Hinfinity/LPV observer for an industrial semi-active suspension
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Abstract—In this paper, an $H_{\infty}/LPV$ observer to be used in an automotive suspension control application is proposed. The system considered is a road disturbance affected quarter car equipped with an industrial SOBEN damper. This observer is designed in the $H_{\infty}$ framework in order to minimize the effect of the unknown road disturbance on the estimated states. The damper studied in this paper is highly nonlinear, therefore an adaptive linear parameter varying (LPV) structure is proposed to improve the robustness of the observer. The observer presented here uses a single position sensor and is easy to implement in a real industrial application because of its simple linear structure. Some simulation results highlight the performances of this observer in realistic noise and uncertainty conditions. The estimated state variables of the quarter car model could be used for example in a state feedback control strategy to improve the comfort and roadholding level of a vehicle.

I. INTRODUCTION

Suspension control based on quarter vehicles has been widely explored in the past few years to improve vertical movements. Active control laws have been developed [5], [7], [6], and semi-active control laws [17], [3], [8], [14]. Active suspensions provide excellent performances but are not realistic in an industrial context because of the excessive cost of the actuators and their huge energy consumption. Semi-active suspensions provide satisfying performances and can be adopted in mass-produced vehicles if the number and the cost of the sensors required by the control strategy is low, which has not always been the case in the past studies. Furthermore, many control strategies assume a full-state measurement [18], [21], or require at least two sensors as in the well-known Skyhook control strategy [17], [14]. Therefore the state estimation problem is very important if we wish to reduce the number of sensors, i.e. reduce the cost and improve the reliability of the system. Unknown input observers have been studied by many authors [11], [10], [13], [12], [20], [19], and also applied to automotive systems affected by road disturbances [9], [22]. In [22], a disturbance decoupled quarter car observer is designed using the vertical accelerations of the sprung and unsprung masses, but these measurements are very noisy and the sensors are very expensive. Therefore this observer is difficult to implement and sensible to measurement noises.

The main contribution of this paper is to build an observer that estimates the state of the vertical quarter car model using a single reliable and cheap deflection sensor. The observer is designed in the $H_{\infty}$ framework in order to minimize the effect of the unknown road disturbance on the estimated states. The real damper considered in the application under study in this paper and described in a previous paper [2] is a SOBEN industrial damper. This system is highly nonlinear, therefore an adaptive linear parameter varying (LPV) structure is proposed to improve the robustness of the observer in front of damping nonlinearities.

This paper is organised as follows: Section II presents the system to be observed, Section III formulates the estimation problem considered in this paper, Section IV deals with the synthesis of the $H_{\infty}/LPV$ observer and Section V gives some simulation results that emphasize the performances of the proposed observer. This paper is finally concluded in Section VI and some possible future works are proposed.

II. VEHICLE MODEL

In this section, the system to be observed is presented. This is a vertical linear quarter car model represented on Figure 1.

![Vertical quarter car vehicle](image)

This simple vehicle model is made up of a sprung mass, a spring, a damper, an unsprung mass and a tire modelled by a spring. The parameters of this model are given in the Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QUARTER CAR PARAMETERS AND VARIABLES</strong></td>
</tr>
<tr>
<td>$m_s$, $m_{us}$</td>
</tr>
<tr>
<td>$k$, $k_t$</td>
</tr>
<tr>
<td>$z_s$, $\ddot{z}_s$</td>
</tr>
<tr>
<td>$z_{us}$, $\ddot{z}_{us}$</td>
</tr>
<tr>
<td>$z_{def} = z_s - z_{us}$</td>
</tr>
<tr>
<td>$F_s$</td>
</tr>
</tbody>
</table>

The equations of this model are given by (1).
\[
\begin{align*}
&\left\{ \begin{array}{l}
m_a \ddot{z}_x = k(z_{us} - z_x) + c \cdot (\dot{z}_x - \dot{z}_s) \\
m_{us} \ddot{z}_{us} = k(z_x - z_{us}) + c \cdot (\dot{z}_x - \dot{z}_{us}) + k_t(z_r - z_{us})
\end{array} \right.
\end{align*}
\]

where \( c \) is a varying parameter that represents the damping rate of the suspension. This parameter depends on the nonlinearities and on the control signal of the damper as well. Therefore considering \( c \) as a varying parameter in the observer allows the estimation to take the control signal and the nonlinearities of the damper into account. The calculation of this parameter in an online application is detailed in Section IV.

