AW Implementation using Multifiltering for Fault Detection

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Abstract: An approach for implementation of control system with anti-windup compensation using fault detection multifiltering is presented. The residual signal used for anti-windup compensation is obtained from a filter bank (i.e. multifiltering) for fault detection, thus it is not necessary its explicit measurement. This residual signal is considered as a fault, in order to design the fault detection filter. The filter bank is synthesized using robust LMI based control techniques. Additional LMI restrictions have been used in the optimization process, to garantice better performance. This method allows to consider multiobjective performance indexes, for different actuator saturation conditions, in the same way as in fault diagnosis problems. A numerical example to probe the proposed implementation method effectiveness is also presented.

Key–Words: Anti-Windup compensation, Fault Detection, Bounded Control, Fault Tolerant Control.

1 Introduction

The necessity of more secure and efficient control systems had generated an wide research to guarantee such conditions. Thus, in control theory, one of the most common challenges in the literature has been ensure stability and performance conditions when there are damages or any limitation in the functionality of the control systems. The formal condition that consider the stability is referred to *Fault Tolerant Control Systems* (FTCS) [5, 8, 2], and the performance condition is related to *Bounded Control* techniques. For bounded control the *Anti-Windup* strategies (AW) can be applied, which try to compensate the negative effects produced by actuator saturating or by the controller switching in different operation points for some controllers.

As consequence of the presence of actuator physical limitations and of changes in the control system operation points, given for production rules, it is common to find in the practice, an inconsistence between the process control input and the controller output. The inconsistence between these signals has as result that the controller states are forced to their upgrade, which produces undesired effects like large overshoot, adding even more actuators saturation, in some extreme cases producing an unstable closed loop. This effect is called *windup*, and its solution have been studied since many decades ago. The windup problem can be handled by means of compensation where, in a first stage, the control system is designed without taking into account the restrictions, and in a second stage, some compensation scheme is found, with the purpose of minimizing the limitations and commutations effect [6].

For practical implementation, the AW compensation requires one *residual signal* obtained as the difference between the controller output and the actuator nonlinear output. Measuring of such a residual constitutes an additional problem, from the point of view of the installation of the selected compensation scheme, because it is not always possible to obtain. This generates some limitation for the implementation of the AW compensation. It becomes fundamental to obtain a measure of the residual, which in many cases is difficult to achieve and that demands the use of actuator models, by example. The use of models has the additional drawback of not generating the appropriate residuals for changes in the operation of actuators, this is, it does not correct the saturation levels changes that can appear. Thus, some approaches have been proposed in order to implementer AW compensation in industrial processes [10, 11].

On the other hand, FTC systems are formed by *Fault Detection and Isolation* (FDI) elements, which determinate when and where a fault is done, taking as basis the information contained in residual signals [4]. The way as those residuals are generated vary according to the method for FDI filter design. Generally, if detectability and separability conditions are fulfilled, we design a single FDI filter for diagnosis, whereby some restrictive and conservative results may be obtained. Another approach is to use multiple filtering, in this case a filter bank is builded, which allows to generate residuals for any particular failure [7].

In this contribution, a detection filter bank for (*multifiltering*) is designed to the practical implementation of AW compensation techniques, where each one filter is designed satisfying performance indexes characterized as LMIs. This method is based on FTC.

As is known, a FTC systems main component is the decision mechanism, who takes the residual contained information and decides if there is a failure presence or not. FTC systems are classified as *passive*, which use some techniques as robust control in a closed loop single design, making the control system resistant to a relative small fault group (in some cases taken as perturbations); on the other side are the *active* FTC systems, which can make changes on some loop elements, generally the controller is changed, in different ways, since a new controller parameters to a different controller structure. The FTC philosophy is used in order to implanter AW compensation schemes.

Such as has been said, the AW approaches are mainly treated in a two step methodology: 1) To design a controller assuming there is not any condition different to normal, 2) To design some compensation (dynamic or static) which keeps the operation conditions under some situation, as windup problems for instance, or overshoots because of controller operation states changes [6]. In this work, this two step approach is used. The research and information about control problems under actuators restrictions is wide. In particular, we study the approach for AW compensation gain synthesis given in [3], which is based on LMIs.

