a follower, to see how the system behaves. The Simulink setup is shown in Figure 1.

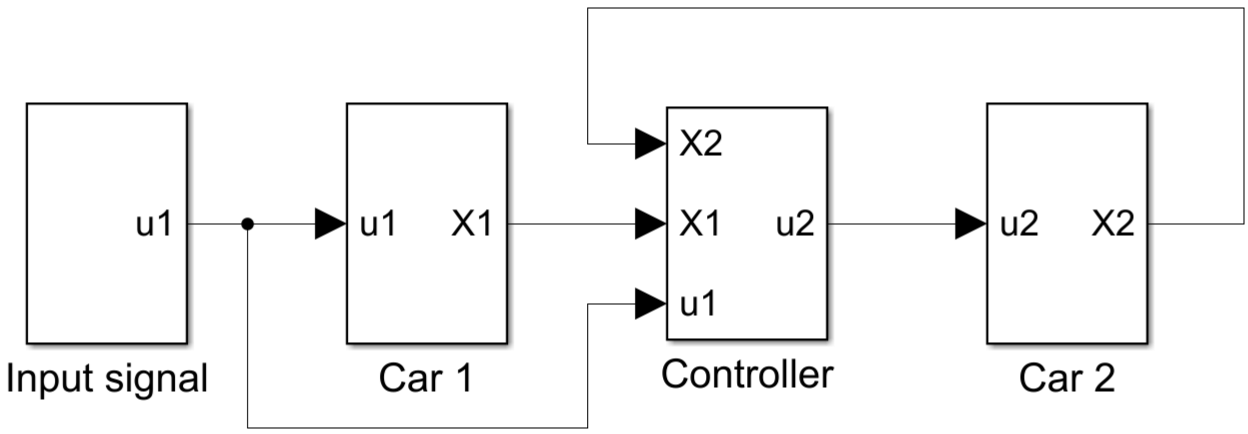

Figure 1: Simulink setup

Here, the Simulink blocks Car 1 and Car 2 contain Equation 1 and the Simulink block for the controller contains Equation 2, Equation 3 and Equation 4. The Simulink block for the Input signal contains the intput signal to the leader, which consists of a simple impulse signal, which is equal to 0 for $50 > t > 0$ and $t > 75$ and equal to 1 for $75 > t > 50$. The input signal is shown in Figure 2.

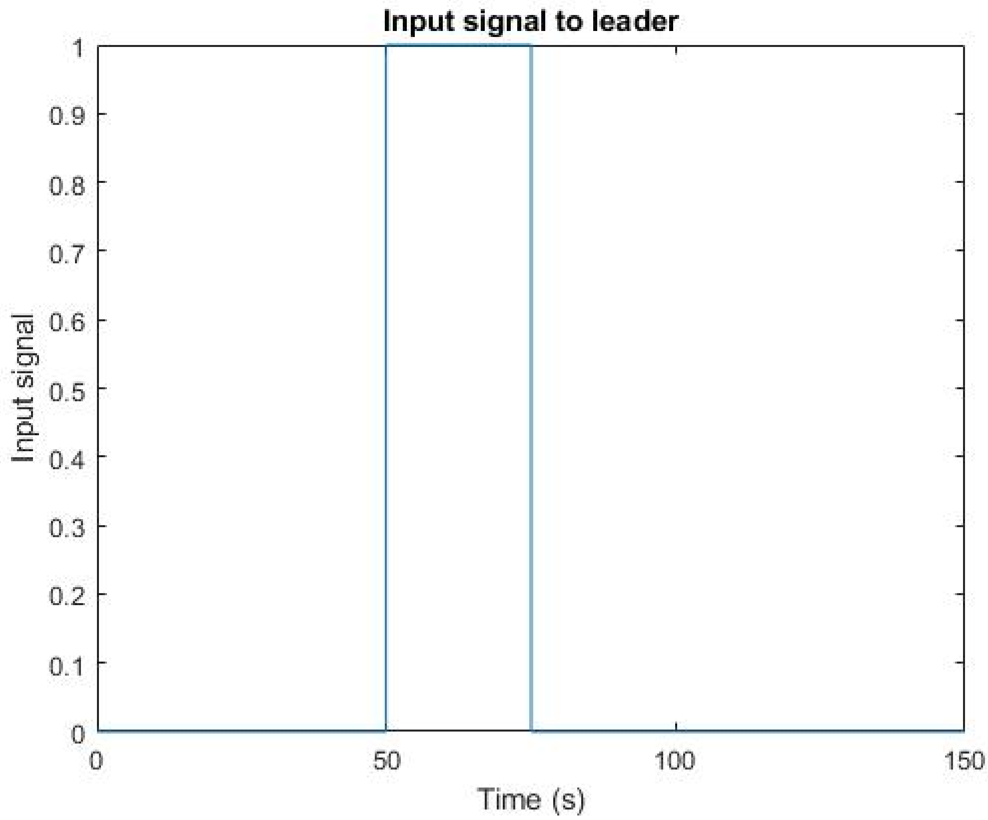

Figure 2: Input signal to leader

The values used for the vehicle parameters r_2, L_2 and τ and the controller coefficients h, k_p, k_d and k_{dd} are shown in Table 1. The same τ is used for both the leader and the follower. The same values are used for k_p, k_d, k_{dd}, τ and h as used in [4]. The value used for L_2 is based on the average car length [5]. The value used for r_2 is based on the average standstill distance for aggressive driving behaviour [6].

Variable	Value
h	0.6
r_2	1.5
L_2	4.5
k_p	0.2
k_d	0.7
k_{dd}	0
τ	0.1

Table 1: Controller and vehicle parameters

The simulation time is set to 150 seconds and the results for the position, velocity and acceleration are shown in Figure 3, Figure 4 and Figure 5.