This quarter car model will be used in the synthesis of the observer and can be formulated as a LPV system given by

\[
\begin{align*}
&\dot{x} = A(c) \cdot x + D \cdot v \\
y = C \cdot x
\end{align*}
\] (2)

where \( c \) is the variable damping rate, \( v = \dot{z}_r \in \mathbb{R}^d \) is the unknown road disturbance, \( x = (z_{def}, \dot{z}_s, z_{us} - \dot{z}_r, \dot{z}_{us})^T \in \mathbb{R}^n \) are the state variables of the quarter car model, \( y \in \mathbb{R}^m \) is the deflection of the suspension given by a position sensor and \( A \in \mathbb{R}^{n,n}, D \in \mathbb{R}^{n,d} \) and \( C \in \mathbb{R}^{m,n} \) are given by

\[
A(c) = \begin{bmatrix}
  0 & 1 & 0 & -1 \\
  -\frac{k}{m_a} & \frac{c}{m_a} & 0 & \frac{c}{m_a} \\
  m_{us} & -m_{us} & 0 & 1 \\
  \frac{k}{m_{us}} & \frac{c}{m_{us}} & -m_{us} & -m_{us}
\end{bmatrix},
\]

\[
D = \begin{bmatrix}
  0 & 0 & 0 & 0 \\
  0 & 0 & 0 & -1 \\
  0 & 0 & -1 & 0
\end{bmatrix},
\]

\[
C = \begin{bmatrix}
  1 & 0 & 0 & 0
\end{bmatrix}
\]

**Remark:** In (2), no control signal \( u \) is considered, because in a suspension control application, the control signal modifies the damping rate \( c \), which is already considered here as a varying parameter.

### III. PROBLEM STATEMENT

The system to be observed is the quarter car model presented in Section II and given in (2). The full-order observer synthesized in this paper has the general structure given by (3). In a first approach, the varying parameter \( c \) is considered as a constant parameter, and the problem is formulated as a linear time invariant (LTI) problem. The LPV form of the observer is given in paragraph IV-D.

\[
\begin{align*}
&\dot{\tilde{z}} = N \cdot \tilde{z} + L \cdot y \\
&\dot{\tilde{x}} = \tilde{z} - E \cdot y
\end{align*}
\] (3)

Where \( \tilde{z} \in \mathbb{R}^n \) is the state variable of the observer and \( \tilde{x} \in \mathbb{R}^n \) the estimated state variables. \( N \in \mathbb{R}^{n,n}, L \in \mathbb{R}^{n,m}, E \in \mathbb{R}^{m,n} \) are matrices to be designed. Then considering (2) and (3), the estimation error can be expressed as

\[
e = x - \tilde{x} = (I_n + EC) \cdot x - y
\] (4)

and then the dynamics of the estimation error is:

\[
\dot{e} = \dot{x} - \dot{\tilde{x}} = Ax + Dv - Nz - Ly + EC(Ax + Dv)
\] (5)

By using (4), (5) leads to

\[
\dot{e} = Ne + (A - N(I_n + EC) - LC + ECA)x + (D + ECD)v
\] (6)

Let us define \( K = NE + L \) and \( P = I_n + EC \), then (6) turns into

\[
\dot{e} = Ne + (PA - (N + KC))x + PDv
\] (7)

The state \( \tilde{x} \) is an asymptotic estimate of \( x \) for any \( \tilde{x}(0) \) and \( x(0) \) if and only if \( N \) is Hurwitz and

\[
\begin{bmatrix}
N = PA - KC \\
PD = 0
\end{bmatrix}
\] (8)

The design of the observer involves the calculation of \( N \in \mathbb{R}^{n,n}, L \in \mathbb{R}^{n,m}, E \in \mathbb{R}^{m,n} \) satisfying (8). A method to solve this problem is proposed in Section IV.

### IV. OBSERVER DESIGN

In this section, a method is proposed to synthesize a road disturbance decoupled \( \mathcal{H}_\infty / LPV \) full-order observer based on the deflection measurement. The problem formulated in Section III is solved. Some previous works on this topic have been used [12], [13].