In the whole cases, the signal used to implement the AW compensation must be measured directly from the process, generally as the difference between the controller output signal (which is almost always known beforehand) and the given one by the actuators to the plant.

As is known, in some cases this signal measurement possibility neither is done, nor would be economically viable add more instrumentation to the process. Some methodologies to do such implementation consist of using actuator models, [1], which should reproduce the actuators performance, the main problem with this approach as in any model based one, is that a limited model capacity is achieved; in time, by unavoidable actuators changes produced by its own working, or in reliability, by an low precision model.

The proposed solution consist of obtaining this signal by mean of a estimation using FDI filters, in such a way that the residual signal produced by them is used to do the AW compensation, just as has been proposed in [9]. Figure 1 presents this implementation methodology proposed. The main advantage of filter

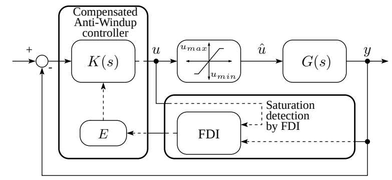


Figure 1: AW compensated system using FDI.

bank use is, conservative results present in a single design, are reduced in part, given that for every filter designed, i.e., for each failure or actuator saturation, is possible to use different conditions. Moreover, it lets us to consider many performance objectives according to saturation conditions. It enlarges the compensation synthesis design possibilities.

This document is organized as follows. In the Section 2 resumes briefly an approach for design AW compensation technique based on LMI, which has been presented in [3]. As this method is based on LMIs, we use the results in order to propose the implementation of AW compensation by estimation of the residual signal based on LMI too, which allows to consider multiobjective criteria. In the Section 3 the SDI (Saturation Detection and Isolation) proposal is presented, as well as the main result for its obtention. In the Section 4 shows a numerical example as an application to the proposed AW implementation alternative. Used notation is standard, in any different case it will be noted there.

2 AW compensation design

In this section a short review of the AW compensator design technique is presented. Let us assume we have the system

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t), \end{aligned} \tag{1}$$

and a dynamic output feedback controller

$$\begin{aligned} \dot{x}_k(t) &= A_k x_k(t) + B_k y(t) \\ u_k(t) &= C_k x_k(t) + D_k y(t) \end{aligned} \tag{2}$$

is done. Let us assume now the control signal is under saturation, i.e., [1],

$$-u_{0(i)} \leq u_{(i)} \leq u_{0(i)}, \quad u_{0(i)} > 0,\ i = 1, \ldots, m, \tag{3}$$

now, the control signal reads

$$u(t) = \mathrm{sat}(u_k(t)) = \mathrm{sat}\big(C_k x_k(t) + D_k y(t)\big). \tag{4}$$

[1]The notation $A_{(i)}$ means the i-th A row.

To reduce the negative effects produced by saturation, we introduce a compensation by additional feedback

$$e_k(t) = E_k\big[\mathrm{sat}(u_k(t)) - u_k(t)\big],$$

then the closed loop system can be written as

$$\dot{\xi}(t) = \mathcal{A}\xi(t) - (\mathcal{B} - \mathcal{R}E_k)\psi\big(\mathcal{K}\xi(t)\big). \qquad (5)$$

where, $\xi(t) = [x(t)^T \; x_k(t)^T]^T \in \Re^{n+n_k}$ is an extended state vector and the matrices

$$\mathcal{A} = \begin{bmatrix} A + BD_kC & BC_k \\ B_kC & A_k \end{bmatrix}, \quad \mathcal{B} = \begin{bmatrix} B \\ 0 \end{bmatrix},$$

$$\mathcal{R} = \begin{bmatrix} 0 \\ I_{n_k} \end{bmatrix}, \qquad \mathcal{K} = \begin{bmatrix} D_kC & C_k \end{bmatrix}.$$

With all this considerations in mind, the next result is given.

