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SENSOR FAULTS DIAGNOSIS IN AIRCRAFT LATERAL FLIGHT CONTROL USING MODEL BASED APPROACHES

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ABSTRACT
In this paper, sensor fault detection and isolation schemes are proposed. Fault detection and isolation techniques are used in fail safe control systems such as aerospace. In these systems, failures can cause to arise undesirable results. Using model based approaches, sensor faults can be detected and isolated. To detect sensor faults, some kind of observers can be used while isolating the faulty sensors, some kind of schemes can be used. In this study, sensor fault detection and isolation are obtained on an aircraft lateral flight control system using model based approaches. Full Order Observer and Reduced Order Observer are used for sensor fault detection while Dedicated Observer Scheme (DOS) and Generalized Observer Scheme (GOS) are used for sensor isolation. Fault detection and fault isolation methods are analyzed and compared with each other.

Keywords: *Flight Control, Fault Detection, Fault Isolation, Model Based Approaches.*

MODELE DAYALI YAKLAŞIMLAR KULLANILARAK UÇAK YANLAMASINA UÇUŞ KONTROL SİSTEMİNDE SENSÖR ARIZALARININ TEŞHİSİ

ÖZET
Bu çalışmada, algılayıcı arızası tespiti ve ayrımı ele alınmaktadır. Havacılık gibi yüksek emniyet gerektiren kontrol sistemlerinde arıza tespiti ve ayrımı teknikleri kullanılmaktadır. Böyle sistemlerde, arızalar istenmeyen sonuçlar doğurabilir. Modellemeye dayalı yaklaşımlar kullanılarak algılayıcı arızaları tespit edilebilir ve ayrımları gerçekleştirilebilir. Algılayıcı arızalarını tespit etmek çeşitli gözleyiciler kullanılabilirken arıza ayrımı için ise çeşitli tertibatlar kullanılır. Bu çalışmada, modellemeye dayalı yaklaşımlar kullanılarak bir uçağın yanlamasına uçuş kontrol sistemi için algılayıcı arızası tespiti ve ayrımı gerçekleştirilmiştir. Tam mertebe ve indirgenmiş mertebe gözleyiciler ile algılayıcı arızası tespiti yapılırken Adanmış Gözleyici Yapısı ve Genelleştirilmiş Gözleyici Yapısı kullanılarak algılayıcı arızası ayrımları gerçekleştirilmiştir. Arıza tespit ve ayrım metotları analiz edilmiş ve birbirleriyle karşılaştırılmıştır.

Anahtar Kelimeler: *Uçuş control, Arıza Tespiti, Arıza Ayrımı, Modellemeye Dayalı Yaklaşımlar.*

1. INTRODUCTION

Sensor faults in the systems are detected by setting thresholds on residuals generated from the difference between real system measurements and estimates of the system measurements using the model. Using some residuals analysis methods, sensor faults are isolated. To generate residuals, observers can be used. Sevinç proposed an adaptive observer estimating all parameters and load torque for DC servo motor. Using current and speed measurements, he claims that simulation results are satisfactory [1].

Demirci and Kerestecioğlu presented a controller design method for linear MIMO systems. Faults are detected with the residual vector generated from a standard linear observer. Once a fault has been detected the fault distribution matrix can be obtained and used to update the corrective or equivalent control parts of the sliding mode controller [2].

Göksu and Hava studied estimation methods on different motor. They investigated a hybrid algorithm using flux observer. They claim that the algorithm helps the motion control engineers select the suitable motor [3].

Cai, Kebairi, Becherif and Wack studied fault detection of an engine. Using a state observer and fuzzy logic, they detected faults [4].

Dal and Teodorescu studied observer based methods to maintain good chattering reduction for current regulation [5].

Aksoy and Mühürcü presented an algorithm for state estimation of a motor. They claimed that the proposed algorithm estimated the states of a motor and performed better than extended Kalman Filter [6].

Aydeniz and Şenol proposed an algorithm for a motor. Firstly, they find observer constants in Matlab program and then they used this parameters on an induction motor [7].

Leblebici, Çallı, Ünel, Sabanovic, Bogosyan and Gökaşan studied a sliding mode observer to predict states of the slave system [8].