#### A. Road disturbance decoupling

The first condition of (8) is equivalent to

\[
\begin{bmatrix}
z \cdot \psi = A \\
\end{bmatrix}
\] (9)

where \( z \in \mathbb{R}^{n+2m} \) and \( \psi \in \mathbb{R}^{n+2m,n} \) are defined by

\[
\begin{bmatrix}
z \\
\psi
\end{bmatrix} = \begin{bmatrix}
N & K \\
I_n & C \\
-CA
\end{bmatrix}
\] (10)

There exist a solution \( z \) of (9) if

\[
rank(\psi) = rank\left( \begin{bmatrix}
\psi \\
A
\end{bmatrix} \right)
\] (11)

Since condition (11) is satisfied, the solution exists and is of the form \( z = \alpha + \gamma \beta \) where

\[
\begin{bmatrix}
\alpha = A \cdot \psi^+ \\
\beta = I_n + 2m - \psi \cdot \psi^+
\end{bmatrix}
\] (12)

\( \gamma \) is any matrix with appropriate dimensions and \( \psi^+ \) is any generalized inverse matrix of \( \psi \). The matrix \( \gamma \) will be determined later. From \( z = \alpha + \gamma \beta \), (4) turns into

\[
\dot{e} = Ne + (I_n + EC)D \cdot v
\] (13)

Let us define \( \tilde{N} \in \mathbb{R}^{(n+2m),n} \) and \( \tilde{E} \in \mathbb{R}^{(n+2m),m} \) such that

\[
\tilde{N} = \begin{bmatrix}
I_n \\
0_{m,n}
\end{bmatrix}, \quad \tilde{E} = \begin{bmatrix}
0_{n,m} \\
I_{m,m}
\end{bmatrix}
\]

Therefore we have

\[
N = z \cdot \tilde{N}, \quad E = z \cdot \tilde{E}
\]
Finally, (13) can be expressed as
\[ \dot{e} = A_0 \cdot e + B_0 \cdot v \tag{14} \]
with \( A_0 = (\alpha + Y \beta) \tilde{N} \) and \( B_0 = (I_n + (\alpha + Y \beta) \tilde{EC}) D \).

The equation (14) that rules the estimation error is affected by the unknown road disturbance \( v \). If \( E \) and \( Y \) can be found such that \( B_0 = 0 \), the disturbance decoupling is perfect. Otherwise the disturbance effect has to be minimized. Therefore the problem is to find \( Y \) such that \( A_0 \) is stable and the effect of \( v \) on \( e \) is minimized.

**Proposition 4.1:** There exist a full-order LTI observer ensuring (17) if there exist \( X = X^T \succ 0 \), \( Y \) and a scalar \( \gamma_\infty \) that solve the LMI (15),
\[
\begin{pmatrix}
Q_1 + Q_1^T & Q_2 \\
* & -\gamma_\infty I_d & I_n \\
* & * & -\gamma_\infty I_n
\end{pmatrix} \prec 0
\tag{15}
\]

Where \( X = X^T \succ 0 \), \( \dot{Y} = XY \) are the decision variables and
\[
\begin{align*}
Q_1 &= (X \alpha + \tilde{Y} \beta) \tilde{N} \\
Q_2 &= (X + (X \alpha + \tilde{Y} \beta) \tilde{EC}) D
\end{align*}
\tag{16}
\]

**Remark:** \( \gamma_\infty \) has to be minimized in order to minimize the road disturbance effect on the estimated variables.

**Proof:** In the application considered here, the effect of the road disturbance on the estimation error has to be eliminated or minimized. Here the gains of the observer are determined by studying the stability and the \( \mathcal{H}_\infty \)-norm bound of the transfer \( e/v \) generating the estimation error. This problem can be solved by minimizing \( \gamma_\infty \) such that
\[
\| e/v \|_\infty < \gamma_\infty
\tag{17}
\]
The Bounded Real Lemma [15] (BRL) applied to the system (14) gives the solution of (17) and leads to the bilinear matrix inequality (BMI) (18) where \( X = X^T \succ 0 \) and \( Y \) are the unknown matrices to be determined. Therefore the full order, stable and disturbance decoupled observer design problem consists in solving (18),
\[
\begin{pmatrix}
Q_1 + Q_1^T & Q_2 \\
* & -\gamma_\infty I_d & I_n \\
* & * & -\gamma_\infty I_n
\end{pmatrix} \prec 0
\tag{18}
\]

In (18), \( Q_1 \) and \( Q_2 \) are given by
\[
\begin{align*}
Q_1 &= X A_0 = (X \alpha + X Y \beta) \tilde{N} \\
Q_2 &= XB_0 = (X + (X \alpha + X Y \beta) \tilde{EC}) D
\end{align*}
\tag{19}
\]
The matrix inequality (18) is a BMI because \( Q_1 \) and \( Q_2 \) are bilinear. Therefore the variable change \( \tilde{Y} = XY \) is introduced to transform the BMI into a solvable LMI where \( Q_1 \) and \( Q_2 \) become
\[
\begin{align*}
Q_1 &= (X \alpha + \tilde{Y} \beta) \tilde{N} \\
Q_2 &= (X + (X \alpha + \tilde{Y} \beta) \tilde{EC}) D
\end{align*}
\tag{20}
\]