Proposition 2.1 *If there exist a symmetric positive definite matrix $W \in \Re^{(n+n_c)}$, and a matrix $Y \in \Re^{m\times(n+n_c)}$, and a matrix $Z \in \Re^{n_c\times m}$, a diagonal positive definite matrix $S > 0 \in \Re^m$ satisfying*

$$\begin{bmatrix} W\mathcal{A}^T + \mathcal{A}W & \mathcal{B}S + \mathcal{R}Z - Y^T \\ S\mathcal{B}^T + Z^T\mathcal{R}^T - Y & -2S \end{bmatrix} < 0; \qquad (6)$$

$$\begin{bmatrix} W & W\mathcal{K}_{(i)}^T - Y_{(i)}^T \\ \mathcal{K}_{(i)}W - Y_{(i)} & u_{0(i)}^2 \end{bmatrix} \geq 0, \quad i = i, \ldots, m \qquad (7)$$

then the gain matrix $E_k = ZS^{-1}$, is such that the ellipsoid $\mathcal{E}(P) = \big\{\xi \in \Re^{n+n_c} : \xi^T P\xi \leq 1\big\}$, with $W = P^{-1}$, is an asymptotic stability region for system (5).

Proof
See [3]. ■

In this method changes in the saturation limits of the actuators are not considered, and for implementation the residual signal is necessary in order to guarantee the compensation performance.

3 SDI filters design

According to which we said the last section, the necessary signal for AW implementation (generally given by the difference between the output controller and the final actuator applied signal) must be constructed, to get this aim, we use a FDI system. The diagnostic model

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B_1w(t) + B_2u(t) + \sum_{i=1}^{M} L_i\nu_i(t) \\ z(t) &= C_1x(t) \\ y(t) &= C_2x(t), \end{aligned} \qquad (8)$$

is the classic form to represent system faults, where $x \in \Re^n$ are the states, $w \in \Re^q$ the exogen perturbation signals, $u \in \Re^m$ the control signals, $z \in \Re^p$ the controlled outputs and $y \in \Re^s$ the measured signals. $\nu_i \in \Re^f$ signals represent fault modes, unknown signals. A, B_1, B_2, C_1, C_2 and L_i matrices are constant, known and have right dimensions. Assuming in this case, that the faults are given by saturating actuators, (9) can be rewritten as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B_1w(t) + B_2\,\mathrm{sat}(u(t)) \\ &= Ax(t) + B_1w(t) + B_2u(t) + B_2\psi(u(t)) \\ z(t) &= C_1x(t) \\ y(t) &= C_2x(t), \end{aligned} \qquad (9)$$

with the function $\psi(\cdot)$ defined as

$$\psi(x) := \mathrm{sat}(x(t)) - x(t). \qquad (10)$$

Then, we define a state estimator given by

$$\begin{aligned} \dot{\hat{x}}(t) &= A\hat{x}(t) + B_2u(t) + \mathcal{D}\big(y(t) - C_2\hat{x}(t)\big) \\ \hat{z}(t) &= C_1\hat{x}(t), \end{aligned} \qquad (11)$$

where, $\hat{x}(t)$ y $\hat{z}(t)$ represent the estimated controlled outputs, the both with appropriate dimensions and $\mathcal{D}$ is the estimator gain which must be designed. The SDI name is an analogy with FDI filters, as a particular case where the faults detected are saturations. Defining an estimation error as

$$e(t) = x(t) - \hat{x}(t), \qquad (12)$$

thus, the estimator dynamic is given by

$$\begin{aligned} \dot{e}(t) &= \dot{x}(t) - \dot{\hat{x}}(t) \\ &= \big(A - \mathcal{D}C_2\big)e(t) + B_1w(t) + B_2\psi(u(t)). \end{aligned} \qquad (13)$$

Additionally, the output prediction error reads

$$e_z(t) = C_1x - C_1\hat{x}(t) = C_1e(t). \qquad (14)$$

From the last equation, the requirements which must be sufficed in the estimator gain $\mathcal{D}$ design are evident. In every state estimation process, we wish the states be the same as the real ones, this is, the estimation error must be null in a finite time, for it, making $\psi(t) = 0$

1. $\big(A - \mathcal{D}C_2\big)$ must be asymptotically stable.
2. The effect due to $w(t)$ over $e_z(t)$ must be minimized , assigning some norm $(2, \infty)$.