Shoukry, Kunt and Sabanovic formulated a framework which allows identifying system parameters and observing system states through measurements taken from the actuator side. They performed on an inertial lumped flexible system with three degrees of freedom. They claimed that the study results demonstrate the validity of the proposed technique where the difference between the identified parameters and the actual known previously ones is less than five percent [9].

Gürcan and Kartal proposed an approach to recommend a manoeuvre to the observer. Here observer is used to estimate the position of the target [10].

In this study, sensor fault detection and isolation are obtained on an aircraft lateral flight control system. Model based approaches are considered. Full Order Observer and Reduced Order Observer are used for sensor fault detection while Dedicated Observer Scheme (DOS) and Generalized Observer Scheme (GOS) are used for sensor isolation. Both fault detection and fault isolation methods are analysed and compared each other. Advantages and disadvantages are seen on simulations using Matlab program.

2. PRINCIPLES OF MODEL BASED SENSOR FAULT DETECTION AND ISOLATION

2.1. Observer Based Approaches

The continuous time, time invariant, linear dynamic model in a state space form is considered as Equation (1) [11-14]:

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

Here, $\mathbf{x(t)} \in R^{nx1}$ is the state vector, $\mathbf{u(t)} \in R^{mx1}$ is the input vector, $\mathbf{y(t)} \in R^{nx1}$ is the real system output vector and **A**, **B** and **C** are known system matrices with appropriate dimensions.

The state space model of a full -observer is described as Equation (2):

$$\dot{\mathbf{z}}(\mathbf{t}) = \mathbf{Fz}(\mathbf{t}) + \mathbf{Gy}(\mathbf{t}) + \mathbf{Lu}(\mathbf{t}) \tag{2}$$

Here, $\mathbf{z(t)} \in R^{nx1}$ is the observation vector, $\mathbf{F} \in R^{nxn}$ is the observer dynamics matrix, $\mathbf{G} \in R^{nxn}$ is the measurement distribution matrix and $\mathbf{L} \in R^{nxm}$ is the control distribution matrix.

If the state vector of Equation (1) are multiplied by a $\mathbf{T} \in R^{nxn}$ matrix and subtracting from Equation (2), Equation (3) is obtained:

$$\dot{\mathbf{z}}(\mathbf{t}) - \mathbf{T}\dot{\mathbf{x}}(\mathbf{t}) = \mathbf{Fz}(\mathbf{t}) + \mathbf{Lu}(\mathbf{t}) + \mathbf{GCx}(\mathbf{t}) - \mathbf{TAx}(\mathbf{t}) - \mathbf{TBu}(\mathbf{t}) \tag{3}$$

If the error vector is described as Equation (4),

$$\mathbf{e}(\mathbf{t}) = \mathbf{z}(\mathbf{t}) - \mathbf{Tx}(\mathbf{t}) \tag{4}$$

the derivative of the error vector is obtained Equation (5):

$$\mathbf{\dot{e}(t) = F(z(t) - Tx(t)) + (FT - TA + GC)x(t) + (L - TB)u(t)} \quad (5)$$

If the bellowed conditions are satisfied,

$$\mathbf{FT - TA + GC = 0} \quad (6)$$
$$\mathbf{L - TB = 0} \quad (7)$$

Equation (5) can be rewritten as Equation (8):

$$\mathbf{\dot{e}(t) = Fe(t)} \quad (8)$$

The solution of the Equation (8) is obtained as Equation (9):

$$\mathbf{e(t) = e^{Ft}e(0)} \quad (9)$$

If the matrix **F**'s eigenvalues are in the left half of the complex system, the solution goes to zero asymptotically:

$$\lim_{t\to\infty} \mathbf{e(t) = 0} \quad (10)$$

and Equation (11) is obtained:

$$\lim_{t\to\infty} \mathbf{z(t)} = \lim_{t\to\infty} \mathbf{Tx(t)} \quad (11)$$

If the **T** matrix is $\in R^{vxn}$ and v < n, all of the states are not obtained. This kind of observer is reduced order observer and it is satisfied following conditions:

$$\mathbf{\hat{x}(t) = Ez(t) + Dy(t) = [D \quad E]\begin{bmatrix} y(t) \\ z(t) \end{bmatrix}} \quad (12)$$
$$\mathbf{I_n = ET + DC} \quad (13)$$

Here, $\mathbf{\hat{x}(t)} \in R^{nx1}$ is the estimated state vector, z(t) and y(t) are vectors with appropriate dimensions. **C**, **D**, and **E** are matrices with appropriate dimensions.