Solving (18) with (20) leads to find \( X \) and \( \tilde{Y} \). Thereafter \( Y = X^{-1} \tilde{Y} \) and then \( z = \alpha + Y \beta \) can be deduced using (12). \( N, K \) and \( E \) are given by \( z \) and \( L = K - NE \) can be computed. Finally, the observer proposed is designed so that the first and second conditions of (8) are respected, and the third one is approached by minimizing \( \gamma_\infty \) subject to (17).

### B. Filtering

In this paragraph, a weighting filter has been added to the system to focus the interesting frequency range where the disturbance effect minimization has to be done. The new estimation variable to be considered in this section is the filtered estimation variable \( \tilde{e}_f \). Therefore the problem is now to minimize \( \gamma_\infty \) such that
\[
\| \tilde{e}_f/v \|_\infty < \gamma_\infty
\tag{21}
\]

**Proposition 4.2:** There exist a full-order LTI observer ensuring (21) if there exist \( X_1 = X_1^T \succ 0 \), \( X_2 = X_2^T \succ 0 \), \( Y \) and a scalar \( \gamma_\infty \) that solve (22),
\[
\begin{pmatrix}
A_0^T X_1 + X_1 A_0 & O_n & X_1 B_0 & O_n \\
X_2 B_f & X_2 A_f & O_{n,d} & I_n \\
* & * & -\gamma_\infty I_d & O_{n,d} \\
* & * & * & -\gamma_\infty I_n
\end{pmatrix} \prec 0
\tag{22}
\]

Where \( X = X^T \succ 0 \) is defined such that
\[
X = \begin{pmatrix} X_1 & O_n \\ O_n & X_2 \end{pmatrix}
\tag{23}
\]

\( A_f \in R^{n,n} \) and \( B_f \in R^{n,n} \) determine a given weighting filter.

**Proof:** From (14) the augmented system (24) is built using the state variable \( x_a = (x, e_f)^T \) and the weighting filter: \( \tilde{e}_f = A_f \cdot e_f + B_f \cdot e \).
\[
\begin{align*}
\dot{x}_a &= A_a \cdot x_a + B_a \cdot v \\
e_f &= C_a \cdot x_a + D_a \cdot v
\end{align*}
\tag{24}
\]

Where \( A_a \in R^{2n}, B_a \in R^{2n,d}, C_a \in R^{n,2n} \) and \( D_a \in R^{n,d} \) are given by
\[
A_a = \begin{pmatrix} A_0 & O_n \\ B_f & A_f \end{pmatrix}, B_a = \begin{pmatrix} B_0 \\ O_{n,d} \end{pmatrix}, C_a = \begin{pmatrix} O_n \\ I_n \end{pmatrix}, D_a = O_{n,d}
\tag{25}
\]

The weighting filter can be chosen as \( A_f = -\text{diag}(\frac{1}{T}) \in R^{n,n} \) and \( B_f = -\text{diag}(G) \in R^{n,n} \), for example with \( \tau = \frac{\pi}{2 \times 30} \) and \( G = 2 \). The function \( \text{diag}(x) \) refers to a diagonal matrix with the term \( x \) on the diagonal. This corresponds to a first simple order low-pass filter with a cut-off frequency equal to \( 30Hz \), appropriate in the case of the application considered here.

Then applying the bounded real lemma to system (24) leads to the BMI (26),
\[
\begin{pmatrix}
A_0^T X + X A_0 & XB_a & C_a^T \\
* & -\gamma_\infty I_d & D_a^T \\
* & * & -\gamma_\infty I_n
\end{pmatrix} \prec 0
\tag{26}
\]
Let us define the unknown matrix $X \in \mathbb{R}^{2n,2n}$ such that
\[
X = \begin{pmatrix}
X_1 & O_n \\
O_n & X_2
\end{pmatrix}
\] (27)

Therefore, from (25) and (27), (26) turns into
\[
\begin{pmatrix}
A_0^T X_1 + X_1 A_0 & O_n \\
X_2 B_f & X_2 A_f
\end{pmatrix}
\begin{pmatrix}
X_1 B_0 & O_n \\
O_n & X_2 A_f
\end{pmatrix}
\begin{pmatrix}
* & * \\
* & -\gamma \in I_d & O_{n,d} \\
* & * & -\gamma \in I_n
\end{pmatrix} < 0
\]

(28)

Then using $\dot{Y} = X_1 Y$ as a variable change, (28) can be easily transformed into a solvable LMI where the unknown matrices are $\dot{Y}, X_1 = X_1^T > 0$ and $X_2 = X_2^T > 0$.