In this case the estimation error never will be null, because always there will be some perturbations influence. This fact implies the bound existence, within which we consider that there is a situation normal or may exist a fault presence.

Provided that, in a i-input system, we have the same actuators number, the separation problem in this case consist of determining which actuator is saturated. It is worth noting that the saturation problem may appear in many actuators at the same time, and even so the residual signal must be separated.

3.1 The separation problem: Multifiltering

The main problem now, is that the whole fault information presence (saturation in this case) is contained in the error signal, but in this instance it is not possible to identify in which actuator the problem is. The solution presented here, is to design different gains associated to different faults, obtaining by this way a filter bank for residual generation.

Using this framework the filter bank is given by

$$\begin{aligned} \dot{\hat{x}}_i(t) &= A\hat{x}_i(t) + B_2 u(t) + \mathcal{D}_i\big(y(t) - C_2\hat{x}_i(t)\big) \\ \hat{z}_i(t) &= C_1\hat{x}_i(t), \qquad\qquad i = 1, \ldots, m, \end{aligned} \tag{15}$$

where every $\hat{z}_i(t)$ constitutes an estimated controlled output, each one obtained by means of a $\mathcal{D}_i$ gain. Every filter is designed in such a way that attenuates external perturbations and detects only one fault in a particular actuator. Now, the prediction errors for the filter bank are

$$\begin{aligned} \dot{e}_i(t) &= \mathcal{A}e_i(t) + \mathcal{B}_i\tilde{w}(t) + B_{2i}\psi_i(t) \\ e_{zi}(t) &= C_1 e_i, \qquad\qquad i = 1, \ldots, m, \end{aligned} \tag{16}$$

with

$$\begin{aligned} \mathcal{B}_i &= \begin{bmatrix} B_1 & B_{20} \end{bmatrix} \\ \mathcal{A} &= A - \mathcal{D}_i C_2. \end{aligned} \quad \text{y} \quad \tilde{w}(t) = \begin{bmatrix} w(t) \\ \psi_0(t) \end{bmatrix}. \tag{17}$$

B_{2i} and $\psi_i(t)$ are the fault signature and mode, for the i-th filter been designed. It could be noted that the i-th fault is associated to the i-th actuator, that is the reason to have the i-th B_2 matrix column as fault signature. B_{20} and $\psi_0(t)$ contain the rest of fault signatures and modes respectively.

It is worth noting that the additional modes and signatures, different to the filter associated, i.e., the currently designed one, are inside the extended perturbation matrix $\mathcal{B}_i$ and the extended exogenous perturbation signals $\tilde{w}(t) \in \Re^{q+f-1}$ respectively. It means, those faults are taken as perturbations in the design process, and consequently their effect will be minimized on the same way. In this way, the generated residual by this filter, only corresponds to the fault $\psi_i(t)$, since the effect produced by the another faults is attenuated by the $\mathcal{D}_i$ matrix as a result of the optimization process. Particularly it is desired

$$\big\| G_{\hat{w}\to e_{zi}}(s) = C_1\big(sI - \mathcal{A}\big)^{-1}\mathcal{B}_i \big\|_\infty < \gamma \tag{18}$$

$$\big\| G_{\psi_i\to e_{zi}}(s) = C_1\big(sI - \mathcal{A}\big)^{-1}B_{2i} \big\|_\infty \gg \gamma. \tag{19}$$

The reason for the second inequality is to maintain the system $G_{\psi_i\to e_{zi}}(s)$ gain (in this case expressed as a ∞-norm) as high as is possible, in such a way that the fault will not be confused with effects produced by perturbations.

To solve the filter design problem, we use a classic result known as *Bounded Real Lemma* and LMI stability regions, resumed on the next result.