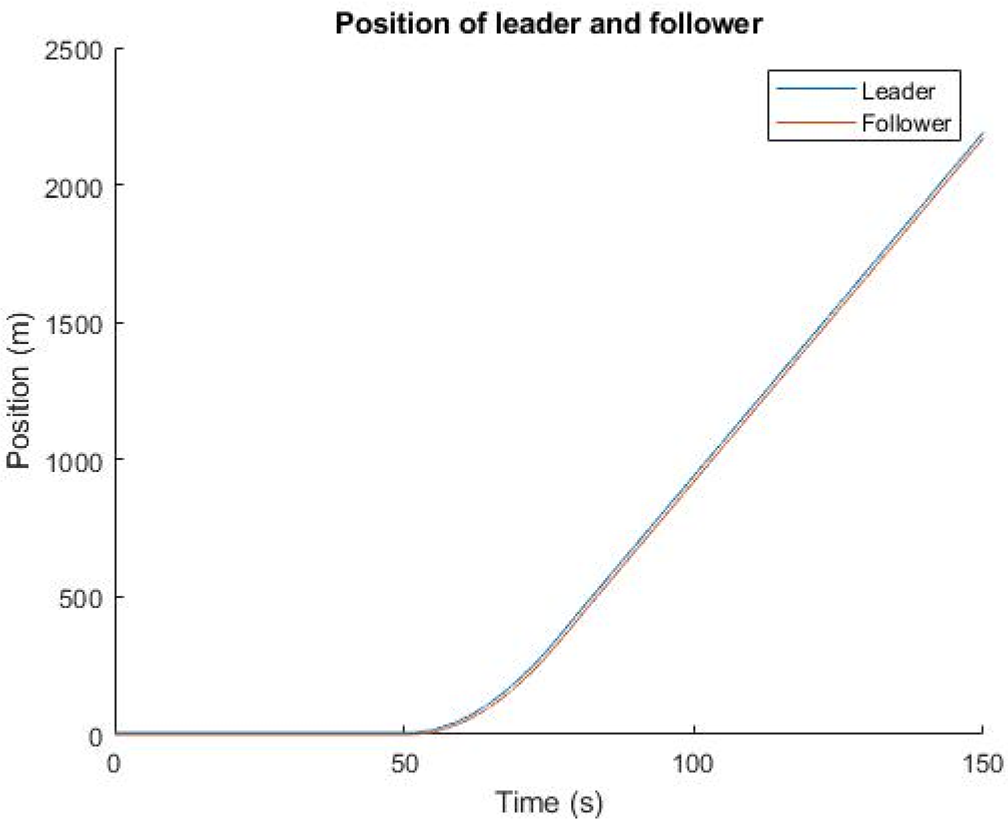

Figure 3: Position of the leader and follower

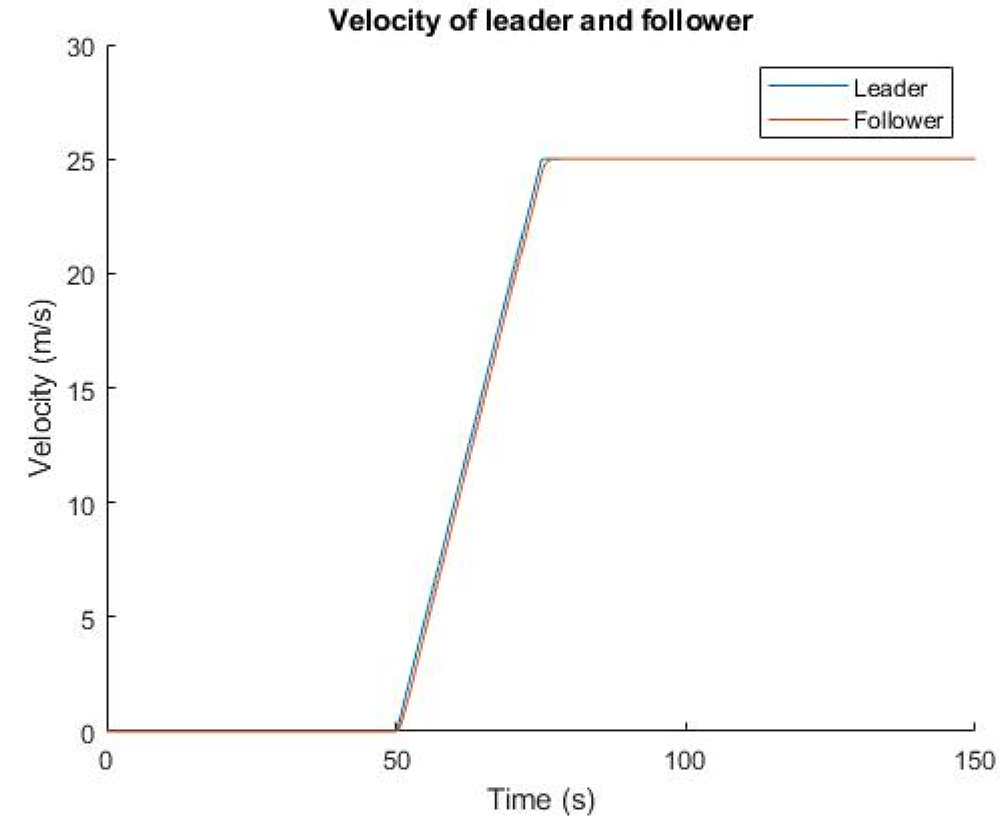

Figure 4: Velocity of the leader and follower

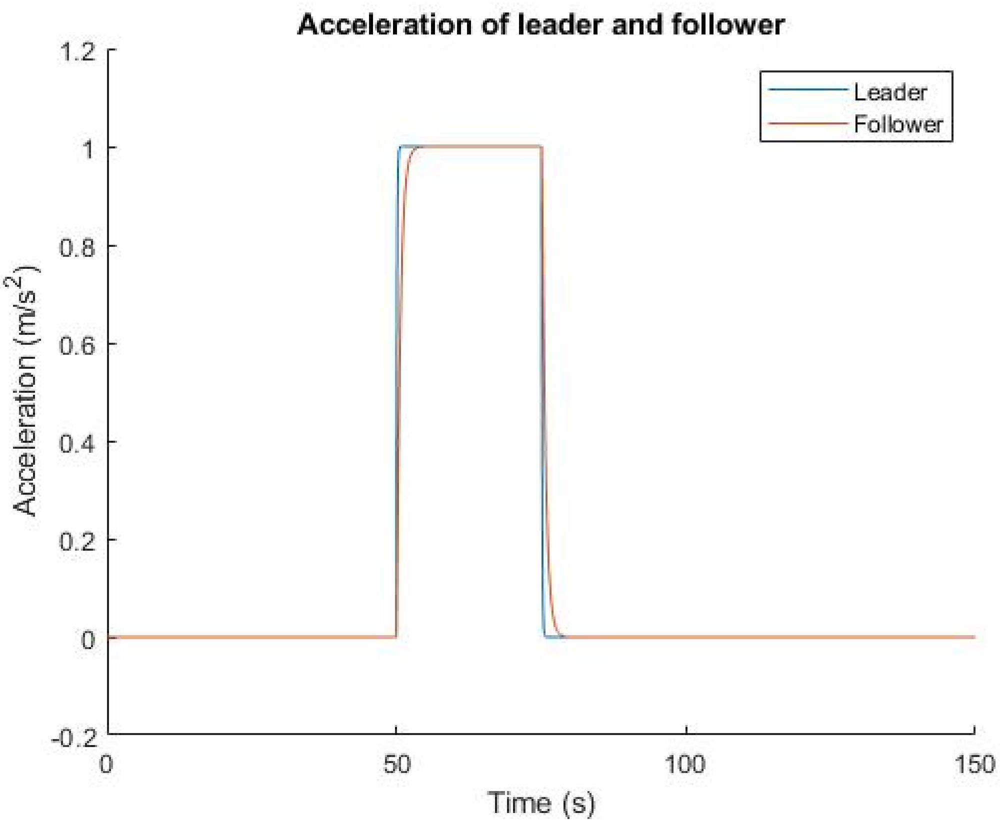

Figure 5: Acceleration of the leader and follower

3 Modelling faulty dynamics

Before residual generators can be designed, first the faulty dynamics need to be modelled. In the CACC system there are a total of 5 possible faults, 4 are in the onboard sensors and 1 in the inter-vehicle communication. The faults in the onboard sensors are in the inter-vehicle distance sensor $q_{i-1} - q_i - L_i$, the velocity sensor v_i, the velocity difference sensor Δv_i and the acceleration sensor a_i. The fault in the inter-vehicle communication will appear in the input signal of the leader u_{i-1}. By inserting these faults into Equation 4, using Equation 5 for $\dot{e}_i$ and considering $k_{dd} = 0$, as defined in Table 1, a new expression for the dynamic controller is found which includes the possible faults, shown in Equation 6.

$$\dot{e}_i = \Delta v_i - h a_i, \quad i \in S_m \backslash \{1\} \tag{5}$$

$$\begin{aligned} \dot{u}_i = &-\frac{1}{h} u_i + \frac{1}{h}(k_p(e_i + f_1 - h f_2) + k_d(\Delta v_i + f_3 - h(a_i + f_4))) \\ &+ \frac{1}{h}(u_{i-1} + f_5), \quad i \in S_m \backslash \{1\} \end{aligned} \tag{6}$$

Here, the faults are denoted by f_1 to f_5. With f_1 being the fault in the distance sensor, f_2 in the velocity sensor, f_3 in the velocity difference sensor, f_4 in the acceleration sensor and f_5 in the inter-vehicle communication.

Before the residual generators can be designed in the frequency domain, a state-space model that captures all faults, sensors and dynamics of the interconnected cars must be derived. First in the time domain, and then transformed to transfer matrices in the frequency domain. This state-space representation is needed in order to derive transfer matrices which are needed to design the residual generators. By using the expressions in Equation 1, Equation 5, Equation 6 and a new expression for $\Delta \dot{v}_i$ in Equation 7, a state-space representation for the faulty dynamics is derived, which is shown in Equation 8.

$$\Delta \dot{v}_i = a_{i-1} - a_i, \quad i \in S_m \backslash \{1\} \tag{7}$$

$$\begin{aligned} \dot{X}_{ei} &= \begin{bmatrix} 0 & 0 & -h & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{\tau} & \frac{1}{\tau} & 0 & 0 \\ \frac{k_p}{h} & 0 & -k_d & -\frac{1}{h} & \frac{k_d}{h} & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{\tau} \end{bmatrix} X_{ei} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{h} \\ 0 \\ \frac{1}{\tau} \end{bmatrix} u_{i-1} + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \frac{k_p}{h} & -k_p & \frac{k_d}{h} & -k_d & \frac{1}{h} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} F_i \\ &=: A X_{ei} + B u_{i-1} + E F_i \\ Y_{ei} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} X_{ei} + \begin{bmatrix} 1 & -h & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} F_i \\ &=: C X_{ei} + D F_i \\ &\textit{with } X_{ei} = \begin{bmatrix} e_i & v_i & a_i & u_i & \Delta v_i & a_{i-1} \end{bmatrix}^T \\ &\quad\; F_i = \begin{bmatrix} f_1 & f_2 & f_3 & f_4 & f_5 \end{bmatrix}^T \end{aligned} \tag{8}$$

Here, X_{ei} are the state variables used by the follower, u_{i-1} is the input signal of the leader and F_i are the faults in the sensors which reside on the follower and inter-vehicle communication. Vector Y_{ei} is the output of this extended system, which are in this case the values obtained by the onboard sensors. The faults in the sensors and communication both have a direct effect on the readings from the senors described by matrix D and an indirect effect on the readings through the changes in the dynamics described by matrix E.

4 Residual generators

4.1 Transfer matrices

From a state-space representation of the faulty dynamics, transfer matrices which describe the faulty dynamics of the CACC system can be derived. First we consider the state-space representation in time-domain shown in Equation 9 with matrices A, B, C, D and E being the same matrices as defined in Equation 8, $x(t)$, $u(t)$, $f(t)$ and $y(t)$ representing the state variables, input signal of the leader, faults and output variables.

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Ef(t) \\ y(t) &= Cx(t) + Df(t) \end{aligned} \tag{9}$$

By taking the Laplace transform [7], which transforms a function from the time domain to the frequency domain, of the first expression in Equation 9, Equation 10 is obtained.

$$sX(s) - x(0) = AX(s) + BU(s) + EF(s) \tag{10}$$

Here, $x(0)$ are the initial conditions and $X(s)$, $U(s)$ and $F(s)$ are the state variables, input signal and faults in frequency domain. By rewriting Equation 10 an expression for $X(s)$ in terms of $x(0)$, $U(s)$ and $F(s)$ is obtained. This expression is shown in Equation 11.

$$X(s) = (sI - A)^{-1}(x(0) + BU(s) + EF(s)) \tag{11}$$

By taking the Laplace transform of the second expression in Equation 9 and substituting Equation 11 for $X(s)$ a expression for $Y(s)$ in terms of $U(s)$ and $F(s)$ is obtained. This expression is shown in Equation 12.

$$\begin{aligned} Y(s) = C((sI - A)^{-1}x(0) + (sI - A)^{-1}BU(s) \\ + (sI - A)^{-1}EF(s)) + DF(s) \end{aligned} \tag{12}$$

This expression is then simplified in Equation 13 to make the expressions less cluttered when designing the residual generators. Also zero initial conditions are assumed, therefore the $x(0)$ term vanishes.

$$\begin{aligned} Y(s) &= G(s)U(s) + K(s)F(s) \\ G(s) &= C(sI - A)^{-1}B \\ K(s) &= C(sI - A)^{-1}E + D \end{aligned} \tag{13}$$

Now that an expression for $Y(s)$ in terms of $U(s)$ and $F(s)$ is attained, the residual generator can be designed.