C. Pole placement

This method ensures the stability of the observer and the minimization of the disturbance effect, but the poles of the observer may be excessively high and comprise imaginary parts. Such poles may render the observer oscillating and sensible to measurement noises. In order to avoid such a behavior that may lead to implementation problems and bad estimation performances, a pole placement method [4] using LMI regions has been introduced. The poles of the observer can be placed in the intersection of a cone $D_1$, given by the LMI region (29) and a half plane $D_2$, given by (30). The cone is defined with apex at the origin and inner angle $2\theta$ to ensure that the observer is stable and has poles with moderate imaginary parts. The half plane is delimited by a vertical straight line to ensure that the poles have real parts higher than $-p_m$.

\[
D_1 = \{ z \in \mathbb{C} : \frac{\sin \theta(z + \bar{z})}{\cos \theta(z - \bar{z})} < \gamma \in I_d \}
\]

(29)

\[
D_2 = \{ z \in \mathbb{C} : -z - \bar{z} - 2p_m < 0 \}
\]

(30)

**Proposition 4.3:** There exist a full-order LTI observer ensuring (21) with poles in LMI regions $D_1$ and $D_2$ if there exist $X_1 = X_1^T > 0$, $X_2 = X_2^T > 0$, $\dot{Y}$ and a scalar $\gamma$ that solve (31) and (32).

\[
\begin{pmatrix}
M_{11} & M_{12} & M_{13} \\
M_{21} & M_{22} & M_{23}
\end{pmatrix}
\begin{pmatrix}
Q_1 + Q_1^T + 2p_m & O_n & Q_2 \\
X_2 B_f & X_2 A_f & O_{n,d} \gamma \in I_d
\end{pmatrix}
\begin{pmatrix}
O_n & -I_n \\
O_{n,d} & \gamma \in I_n
\end{pmatrix} > 0
\]

(31)

(32)

Where the $M_{ii}$ terms are given by
\[
M_{11} = \begin{pmatrix}
\sin \theta(XX_A - A'_T X) & \cos \theta(XX_A - A'_T X) \\
-\cos \theta(XX_A - A'_T X) & \sin \theta(XX_A + A'_T X)
\end{pmatrix}
\]

\[
M_{12} = \begin{pmatrix}
XX_B & O_{2n,d} \\
O_{2n,d} & XX_B
\end{pmatrix}
\]

\[
M_{13} = \begin{pmatrix}
\sin \theta(ON) & \cos \theta(ON) \\
-\cos \theta(ON) & \sin \theta(ON)
\end{pmatrix}
\]

\[
M_{22} = -\gamma \in I_d \\
M_{23} = O_{2d,2n} \\
M_{33} = -\gamma \in I_d
\]

(33)


and $XA_a$ and $XB_a$ are expressed as
\[
XA_a = \begin{pmatrix}
Q_1 + Q_1^T & O_n \\
X_2 B_f & X_2 A_f
\end{pmatrix}
\begin{pmatrix}
O_n \\
Q_2
\end{pmatrix}
\]

(34)

Where
\[
\begin{pmatrix}
Q_1 & \gamma \in I_d \\
Q_2 & \gamma \in I_n
\end{pmatrix}
\]

(35)

**Proof:** According to the pole placement method proposed in [4] (Theorem 3.3), the regions (29) and (30) have been combined with the disturbance effect minimization constraint (28). Therefore we obtain respectively the two BMI (31) and (32) to be solved at the same time. For more details concerning pole placement in LMI regions intersection, see [4].

The structure of the unknown matrix $X$ has been chosen according to (27), (31) and (32) are deduced from Theorem 3.3 in [4] applied respectively to the LMI regions (29) and (30).