Proposition 3.1 *There exist a detection filter for the i-th fault such that $\big(A - \mathcal{D}_i C_2\big)$ is asymptotically stable, $\big\|G_{\hat{w}\to e_{zi}}(s)\big\|_\infty < \gamma$ with eigenvalues placed on the left of α_i, if only if, there exist matrices $P_i = P_i^T > 0 \in \Re^n$ y $W_i \in \Re^{n\times s}$, $\psi_i(t) = 0$, such that*

$$\begin{bmatrix} A^T P_i + P_i A - W_i C_2 - C_2^T W_i^T & P_i\mathcal{B}_i & C_1^T \\ \mathcal{B}_i^T P_i & -\gamma I & 0 \\ C_1 & 0 & -\gamma I \end{bmatrix} < 0 \tag{20}$$

$$A^T P_i + P_i A - W_i C_2 - C_2^T W_i^T + 2\alpha_i P < 0, \; \alpha_i > 0$$

is satisfied. In that case, the estimator gain is given by $W_i = P_i\mathcal{D}_i$.

Proof

Let us assume (3.1) is feasible and there is a solution to the LMI system, making the variable change $W_i = P_i\mathcal{D}_i$ we have

$$\begin{bmatrix} A^T P_i - C_2\mathcal{D}_i^T P_i + P_i A - P_i\mathcal{D}_i C_2 & P_i\mathcal{B} & C_1^T \\ \mathcal{B}^T P_i & -\gamma I & 0 \\ C_1 & 0 & -\gamma I \end{bmatrix} < 0$$

$$A^T P_i - C_2\mathcal{D}_i^T P_i + P_i A - P_i\mathcal{D}_i C_2 + 2\alpha_i P_i < 0$$

which is equivalent to

$$\begin{bmatrix} (A - \mathcal{D}_i C_2)^T P_i + P_i(A - \mathcal{D}_i C_2) & P_i\mathcal{B} & C_1^T \\ \mathcal{B}^T P_i & -\gamma I & 0 \\ C_1 & 0 & -\gamma I \end{bmatrix} < 0$$

$$(A - \mathcal{D}_i C_2)^T P_i + P_i(A - \mathcal{D}_i C_2) + 2\alpha_i P_i < 0,$$

from the Bounded Real Lemma, we have that $(A - \mathcal{D}_i C_2)$ is stable on the LMI region $\mathcal{R}\big(\mathrm{Re}(s) < -\alpha_i,\ \alpha_i > 0\big)$ and $\big\|G_{\hat{w}\to e_{zi}}(s)\big\|_\infty < \gamma$, if only if, the last inequalities are satisfied. ■

Remark 3.1 *Because of the performance index used, only takes in consideration the transfer function $G_{\hat{w}\to e_{zi}}(s)$ for the optimization process, there is not any warranty of* (19) *satisfaction, i.e., minimizing $\left\|G_{\hat{w}\to e_{zi}}(s)\right\|_\infty$, $\left\|G_{\psi_i\to e_{zi}}(s)\right\|_\infty$ may be seen in an undesired way affected too. To prevent this, it must be sufficed that $\mathcal{B}_i$ and B_{2i} map different subspaces, i.e.,*

$$\mathcal{O}\mathcal{B}_i \cap \mathcal{O}B_{2i} = \emptyset. \tag{21}$$

4 Numerical example

For the LTI system given by,

$$\dot{x} = \begin{bmatrix} -9.9477 & -0.7476 & 0.2632 & -5.0337 \\ 52.1659 & 2.7452 & 5.5532 & -24.4221 \\ 26.0922 & 2.6361 & -4.1975 & -19.2774 \\ 0 & 0 & 1 & 0 \end{bmatrix} x + \begin{bmatrix} 0 & -1 \\ 0 & 1 \\ 1 & 0 \\ 0.1 & 0 \end{bmatrix} w$$

$$+ \begin{bmatrix} 0.4422 & 0.1761 \\ 3.5446 & -7.5922 \\ -5.52 & 4.49 \\ 0 & 0 \end{bmatrix} u \quad ; y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 \end{bmatrix} x,$$

additionally $z = I_{(4)}x$. We wish to design a control system with AW compensation.