4.2 Residual generator design

A general design for the residual generator is shown in Equation 14. Here T_1 and T_2 are to be designed so that each component of $R(s)$ corresponds to one fault, thus decoupling the effect of each fault. A individual component in $R(s)$ should be zero if the corresponding fault is zero and non-zero if the fault is also non-zero.

$$R(s) = T_1(s)Y(s) + T_2(s)U(s) \tag{14}$$

To achieve this, first the expression for $Y(s)$ from Equation 13 is substituted into Equation 14 in order to get an expression for $R(s)$ in terms of $U(s)$ and $F(s)$. This expression is shown in Equation 15.

$$R(s) = (T_1(s)G(s) + T_2(s))U(s) + T_1(s)K(s)F(s) \tag{15}$$

In order to make $R(s)$ only dependent on $F(s)$ the term in front of $U(s)$ in Equation 15 needs to disappear, therefore we get an expression for $T_2(s)$ in terms of $T_1(s)$ shown in Equation 16.

$$T_2(s) = -T_1(s)G(s) \tag{16}$$

Now all that is left is finding an expression for $T_1(s)$ such that the effects of the faults are decoupled. The easiest way to achieve this is by taking the inverse of $K(s)$. This results in the results shown in Equation 17.

$$T_1(s) = K^{-1}(s) = \begin{bmatrix} 1 & h & 0 & \frac{1}{s^2+s^3\tau} & 0 \\ 0 & 1 & 0 & -\frac{1}{s+s^2\tau} & 0 \\ 0 & 0 & 0 & \frac{1}{s+s^2\tau} & 0 \\ 0 & 0 & 1 & -\frac{1}{1+s\tau} & 0 \\ -k_p & 0 & hk_d & 1+hs & -k_d \end{bmatrix} \tag{17}$$

In this transfer matrix, there is, however, an improper transfer function, $1 + hs$, in other words the order of numerator is greater than order of denominator and thus has more zeros than poles. When a transfer function has more zeros than poles the transfer function is not causal [8]. To make all transfer functions proper, and keep the decoupling effect, all transfer functions in the transfer matrix are multiplied with $\frac{1}{s}$. This results in the transfer matrix shown in Equation 18.

$$T_1(s) = K^{-1}(s) * \frac{1}{s} = \begin{bmatrix} \frac{1}{s} & \frac{h}{s} & 0 & \frac{1}{s^3+s^4\tau} & 0 \\ 0 & \frac{1}{s} & 0 & -\frac{1}{s^2+s^3\tau} & 0 \\ 0 & 0 & 0 & \frac{1}{s^2+s^3\tau} & \frac{1}{s} \\ 0 & 0 & \frac{1}{s} & -\frac{1}{s+s^2\tau} & 0 \\ -\frac{k_p}{s} & 0 & \frac{hk_d}{s} & h+\frac{1}{s} & -\frac{k_d}{s} \end{bmatrix} \tag{18}$$

Now with transfer matrix $T_1(s)$ defined and using Equation 16, $T_2(s)$ is defined in Equation 19

$$T_2(s) = \begin{bmatrix} -\frac{1}{s^3+s^4\tau} \\ 0 \\ -\frac{1}{s^2+s^3\tau} \\ 0 \\ -\frac{1}{s} \end{bmatrix} \tag{19}$$

With these definitions for $T_1(s)$ and $T_2(s)$, the residual generator $R(s)$ is only dependent on the faults $F(s)$ and not on the input signal $U(s)$. Shown in Equation 20

$$R(s) = T_1(s)K(s)F(s) = M(s)F(s) \tag{20}$$

With $M(s)$ defined in Equation 21

$$M(s) = \begin{bmatrix} \frac{1}{s} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{s} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{s} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{s} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{s} \end{bmatrix} \tag{21}$$

Here, there are only transfer functions on the diagonal, meaning for each fault there is one component in $R(s)$ which corresponds to said fault, i.e, decoupling the effect of each faulty component. Each transfer function on the diagonal is equal to $\frac{1}{s}$. This results in the output of the residual generator being equal to the integrated faults, from which it is possible to obtain the original values of the faults by taking the derivative of the output of the residual generator.

Another residual generator is designed by adding a constant α, with $T_1(s)$ being defined as $T_1(s) = K^{-1}(s) * \frac{1}{s+\alpha}$. Transfer matrices $T_1(s)$ and $T_2(s)$ for this residual generator are shown respectively in Equation 22 and Equation 23.

$$T_1(s) = \begin{bmatrix} \frac{1}{\alpha+s} & \frac{h}{\alpha+s} & 0 & \frac{1}{(\alpha+s)s^2(1+\tau s)} & 0 \\ 0 & \frac{1}{\alpha+s} & 0 & -\frac{1}{\alpha+s)s(1+\tau s)} & 0 \\ 0 & 0 & 0 & \frac{1}{(\alpha+s)s(1+\tau s)} & \frac{1}{\alpha+s} \\ 0 & 0 & \frac{1}{\alpha+s} & -\frac{1}{(\alpha+s)(1+\tau s)} & 0 \\ -\frac{k_p}{\alpha+s} & 0 & \frac{hk_d}{\alpha+s} & \frac{1+hs}{\alpha+s} & -\frac{k_d}{\alpha+s} \end{bmatrix} \tag{22}$$

$$T_2(s) = \begin{bmatrix} -\frac{1}{(\alpha+s)s^2(\alpha+\tau s)} \\ 0 \\ -\frac{1}{(\alpha+s)s(\alpha+\tau s)} \\ 0 \\ -\frac{1}{\alpha+s} \end{bmatrix} \tag{23}$$

Both the original designed Residual generator, with $T_1(s)$ and $T_2(s)$ shown in Equation 18 and Equation 19 and the alternative residual generator with $T_1(s)$ and $T_2(s)$ shown in Equation 22 and Equation 23 will be tested in a simulation setting for various sorts of faults.

5 Experimentation

In order to validate the original residual generator and to compare the original and the the alternative residual generator, both are tested in a Simulink setting shown in Figure 6 for constant, step and sinusoidal faults. In the Simulink model, the blocks for the input signal and the vehicles are the same as used in Figure 1, the block for the controller now also contains the the faults and a block for the fault isolation is added. This new block contains the residual generator, i.e. the transfer matrices $T_1(s)$ and $T_2(s)$ as defined in Equation 18 and Equation 19. Furthermore this block contains a derivative block to differentiate the residuals and confirm whether this yields the original values of the faults using the original residual generator. For the simulations, the same vehicle parameters and controller coefficients are used as defined in Table 1.

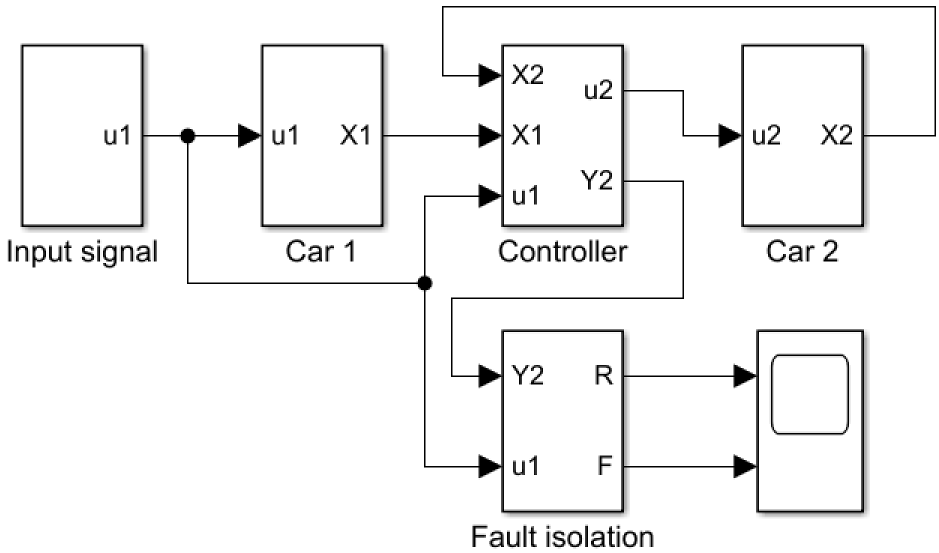

Figure 6: Simulink setup with fault isolation

5.1 Original residual generator

First the original residual generator is tested with a set of constant faults, these range from a value of 1 to 100. This set of faults also includes one fault which is set to 0 in order to confirm the residual also stays equal to 0. This test is done with a simulation time of 150 seconds. The results are shown in Figure 7. The residuals have a slope which ranges from 1 to 100, which is exactly as expected since the relation between the faults and the residuals is $\frac{1}{s}$. Redidual r_5, which corresponds to the fault set to 0, is also equal to 0 during the entire test.