If the Equation is redesign as Equation (14),

$$\mathbf{[D \quad E]\begin{bmatrix} C \\ T \end{bmatrix} = I_n} \quad (14)$$

$l + v = n$ is seen and $\begin{bmatrix} \mathbf{C} \\ \mathbf{T} \end{bmatrix}$ matrix must be square matrix. If the $\det\begin{bmatrix} \mathbf{C} \\ \mathbf{T} \end{bmatrix} \neq 0$, Equation (15) is obtained:

$$\mathbf{[D \quad E] = \begin{bmatrix} C \\ T \end{bmatrix}^{-1}} \quad (15)$$

If the Equation (13) is rewritten, Equation (16) is obtained:

$$\mathbf{\hat{x}(t) = \begin{bmatrix} C \\ T \end{bmatrix}^{-1}\begin{bmatrix} y(t) \\ z(t) \end{bmatrix}} \quad (16)$$

If the $\mathbf{W} \in R^{vxn}$ matrix is chosen instead of T matrix, Equation (17) can be described:

$$\begin{matrix} \scriptstyle lxn \\ \scriptstyle vxn \end{matrix}\mathbf{\begin{bmatrix} C \\ W \end{bmatrix}^{-1} = \begin{bmatrix} \underset{nxl}{V} & \underset{nxv}{E} \end{bmatrix}} \quad (17)$$

Here, $\mathbf{V} \in R^{nxl}$, $\mathbf{E} \in R^{nxv}$ are matrices.

In that case, Equation (18) is obtained

$$\mathbf{[V \quad E]\begin{bmatrix} C \\ W \end{bmatrix} = I_n} \quad (18)$$

If the $\det\begin{bmatrix} \mathbf{C} \\ \mathbf{W} \end{bmatrix} \neq \mathbf{0}$ is chosen, Equation (19) is obtained:

$$\mathbf{EW + VC = I_n} \quad (19)$$

T and **D** matrices are described as Equation (20) and Equation (21):

$$\mathbf{T \overset{\Delta}{=} W - HC} \quad (20)$$
$$\mathbf{D \overset{\Delta}{=} V + EH} \quad (21)$$

If the $\mathbf{H} \in R^{vxl}$ is arbitrary, the reduced order observer is obtained.

F and **G** matrices are described as Equation (22) and Equation (23):

$$\mathbf{F \overset{\Delta}{=} TAE = WAE - HCAE} \quad (22)$$
$$\mathbf{G \overset{\Delta}{=} TAD = WAD - HCAD} \quad (23)$$

Using Equations (20-23), basic observer equations are obtained as Equation (24) and Equation (25):

$$\mathbf{\begin{aligned} FT - TA + GC &= WAET - HCAET - (W - HC)A + WADC - HCADC \\ &= WA[ET - I + DC] - HCA[ET - I + DC] = 0 \end{aligned}} \quad (24)$$
$$\mathbf{L = TB = (W - HC)B = WB + HCB} \quad (25)$$

2.2. Sensor fault detection and isolation

Sensor faults are described as Equation (26):

$$\begin{aligned}\dot{\mathbf{x}}(\mathbf{t}) &= \mathbf{Ax}(\mathbf{t}) + \mathbf{Bu}(\mathbf{t}) \\ \mathbf{y}(\mathbf{t}) &= \mathbf{Cx}(\mathbf{t}) + \mathbf{f}_s(\mathbf{t})\end{aligned} \tag{26}$$

Here, $\mathbf{f}_s(\mathbf{t}) \in R^{nx1}$ is the sensor fault vector.