The fist step is the controller design, to this aim we use robust control techniques based on LMIs, [12]. In the design we want $\left\|G_{w\to z}(s)\right\|_\infty < \gamma = 10$, getting as a solution:

$$\dot{x}_k = \begin{bmatrix} 16.4492 & -42.3638 & 36.8633 & -251.3213 \\ 17.4340 & -26.4725 & 40.3107 & -201.9255 \\ -0.7031 & -67.5364 & 18.5943 & 40.6733 \\ -22.6426 & 21.1050 & -20.8148 & -8.4562 \end{bmatrix} x_k +$$

$$\begin{bmatrix} -556.9948 & 434.4833 & 266.6770 & -104.2621 \\ -467.7747 & 229.1047 & 126.7813 & -274.6119 \\ 62.6969 & 630.3273 & -32.7941 & -142.7127 \\ 543.7264 & 282.8292 & 149.4677 & 68.7639 \end{bmatrix} u_k$$

$$y_k = \begin{bmatrix} -0.1553 & 1.3421 & -0.8592 & 2.0675 \\ -0.1325 & 0.7495 & -0.6592 & 3.0133 \end{bmatrix} x_k +$$

$$\begin{bmatrix} 18.9710 & -3.8393 & 4.9788 & 0.8609 \\ 17.3182 & -2.0116 & 2.6493 & 0.7743 \end{bmatrix} u_k.$$

For the closed loop system, $\left\|G_{w\to z}(s)\right\|_\infty = 1.9258$. Now, let

$$\Xi_0 = \mathrm{Co}\left\{ \begin{bmatrix} 0.1 \\ 0.1 \\ 0.1 \\ -0.1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}; \begin{bmatrix} 0.1 \\ 0.1 \\ -0.1 \\ 0.1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}; \begin{bmatrix} 0.1 \\ -0.1 \\ 0.1 \\ 0.1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}; \begin{bmatrix} -0.1 \\ 0.1 \\ 0.1 \\ 0.1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right\},$$

be the basis set over which the ellipsoid will be maximized , and $U_0 = \begin{bmatrix} 10 & -10 \end{bmatrix}^T$ the actuator bounds. According to was shown before, from proposition 2.1, solving the LMI set we get the AW compensation gain:

$$E_k = \begin{bmatrix} 10.5803 & 5.3608 \\ -87.9023 & 159.4385 \\ -70.6405 & 64.0682 \\ -117.7002 & 236.5860 \end{bmatrix} \times 10^2. \tag{22}$$

For the SDI filters design purpose, the matrices are distributed on the next way. In every design case, the extended perturbation and signature matrix is given by

$$\mathcal{B}_1 = \begin{bmatrix} 0 & -1 & 0.1761 \\ 0 & 1 & -7.5922 \\ 1 & 0 & 4.49 \\ 0.1 & 0 & 0 \end{bmatrix} \qquad B_{21} = \begin{bmatrix} 0.4422 \\ 3.5446 \\ -5.52 \\ 0 \end{bmatrix}$$

$$\mathcal{B}_2 = \begin{bmatrix} 0 & -1 & 0.4422 \\ 0 & 1 & 3.5446 \\ 1 & 0 & -5.52 \\ 0.1 & 0 & 0 \end{bmatrix} \qquad B_{22} = \begin{bmatrix} 0.1761 \\ -7.5922 \\ 4.49 \\ 0 \end{bmatrix}$$

and $\mathrm{rank}\begin{bmatrix} B_1 \; B_2 \end{bmatrix} = 4$. According to proposition 3.1, taking $\gamma_1 = \gamma_2 = 1{\times}10^{-8}$, and $\alpha_{1,2} = 9.9994{\times}10^2$, the solutions are given by, i.e., the detection filters gains are