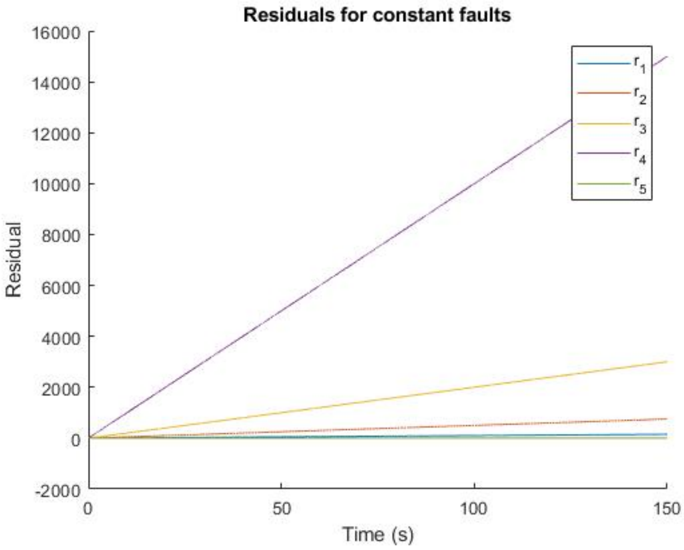

Figure 7: Residuals for constant faults

Then the residual generator is tested using a set of faults which resemble step functions. these faults are equal to 0 until $t = 75$, then 3 faults make a step to values ranging from 1 to 10 and 2 faults remain 0. The simulation time for this test is again 150 seconds. The results are shown in Figure 8. All the residuals remain 0 until the step and then make a slope ranging from 1 to 10. r_1 and r_4, which correspond to the faults which remain 0 throughout the entire test. This is again as expected.

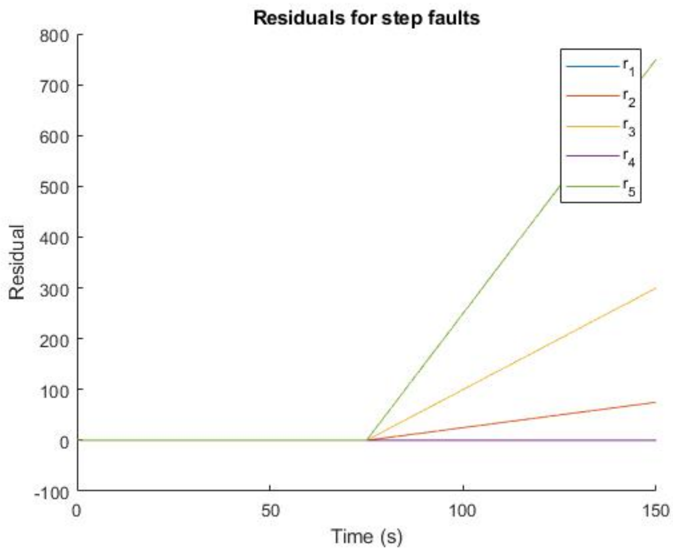

Figure 8: Residuals for step faults

Finally the residual generator is tested using sinusoidal faults with varying amplitudes and frequencies. Here also one fault is set to 0 throughout the entire test. The simulation time for this test is again 150 seconds. The results are shown in Figure 9. Residual r_3, which corresponds to the faults which remains 0, also remains 0 throughout the test. The other residuals are zero in every point the corresponding faults are 0 and non-zero in every point the faults are also non-zero.

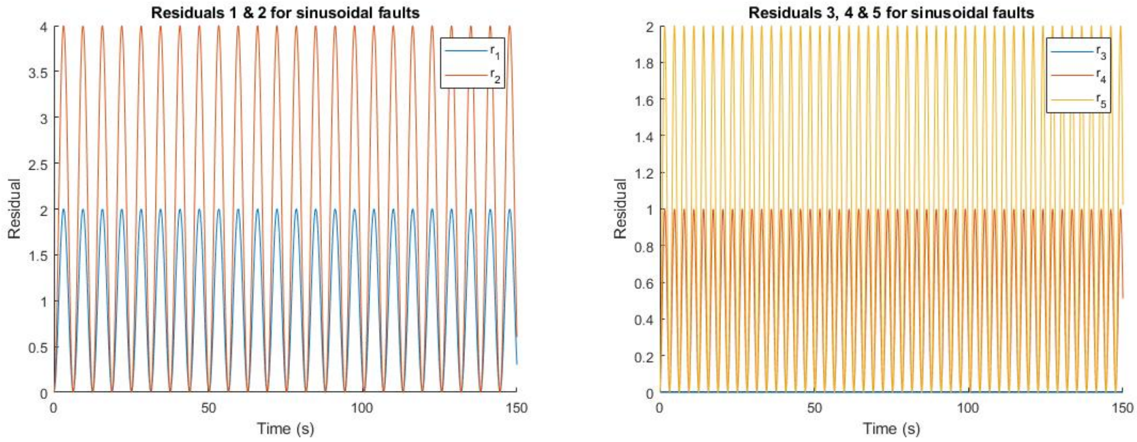

Figure 9: Residuals 1 and 2 (left) and 3, 4 and 5 (right) for sinusoidal faults

The residuals obtained from the tests are derived to confirm the relation of $\frac{1}{s}$ between the faults and the residuals. This derivation is done using the Derivative block in Simulink. The results for the constant faults are shown in Figure 10. The derived residuals for the non-zero faults are 0 for $t = 0$ and equal to the value set for the faults for $t > 0$, this is because the Derivative block in Simulink has an initial output of 0 [9]. The results for the step faults and the sinusoidal faults are shown in Figure 10. The derived residuals exactly match the used faults for the step faults and the sinusoidal faults. Here from can be concluded that the original residual generator can be used for fault isolation and with the original residual generator it is also possible to retrieve the original values of the faults by derivating the residuals.

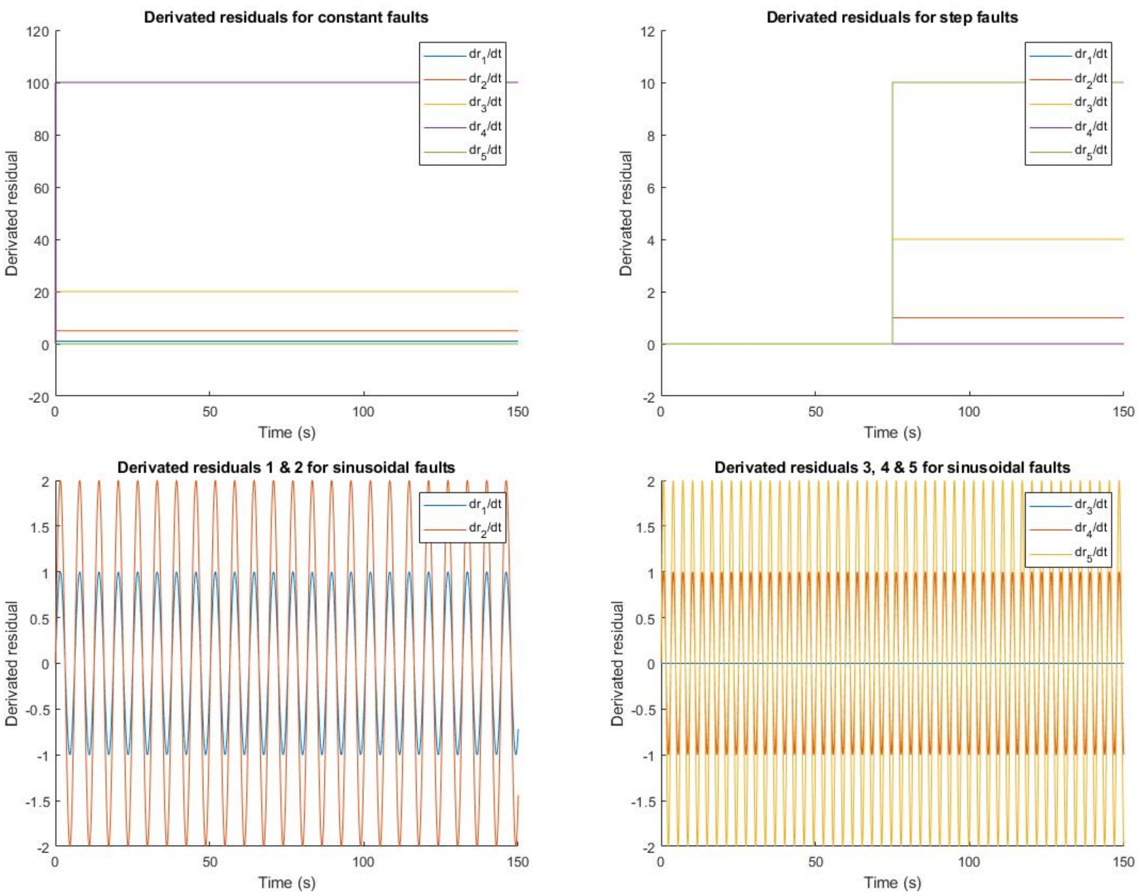

Figure 10: Derivated residuals for constant faults (top left), step faults (top right) and sinusoidal faults (bottom)

5.2 Alternative residual generator

After testing the original residual generator, the alternative residual generator with $T_1(s)$ and $T_2(s)$ shown in Equation 22 and Equation 23 is also tested for for various faults. The simulation setup is exactly the same as for the original residual generator, only using other matrices for $T_1(s)$ and $T_2(s)$. The results for $\alpha = 0.5$ are shown in Figure 11. The residuals are zero when the faults are also zero and non-zero when the faults are also non-zero. The residuals for the constant and step faults approach values which are equal to the values of the faults divided by α. To confirm if these values are indeed dependant on the α which is used, the results for constant faults for $\alpha = 0.1$ and $\alpha = 1.0$ are shown in Figure 12. Also for these values of α the residuals approach the values of the faults divided by α. From this it can be concluded that the alternative residual generator can be used for fault isolation, but it is not as simple to retrieve the faults as with the original residual generator.