Using Equation (26), the derivative of the error vector is obtained as Equation (27):

$$\dot{\mathbf{e}}_{\mathbf{a}}(\mathbf{t}) = \dot{\mathbf{z}}(\mathbf{t}) - \mathbf{T}\dot{\mathbf{x}}(\mathbf{t}) = \mathbf{Fz}(\mathbf{t}) + \mathbf{Lu}(\mathbf{t}) + \mathbf{Gy}(\mathbf{t}) + \mathbf{Gf}_s(\mathbf{t}) - \mathbf{TAx}(\mathbf{t}) - \mathbf{TBu}(\mathbf{t}) \tag{27}$$

Equation (27) can be rewritten as Equation (28):

$$\dot{\mathbf{e}}_{\mathbf{a}}(\mathbf{t}) = \mathbf{F}(\mathbf{z}(\mathbf{t}) - \mathbf{Tx}(\mathbf{t})) + (\mathbf{L} - \mathbf{TB})\mathbf{u}(\mathbf{t}) + (\mathbf{FT} - \mathbf{TA} + \mathbf{GC})\mathbf{x}(\mathbf{t}) + \mathbf{Gf}_s(\mathbf{t}) \tag{28}$$

If Equation (6) and Equation (7) are satisfied and $\mathbf{G} \neq \mathbf{0}$ sensor faults are detected.

If the sensor faults are in the system, the residual vector is described as Equation (29):

$$r(t) = Ce(t) + f_s \tag{29}$$

Sensor vector is effected on the residual and r(t) can be used for isolation as Equation (30)

$$\mathbf{r_i}(\mathbf{t}) = \mathbf{R}(\mathbf{f}_{s\mathbf{i}}(\mathbf{t})) \qquad \mathbf{i} = \mathbf{1}, \mathbf{2} \ldots \mathbf{n} \tag{30}$$

To isolate of the sensor faults, threshold logic can be used as Equation (31):

$$\|\mathbf{r_i}(\mathbf{t})\| > \boldsymbol{\varepsilon}_\mathbf{i} \quad \Rightarrow \quad \mathbf{f}_{s\mathbf{i}} \neq \mathbf{0} \quad \Rightarrow i \text{ . sensor fault} \tag{31}$$

Here, $\boldsymbol{\varepsilon}_\mathbf{i}$ is the chosen threshold.

This kind of isolation method is described as Dedicated Observer Scheme (DOS).

Another method is to isolate of the sensor faults, Generalized Observer Scheme (GOS) can be used as Equation (32):

$$\begin{aligned}&\mathbf{r_1}(\mathbf{t}) = \mathbf{R}(\mathbf{f_2}(\mathbf{t}), \cdots \mathbf{f_n}(\mathbf{t})) \\ &\vdots \\ &\mathbf{r_i}(\mathbf{t}) = \mathbf{R}(\mathbf{f_1}(\mathbf{t}), \cdots \mathbf{f_{i-1}}(\mathbf{t}), \mathbf{f_{i+1}}(\mathbf{t}), \cdots \mathbf{f_n}(\mathbf{t})) \\ &\vdots \\ &\mathbf{r_n}(\mathbf{t}) = \mathbf{R}(\mathbf{f_1}(\mathbf{t}), \cdots \mathbf{f_{n-1}}(\mathbf{t}))\end{aligned} \tag{32}$$

To isolate of the sensor faults in this method, threshold logic can be used as Equation (33):

$$\left.\begin{aligned}&\|\mathbf{r_i}(\mathbf{t})\| \le \boldsymbol{\varepsilon}_\mathbf{i} \\ &\|\mathbf{r_j}(\mathbf{t})\| > \boldsymbol{\varepsilon}_\mathbf{j} \quad \forall \mathbf{j} \in \{\mathbf{1}, \mathbf{2} \ldots \mathbf{i}-\mathbf{1}, \mathbf{i}+\mathbf{1} \ldots \mathbf{n}\}\end{aligned}\right. \Rightarrow \mathbf{f}_{s\mathbf{i}} \neq \mathbf{0} \;\Rightarrow\; i \text{ .sensor fault}$$

3. SIMULATION RESULTS

The steady states matrices of an aircraft lateral flight control are described as Equation (33) [15].

$$\mathrm{A} = \begin{bmatrix} -0.0893 & 0.0019 & -0.9588 & 0.0392 \\ -0.5993 & -0.5646 & 0.0105 & -0.0548 \\ 1.9803 & -0.1143 & -1.8133 & -0.0094 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \mathrm{B} = \begin{bmatrix} 0 & 0.012 \\ 0.14 & 0.15 \\ 0.008 & -0.48 \\ 0 & 0 \end{bmatrix}, C = I4 \tag{33}$$

State variables and input vector may be defined as:

$$\mathbf{x} = \begin{bmatrix} \beta \\ p \\ r \\ \phi \end{bmatrix}, \ \mathbf{u} = \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix} \tag{34}$$

Here, β is the side-slip angle; p is the roll rate, r is the yaw rate; ϕ is the roll angle, δ_a is the aileron deflection; δ_r is the rudder deflection.