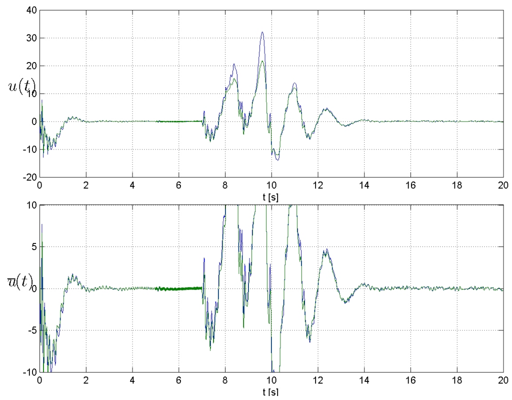
$$\mathcal{D}_1 = \begin{bmatrix} 0.1762 & -0.0487 & 0.0029 & -0.012 \\ -0.0480 & 1.1652 & -0.7053 & 0.2232 \\ 0.0025 & -0.6548 & 0.5439 & -0.0347 \\ 0.0080 & 0.0021 & 0.0118 & 0.0093 \end{bmatrix} \times 10^9$$

$$\mathcal{D}_2 = \begin{bmatrix} 0.2089 & -0.0075 & -0.1107 & -0.0357 \\ -0.0106 & 0.7080 & -0.8319 & -0.0399 \\ -0.1115 & -0.8895 & 1.3676 & 0.2339 \\ 0.0163 & 0.0080 & 0.0062 & 0.0129 \end{bmatrix} \times 10^9.$$

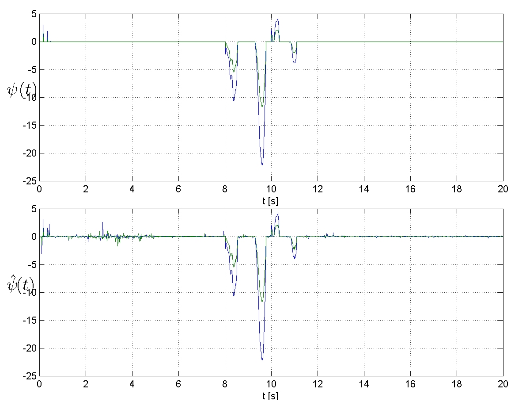
Figure 2 shows the corresponding simulations. 2(a) are the controller output and actuator output, where the saturation is presented. 2(b) shows the measured signal $\psi(t)$, and the estimated signal by SDI filters is showed on the lower part. Finally, 2(c) corresponds to the controlled system output with AW compensation. As the estimated residual signal is adequate, it is possible to use it for effects of implementation of the AW compensation.

5 Concluding remarks

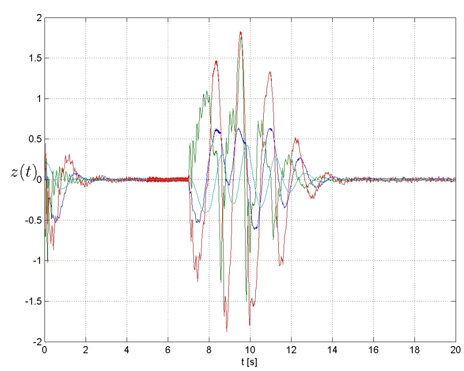
In this contribution, an approach for practical implementation of AW compensation has been presented. The method consists in to estimate the residual signal between the control output and the actuator nonlinear output, applying fault detection and isolation techniques. In this case, the residual signal is considered as fault. Detectability and separability conditions are considered in order to distinguish which actuator is saturated. Thus, a multifiltering is applied for to obtain the residual signals when some actuators are saturated. The residual signals are estimate by means of a filter bank scheme, which allowed to handle the variations in the performance of the actuators. This is, the AW compensation is robust with respect to the changes in the saturation limits of the actuators. The filters are designed using performance indexes defined as LMI restrictions. Also, in order to improve the performance, additional conditions have been applied. An interesting aspect represents the fact that a multiobjective scheme must be used in this framework, according to different saturating conditions or to the different frequencies that are contained in the residual signal. By means of a numerical example the proposed method effectiveness has been shown.



(a) Controller and Actuator outputs.



(b) Measured and estimated $\psi(t)$.



(c) Controlled system output.

Figure 2: Closed loop system simulation using AW compensation.

Acknowledgements: The research was supported by the FONACIT under the grant **2005000170**, and by the CDCHT-ULA, through grant **I-795-04-02-A**.

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