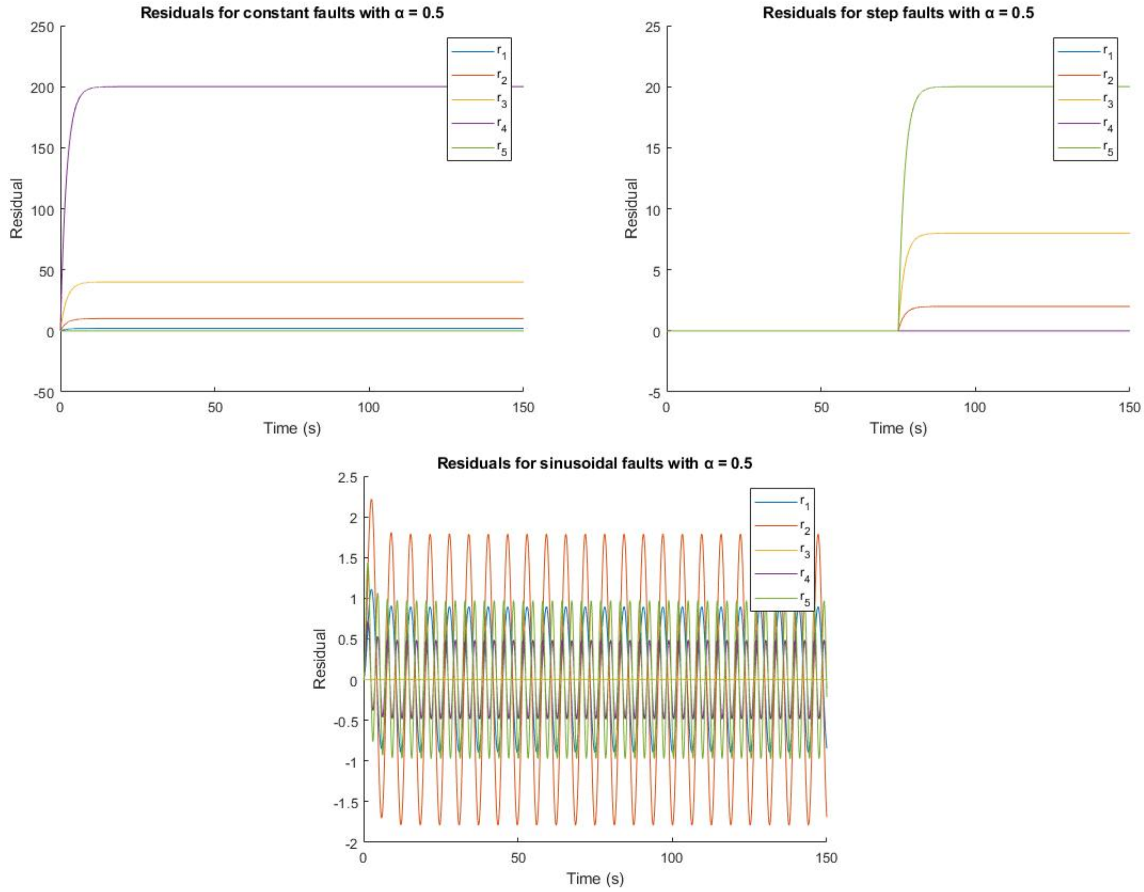

Figure 11: Residuals for constant faults (top left), step faults (top right) and sinusoidal faults (bottom) with $\alpha = 0.5$

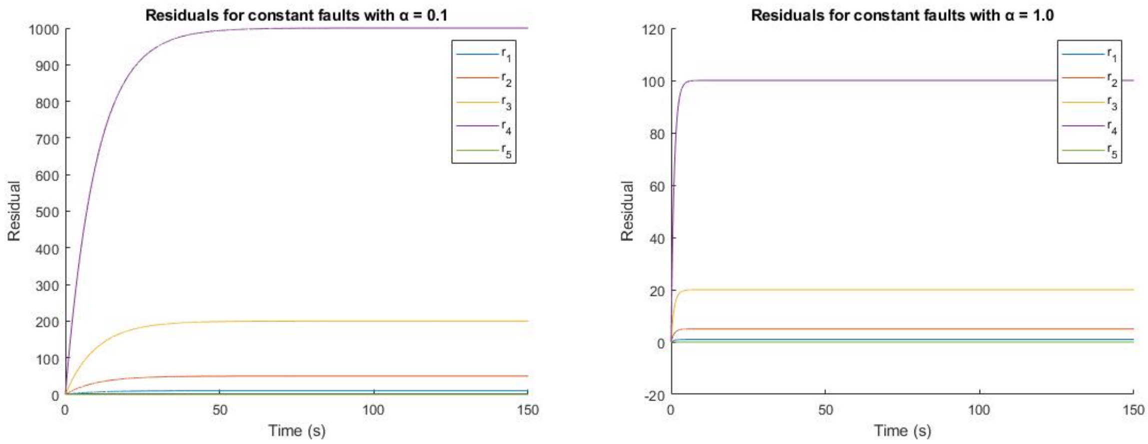

Figure 12: Residuals for constant faults with $\alpha = 0.1$ (left) and $\alpha = 1.0$ (right)

6 Robustness

6.1 Heterogeneous leader dynamics

All the simulations until now assume the drive train dynamics variables τ are known for the leader and the follower. Although in reality the τ of the leader might not always be exactly known by the follower. Therefore, simulations are done in which the τ used for the dynamics of the leader differs from the τ used for the residual generator. This is to see how much this changes the residuals and if the residual generator can still be used for fault isolation if the τ of the leader isn't fully known. The new drive train dynamics variable for the leader is denoted by τ^* and is defined as $\tau^* = \tau + \varepsilon$ with τ being the variable used in the residual generator. The simulation is done for different values of ε to see how the magnitude of change to the drive train dynamics variable effects the value of the residuals. The simulation is also done for different sorts of faults: namely constant faults, step function faults and sinusoidal faults. These are the same as used in previous simulations. Also the same input signal for the leader is used as shown in Figure 2. The results for constant faults are shown in Figure 13. Here the 'error' is defined as the absolute difference between the residuals using τ^* for various values of ε for the dynamics of the leader and the residuals using the original τ for the dynamics of the leader.