If $XA_a$ and $XB_a$ given by (43) are directly expressed with $Q_1$ and $Q_2$ given by (36), the matrices $M_{1,1}$ and $M_{1,2}$ in (31) and (32) contain some bilinear terms due to $X_1$ and $\dot{Y}$.

\[
\begin{pmatrix}
Q_1 = (X_1 \alpha + \dot{Y} \beta) \tilde{N} \\
Q_2 = (X_1 + (X_1 \alpha + \dot{Y} \beta) \tilde{E} C) D
\end{pmatrix}
\]

(36)

Using $\dot{Y} = X_1 Y$ as a variable change, the bilinear form (36) becomes the linear form (35). Therefore (31) and (32) become solvable LMI where the unknown matrices are $\dot{Y}, X_1 = X_1^T > 0$ and $X_2 = X_2^T > 0$.

Therefore to summerize IV-A, IV-B and IV-C, the method to design the proposed LTI observer can be formulated as follows:

1. Choose the weighting filter $A_f$ and $B_f$ appropriate to the system
2. Choose $D_1$ and $D_2$ according to the desired poles real and imaginary parts bound
3. Solve $LMI$ (31) and (32) to find $X_1$ and $\dot{Y}$
4. Calculate $\dot{Y} = X_1^{-1} \dot{Y}, z = \alpha + \dot{Y} \beta$ using (12)
5. Deduce $N, K, E, L = K - NE$

D. LPV observer

In suspension control application, the damper is controlled. Therefore the damping rate $c$ is varying and depends on the control signal. In the previous paragraphs, the control signal has not been taken into account, and $c$ was a constant. Here, $c$ is considered as a varying parameter so that the control signal and the nonlinearities of the damper are taken into account in the observer dynamics. The observer design method proposed in IV-C will be extended to the LPV case using the LPV form of system (14), given by (37).

\[
\dot{e} = A_0(c) \cdot e + B_0 \cdot v
\]

(37)

The parameter $c$ can be computed on-line with the available measurements. In the application considered here, the
The damping rate provided by the damper can be easily computed using measurements, but this part is confidential due to patented results. Another method to evaluate the varying parameter \( c \) in real-time consists in using an off-line identified damper model presented in a previous work to be published [1]. This model provides realistic damping forces. Then dividing the computed force by the deflection velocity \( \dot{z}_u \) estimated by the proposed observer, the damping rate \( c \) can be calculated. This measured or estimated damping rate \( c \) can be used on-line as a varying parameter to schedule the \( H_\infty/LPV \) observer with filtering and pole placement proposed in this section.

**Proposition 4.4:** There exist a full-order LPV observer ensuring (21) with poles in LMI regions \( D_1 \) and \( D_2 \) if there exist \( X_1 = X_1^T > 0, X_2 = X_2^T > 0, Y_{c_{\text{min}}}, Y_{c_{\text{max}}} \) and a scalar \( \gamma_\infty \) that solve the finite set of LMI (38), (39), (40) and (41).

\[
\begin{align*}
\mathcal{M}_{11}(c_{\text{min}}) &\prec 0 \quad (38) \\
\mathcal{M}_{11}(c_{\text{max}}) &\prec 0 \quad (39) \\
\mathcal{M}_{12} &\prec 0 \quad (40) \\
\mathcal{M}_{13} &\prec 0 \quad (41)
\end{align*}
\]

The terms \( \mathcal{M}_{11,1} \) and \( \mathcal{M}_{12} \) in (38) are given by

\[
\begin{align*}
\mathcal{M}_{11} &= \begin{pmatrix}
\sin \theta(XA_a(c)) + \cos \theta(XA_a(c)) \\
\cos \theta(XA_a(c)) + \sin \theta(XA_a(c))
\end{pmatrix}
\begin{pmatrix}
\sin \theta(XA_a(c)) + \cos \theta(XA_a(c)) \\
\cos \theta(XA_a(c)) + \sin \theta(XA_a(c))
\end{pmatrix}^T \\
\mathcal{M}_{12} &= \begin{pmatrix}
X_B(c) \\
X_B(c)
\end{pmatrix}
\begin{pmatrix}
\mathcal{O}_{n,d} \\
\mathcal{O}_{n,d}
\end{pmatrix}
\end{align*}
\]

Where \( XA_a(c), XB(c), Q_1(c_{\text{min}}), Q_2(c_{\text{min}}), Q_1(c_{\text{max}}) \) and \( Q_2(c_{\text{max}}) \) are expressed as

\[
\begin{align*}
Q_1(c_{\text{min}}) &= (X_1^T \theta + \tilde{Y}_{c_{\text{min}}} \beta) \tilde{N} \\
Q_2(c_{\text{min}}) &= (X_1 + (X_1^T \theta + \tilde{Y}_{c_{\text{min}}} \beta) \tilde{E} \mathcal{C}) D \\
Q_1(c_{\text{max}}) &= (X_1^T \theta + \tilde{Y}_{c_{\text{max}}} \beta) \tilde{N} \\
Q_2(c_{\text{max}}) &= (X_1 + (X_1^T \theta + \tilde{Y}_{c_{\text{max}}} \beta) \tilde{E} \mathcal{C}) D
\end{align*}
\]