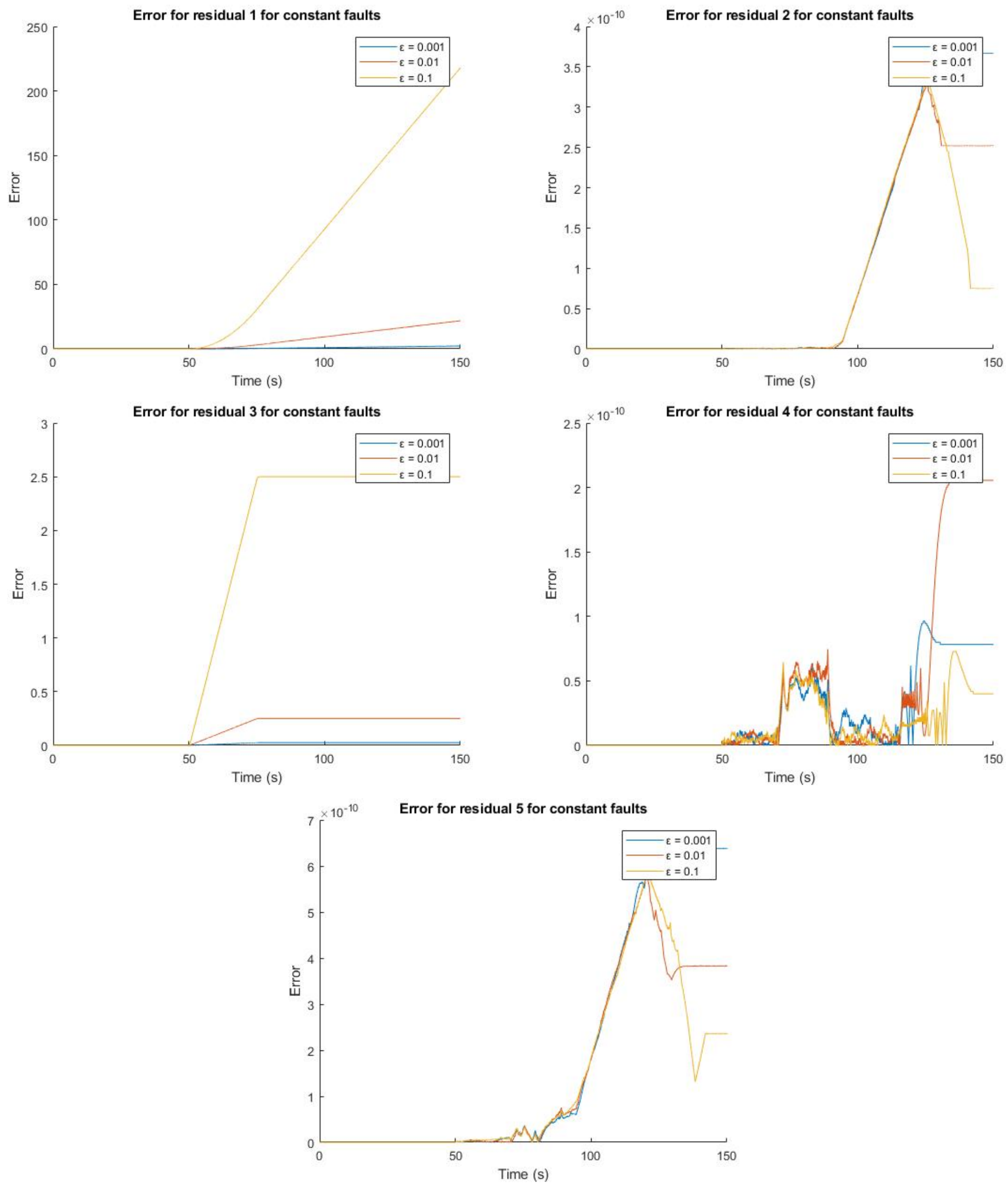

Figure 13: Error for residuals 1 to 5 (top left to bottom) for constant faults

As can be seen the error is practically zero for residuals 2, 4 and 5. The error for residuals 1 and 3 is proportional to the value of ε. For the step and sinusoidal faults the error for residuals 2, 4 and 5 are also practically zero and the error for the residuals 1 and 3 are also non-zero. Even when the faults corresponding to residual 1 and 3 are zero, the error and thus the residuals are non-zero as shown in Figure 14. The error is also exactly the same for the different faults. The errors for the residuals using step and sinusoidal faults are shown in Figure 16 and Figure 17 in the Appendix.

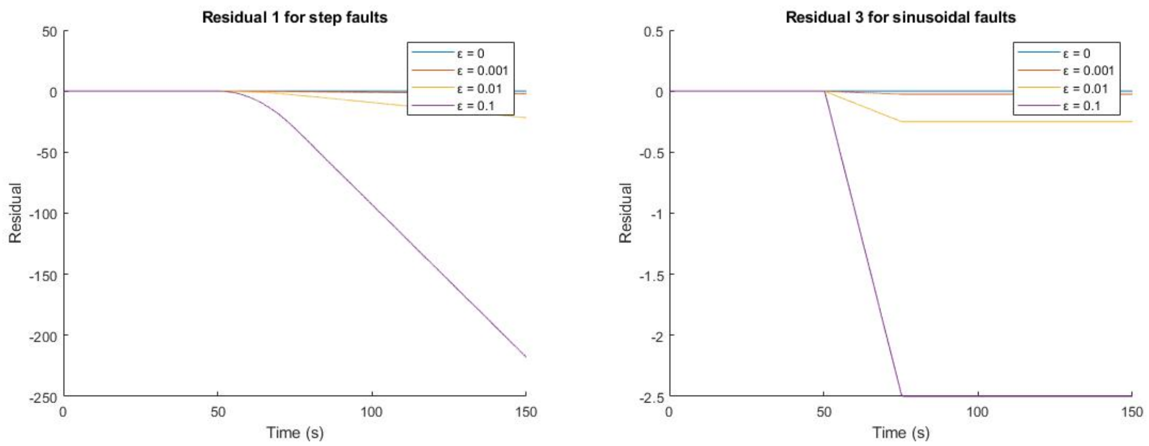

Figure 14: Residuals 1 and 3 for step faults

From this it can be concluded that the residual generator can't be used to detect an isolate all faults accurately if the drive train mechanics of the leader are not fully known by the follower. It can't be used to detect and isolate faults in the inter-vehicle distance sensor and in the velocity difference sensor, however it cant still be used to detect and isolate faults in the velocity sensor, the acceleration sensor and in the inter-vehicle communication.

6.2 Heterogeneous follower dynamics

Apart from having a wrong value for the drive train dynamics of the leader it is also possible that the drive train dynamics variable for the follower itself is not accurate. This can for example be due to a broken component in the vehicle. To test the effect of a different value for τ in the follower the same τ^* is used as before, only now in the follower. The same input signal and faults are used as before. The results for constant faults are shown in Figure 19.

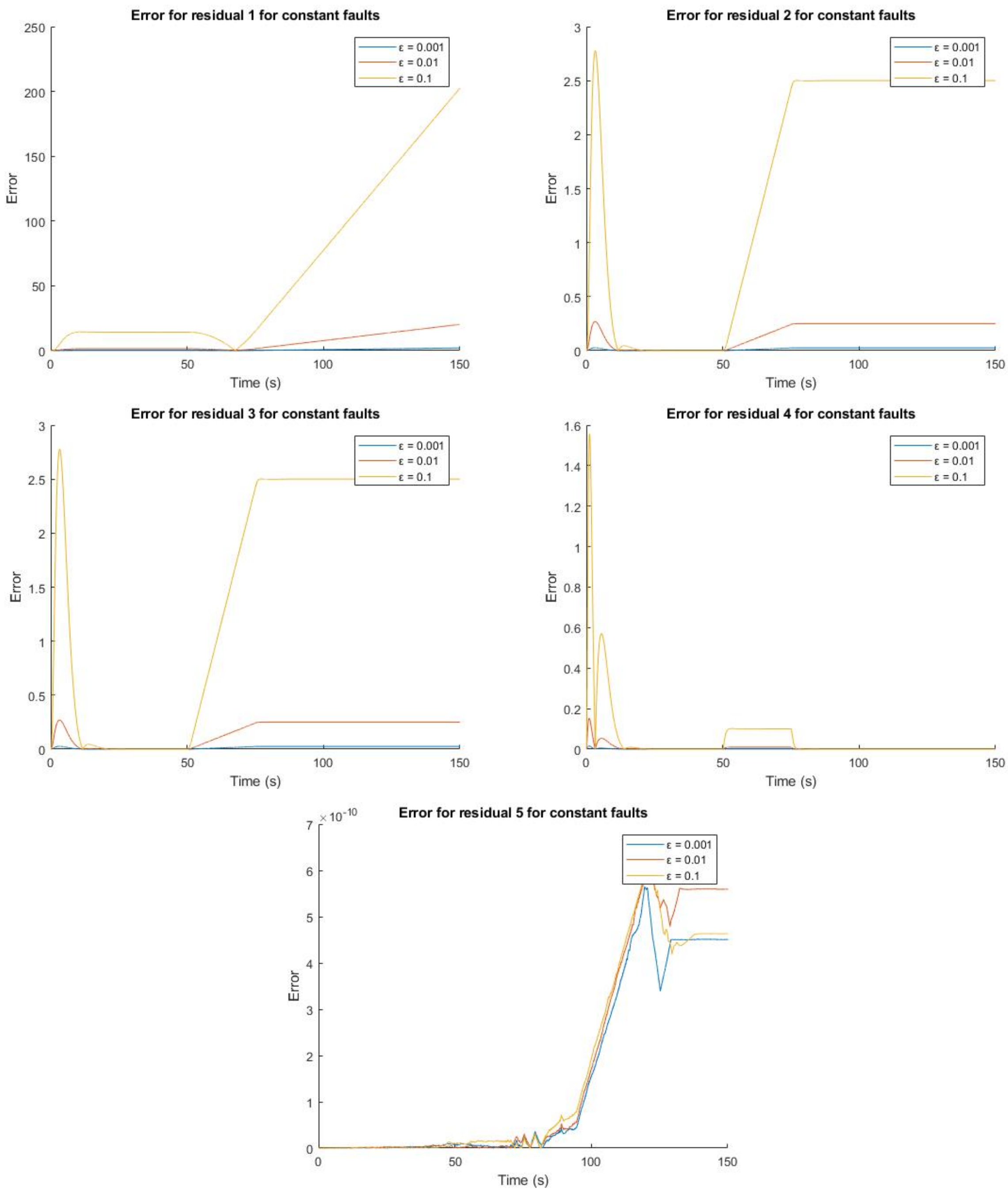

Figure 15: Error for residuals 1 to 5 (top left to bottom) for constant faults

The error is only zero for residual 5 and non-zero for all other residuals, this is the same for step and sinusoidal faults, these are shown in the Appendix. Because of this, the residual generator can only be used to detect and isolate faults consistently in the inter-vehicle communication in the case that the drive train dynamics variable of the follower is not accurately known by the follower.

The chance of not knowing the τ of the leader is much higher than the chance of having an inaccurate value of τ for the follower because this only happens when a component of the vehicle is broken. Because of this the best way to improve the current residual generator and make it more robust is to decrease the influence of the leader's τ on the residuals. One possible way to try and do this is by making the model of the dynamics of the follower independent of the τ of the leader.

7 Conclusions

A residual generator has been designed to detect and isolate faults in a CACC system. This has been done by first taking an already developed CACC model and adding the effect of faults in the onboard sensors and inter-vehicle communication to it. This model has then been converted to a state-space representation in order to obtain a set of transfer matrices which describe the model by taking the Laplace transform. These expressions with the transfer matrices have been rewritten to express the output vector in terms of the input vector and the fault vector. A residual generator has then been designed that uses as input the output vector and the desired acceleration of the leader. With the expression for the output vector, the residual generator has also been rewritten in terms of the input vector and the fault vector. Then the transfer matrices have been designed such that the term in front of the input vector vanishes and the term in front of the fault vector becomes a diagonal matrix. This decouples the effect of each fault and makes each entry of the residual vector corresponds to a single fault. Two different residual generators have been designed that make the matrix in front of the fault vector a diagonal matrix, one with $\frac{1}{s}$ on the diagonal and one with $\frac{1}{s+\alpha}$ on the diagonal with α being a positive number. These have then both been tested for various sorts of faults. Both residual generators work well for fault detection and isolation, i.e, both are zero when the corresponding faults are zero and non-zero when the faults are non-zero. However, for the residual generator with $\frac{1}{s}$ on the diagonal it is easier to obtain the value of the original fault by simply differentiating the residuals, therefore this residual generator has been selected. This residual generator has then been tested with a different drive train dynamics variable τ in the leader and the follower than used in the residual generator to see the effect on the residuals. With another τ in the leader the residual generator, i.e. when the τ of the leader is not known fully known by the follower, faults in the inter-vehicle distance sensor and in the velocity difference sensor cannot be reliably be detected and isolated. When the τ of the follower itself is different only the fault in the inter-vehicle communication can reliably be detected and isolated, all the faults in the onboard sensors can not.

To further improve the residual generator, steps can be taken to make the effect of the τ of the leader on the residuals smaller, such that faults can be better detected and and isolated if the τ of the leader is not of not accurately known by the follower. A possible way to achieve this is by making the model of the dynamics independent of the leader's τ.

References

[1] S. E. Shladover, C. Nowakowski, X. Y. Lu, and R. Ferlis, "Cooperative Adaptive Cruise Control Definitions and Operating Concepts," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2489, no. 1, pp. 145–152, 2015.

[2] G. Naus, R. Vugts, J. Ploeg, R. Van De Molengraft, and M. Steinbuch, "Cooperative adaptive cruise control, design and experiments," in *Proceedings of the 2010 American Control Conference, ACC 2010*, pp. 6145–6150, IEEE Computer Society, 2010.

[3] J. Ploeg, B. T. Scheepers, E. Van Nunen, N. Van De Wouw, and H. Nijmeijer, "Design and experimental evaluation of cooperative adaptive cruise control," *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, pp. 260–265, 2011.

[4] J. Ploeg, *Analysis and design of controllers for cooperative and automated driving.* 2014.

[5] "Study: Average car size is increasing — will roads still be safe for small cars and pedestrians?." `https://www.thezebra.com/resources/driving/average-car-size/#:~:text=According%20to%20Car%20Roar%2C%20the,space%2C%20or%20a%20larger%20engine`.

[6] "Vissim development and calibration report." `https://transportation.ky.gov/Planning/Planning%20Studies%20and%20Reports/Appendix%20B%20-%20VISSIM%20Development%20and%20Calibration%20Report.pdf`, 2014.

[7] "Laplace transform." `https://mathworld.wolfram.com/LaplaceTransform.html`.

[8] "Lecture 3." `https://lewisgroup.uta.edu/ee4314/lectures/Lecture%203.pdf`.

[9] "Derivative." `https://nl.mathworks.com/help/simulink/slref/derivative.html`.