The other terms \( \mathcal{M}_{i,i}, i \neq 1,2 \) in (39) are given by

\[
\begin{align*}
\mathcal{M}_{13} &= \begin{pmatrix}
\sin \theta(O_n) I_n^T \\
-\cos \theta(O_n) I_n^T
\end{pmatrix}
\begin{pmatrix}
\cos \theta(O_n) I_n^T \\
-\sin \theta(O_n) I_n^T
\end{pmatrix} \\
\mathcal{M}_{22} &= -\gamma_\infty I_{2d} \\
\mathcal{M}_{23} &= O_{2d,2n} \\
\mathcal{M}_{33} &= -\gamma_\infty I_{2n}
\end{align*}
\]

**Proof:** The Bounded Real Lemma extended to LPV systems, detailed in [15], [16], has been applied to the system (37). This system depends on the varying parameter \( c \in [c_{\text{min}}, c_{\text{max}}] \), therefore an infinite set of LMI is obtained. The polytopic approach detailed in [15], [16] gives a solution to this problem. This method ensures the quadratic stability using a single Lyapunov function through the evaluation of the previous LMI at each corner of the polytope only, thereafter the infinite problem becomes finite. This polytope is defined by the extremal varying parameters \( [c_{\text{min}}, c_{\text{max}}] \).

The LMI set including (38), (39), (40) and (41) is obtained applying Theorem 3.3 in [4] respectively to the LMI regions (29) and (30) for \( c = c_{\text{min}} \) and \( c = c_{\text{max}} \), according to the polytopic approach.

As a single Lyapunov function has to be used, the same matrix \( X \), chosen according to (27), has been used for the four LMI (38), (39), (40) and (41). The same variable change \( \tilde{Y} = X_1 \tilde{Y} \) has been used to eliminate the bilinear terms. Therefore the unknown matrices to be determined are \( X_1, X_2, \tilde{Y}_{c_{\text{min}}} \) and \( \tilde{Y}_{c_{\text{max}}} \), where \( \tilde{Y}_{c_{\text{min}}} \) and \( \tilde{Y}_{c_{\text{max}}} \) respectively give the observer matrices at the polytope corner \( c = c_{\text{min}} \) and \( c = c_{\text{max}} \).

Then the LPV controller is a linear combination of the controllers computed at each corner. Here there is only one parameter \( c \in [c_{\text{min}}, c_{\text{max}}] \), therefore the corners of the polytope are simply given by \( c_{\text{min}} \) and \( c_{\text{max}} \). Let us define \( G_{c_{\text{min}}} \) and \( G_{c_{\text{max}}} \), the observers calculated at each corner of the polytope. Thereafter, the LPV observer is given by (47).

\[
G_{c_{\text{obs}}} = \frac{c_{\text{max}} - c}{c_{\text{max}} - c_{\text{min}}} G_{c_{\text{min}}} + \frac{c - c_{\text{min}}}{c_{\text{max}} - c_{\text{min}}} G_{c_{\text{max}}}
\]

The method to design the LPV observer can be summarized as follows:

1. Choose the appropriate weighting filter \( A_f \) and \( B_f \) appropriate to the system
2. Choose \( D_1 \) and \( D_2 \) according to the desired poles real and imaginary parts bound
3. Solve LMI (38), (39), (40) and (41)
4. Deduce \( X_1, X_2, \tilde{Y}_{c_{\text{min}}} \) and \( \tilde{Y}_{c_{\text{max}}} \)
5. Calculate \( \tilde{Y}_{c_{\text{min}}} = X_1^{-1} \tilde{Y}_{c_{\text{min}}} \), \( \tilde{Y}_{c_{\text{max}}} = X_1^{-1} \tilde{Y}_{c_{\text{max}}} \)
6. Deduce \( z_{c_{\text{min}}} = \alpha + \tilde{Y}_{c_{\text{min}}} \beta \) using (12), \( N_{c_{\text{min}}} \), \( K_{c_{\text{min}}} \), \( E_{c_{\text{min}}} \) and then \( L_{c_{\text{min}}} = K_{c_{\text{min}}} - N_{c_{\text{min}}} E_{c_{\text{min}}} \)
7. Deduce \( z_{c_{\text{max}}} = \alpha + \tilde{Y}_{c_{\text{max}}} \beta \) using (12), \( N_{c_{\text{max}}} \), \( K_{c_{\text{max}}} \), \( E_{c_{\text{max}}} \) and then \( L_{c_{\text{max}}} = K_{c_{\text{max}}} - N_{c_{\text{max}}} E_{c_{\text{max}}} \)
8. Calculate the scheduling rule (47)
V. RESULTS

In this section, numerical results are given and different simulation results are presented to evaluate the observer performances in different conditions.

A. Numerical results

In this paragraph, the numerical values of the calculated LTI observer are given. The chosen filter is described by the diagonal structure proposed in paragraph IV-B where \( \omega_f = 2\pi \cdot 20 \) and \( G_f = \omega_f \). The LMI regions 29 and 30 are respectively determined by \( \theta = \frac{\pi}{2} \) and \( p_{\min} = 200 \). The minimal \( \gamma_\infty \) obtained solving the LMI of the LTI is \( \gamma_\infty = 2.8 \). The poles \( \text{Poles} \) of the observer are given bellow.

\[
\text{Poles} = \begin{pmatrix}
-194 + 183i \\
-194 + 183i \\
0.0001
\end{pmatrix}
\]

\[
N = \begin{pmatrix}
-124.5 & 0 & 0 & 0 \\
-0.0017 & -0.0755 & 0 & 0.0755 \\
0.0414 & -119.0 & 0 & 12.9 \\
-184.0 & 389.4 & -5546.7 & -389.4
\end{pmatrix}
\]

\[
K = \begin{pmatrix}
124.5 \\
-93.6 \\
-0.94 \\
788.5
\end{pmatrix}, \quad E = \begin{pmatrix}
-1.0 \\
9.4 \\
-11.9 \\
309.4
\end{pmatrix}, \quad L = \begin{pmatrix}
0.0002 \\
-116 \\
-3888 \\
51449
\end{pmatrix}
\]

\[
P = \begin{pmatrix}
9.4483 & 1.0000 & 0 & 0 \\
-11.9291 & 0 & 1.0000 & 0 \\
309.4406 & 0 & 0 & 1.0000
\end{pmatrix}
\]

\[
P A - (N + KC) = 10^{-13},
\]

The numerical values of the observers \( C_{\text{obs}}^{\text{min}} \) and \( G_{\text{obs}}^{\text{min}} \), obtained in the LPV case are not given but they have similar structures.

B. Simulation results

Four simulation cases described in Table II have been tested. On each figure, the estimated state variables (\( \hat{z}_s, \hat{z}_{us} - z_r, \hat{z}_{us} \)) are compared to the state variables of a reference quarter car model. In case 1, 2, the reference quarter car is linear (1), whereas in case 3, 4, the linear damper has been replaced by the identified nonlinear model given in [1]. The Mean Square Error (\( \text{MSE}(x) = \frac{1}{n} \sum_{i=1}^{n}(x_i - \hat{x}_i)^2 \)) has been calculated for each state variable and is given in Table III.

<table>
<thead>
<tr>
<th>Case</th>
<th>Observer</th>
<th>Simulation conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LTI</td>
<td>Without noise, uncertainties, nonlinearities</td>
</tr>
<tr>
<td>2</td>
<td>LTI</td>
<td>With noise, without uncertainties, nonlinearities</td>
</tr>
<tr>
<td>3</td>
<td>LTI</td>
<td>With noise, uncertainties, nonlinearities</td>
</tr>
<tr>
<td>4</td>
<td>LPV</td>
<td>With noise, uncertainties, nonlinearities</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS AND FUTURE WORKS

In this paper, a method to synthesize an observer for a suspension control application has been presented. This observer is based on a reliable and cheap sensor providing the damper deflection measurement. The estimation is decoupled from the real deflection measurement. The estimation is decoupled from the real embedded application. Finally some simulations have been run in realistic conditions and emphasize the observer performance when then measurement is affected by a noise, and the model is uncertain. Future works will...
consist in designing the same kind of observer for a full car. Then this observer will be used with a static state feedback controller and implemented by SOBEN on a testing car in the near future. The objective is to design a global attitude control strategy using the four suspensions. A reduced-order observer version of this observer could also be developed.

REFERENCES