A Appendix A

A.1 Degradation due to heterogeneous leader dynamics

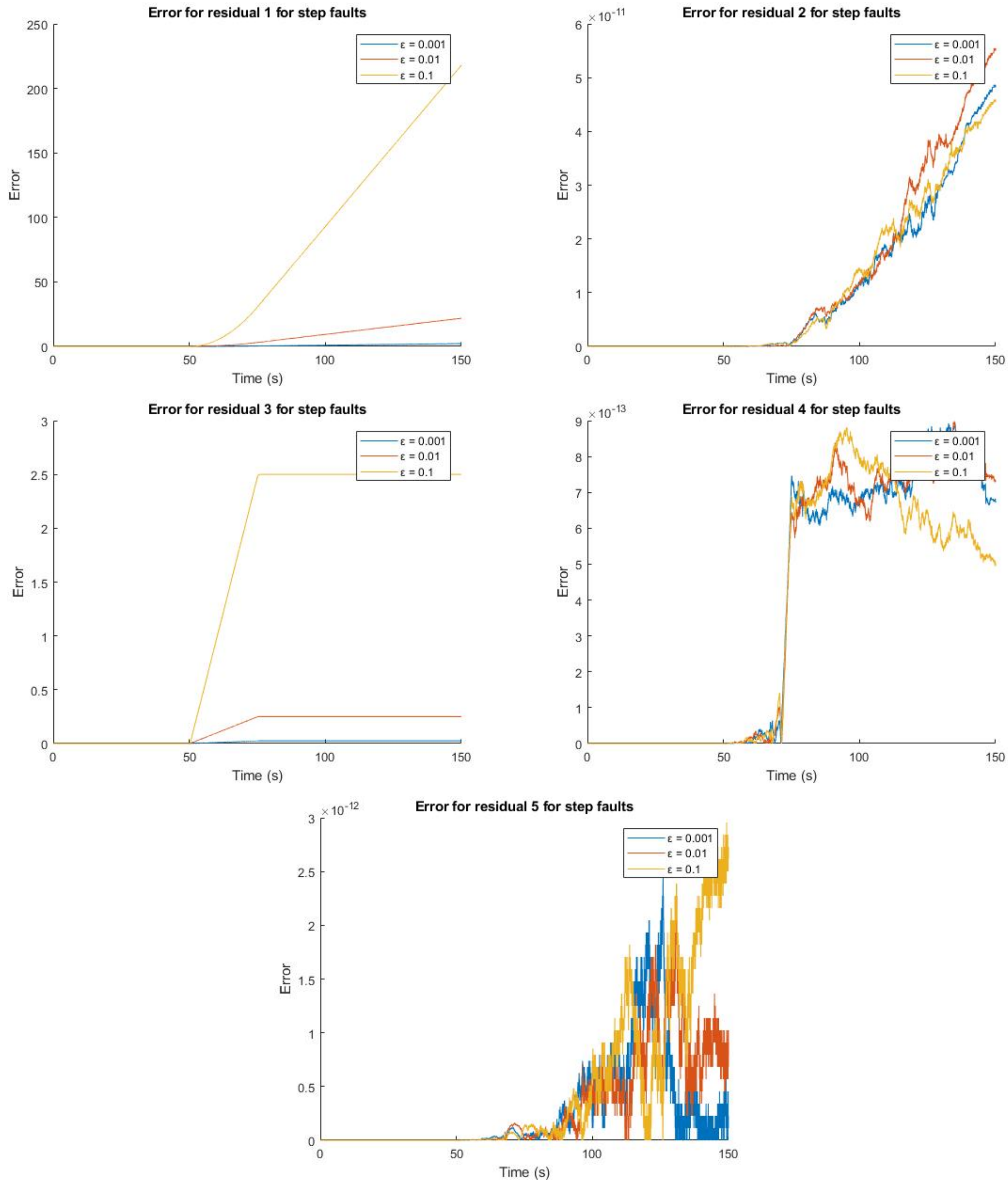

Figure 16: Errors for residuals 1 to 5 (top left to bottom) for step faults

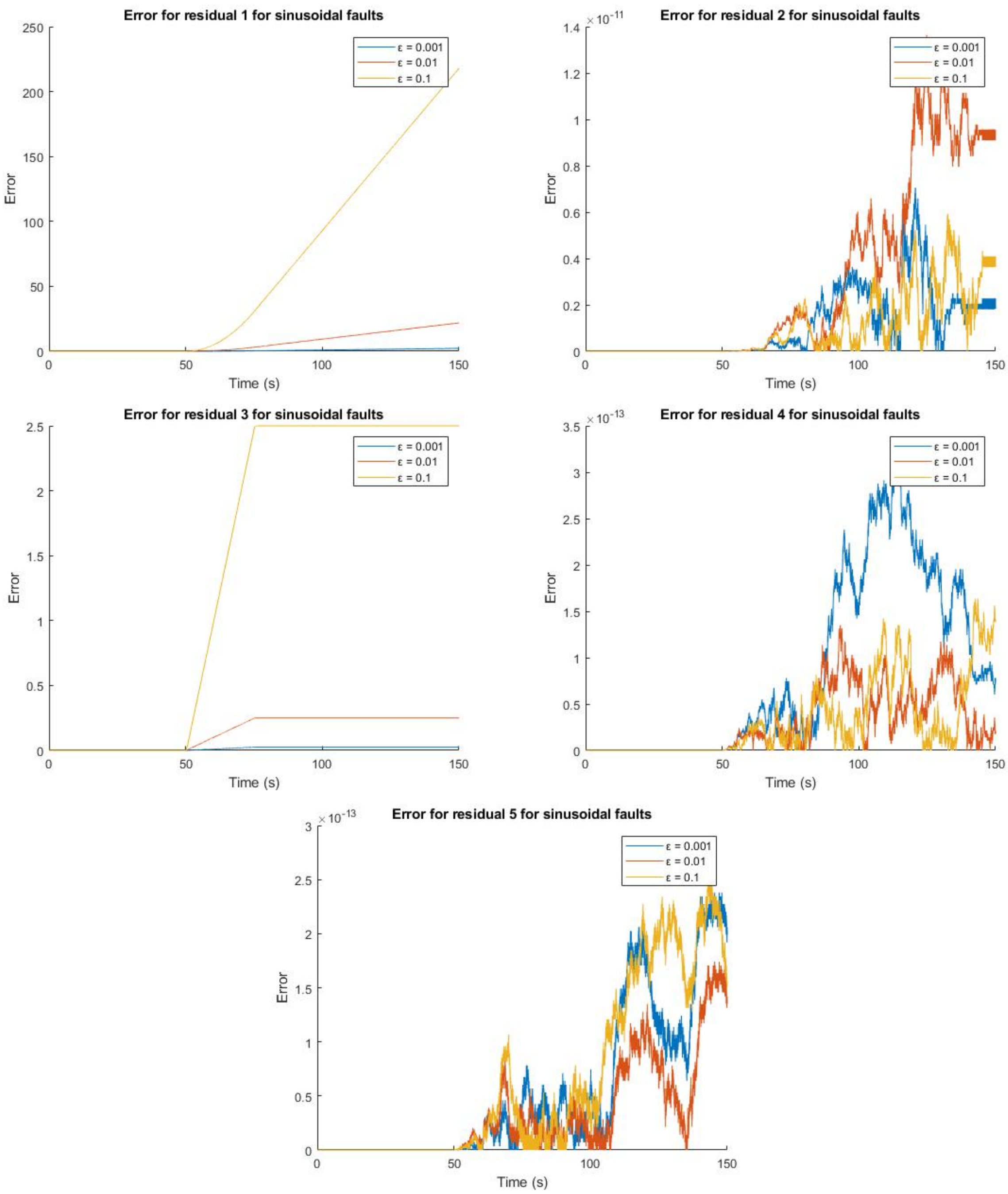

Figure 17: Errors for residuals 1 to 5 (top left to bottom) for sinusoidal faults

A.2 Degradation due to heterogeneous follower dynamics

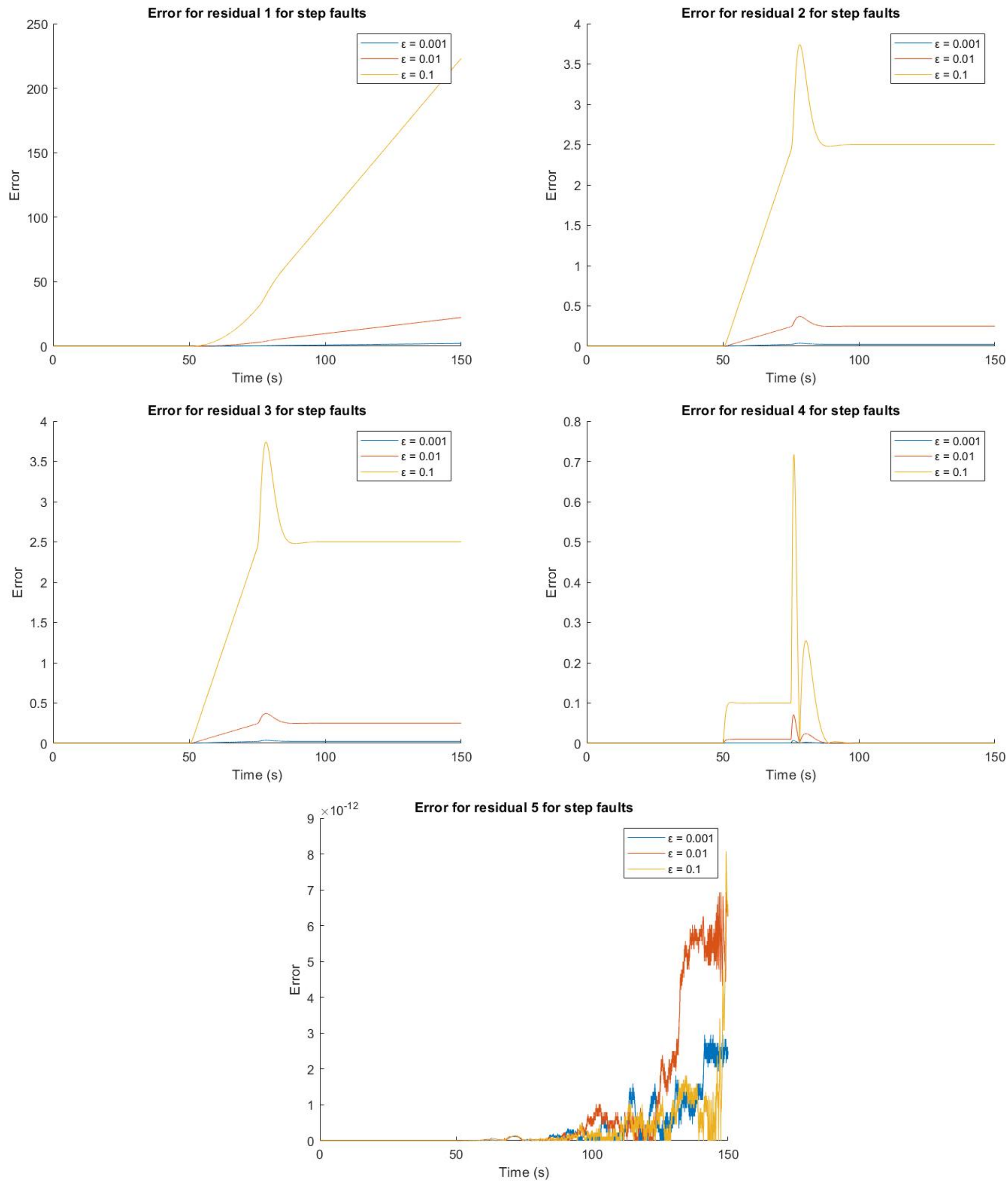

Figure 18: Errors for residuals 1 to 5 (top left to bottom) for step faults

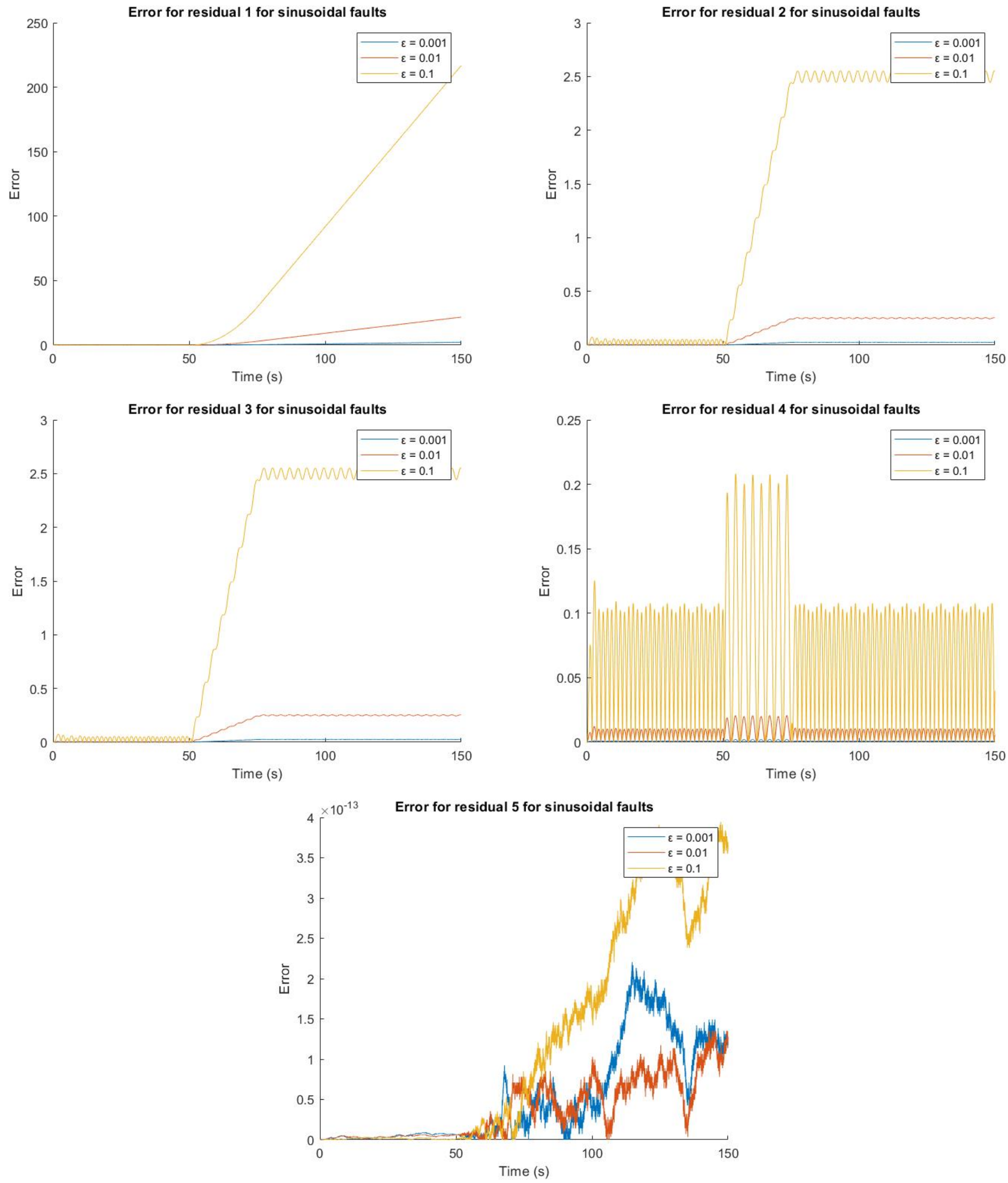

Figure 19: Errors for residuals 1 to 5 (top left to bottom) for sinusoidal faults