A failure simulation prepared in roll rate sensor at iteration time = 250. States of the aircraft lateral flight control system are shown in Figure 1 when a failure occurs in sensor of roll rate. Because of the C=eye (4), states equals outputs. Here, input vector is used as $\mathbf{u} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$. Sensor fault vector is used as $f_s = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$ after roll rate sensor fault is occurred.

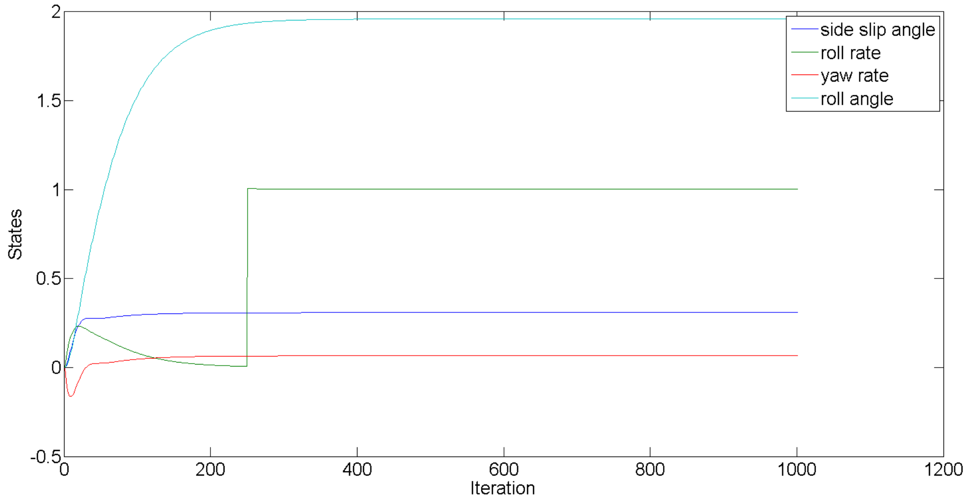

Figure 1. States of the aircraft lateral flight control system.

To obtain fault detection and isolation scenarios, Full Order Observer dynamics matrix is used as $F=\begin{bmatrix}-10 & 0 & 0 & 0\\ 0 & -10 & 0 & 0\\ 0 & 0 & -10 & 0\\ 0 & 0 & 0 & -10\end{bmatrix}$. Matrix T is chosen eye (4). In this case, Full Order Observer coefficients are calculated as $G=\begin{bmatrix}9.9107 & 0.0019 & -0.9588 & 0.0392\\ -0.5993 & 9.4354 & 0.0105 & -0.0548\\ 1.9803 & -0.1143 & 8.1867 & -0.0094\\ 0 & 1 & 0 & 10\end{bmatrix}$ and $L=\begin{bmatrix}0 & 0.012\\ 0.14 & 0.15\\ 0.008 & -0.48\\ 0 & 0\end{bmatrix}$.

Using DOS method, Full Order Observer residuals are obtained as shown in Figure 2.

By checking residuals, it is seen that after 250th iteration, almost residuals increased but the biggest rise is the r2. If the threshold is chosen suitable, sensor fault is isolated. Here, the fault is caused by roll rate sensor.

Using GOS method, residuals are obtained as shown in Figure 3.

By checking residuals, it is seen that after 250th iteration, r1, r3 and r4 increased while r2 did not change. Here, the fault is caused by roll rate sensor.
If C matrix is different from eye (4), all of the states are not obtained. A failure simulation prepared in roll rate sensor at iteration time = 250. The outputs of the system are shown in Figure 4 when a failure occurs in sensor of roll rate. $C=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{bmatrix}$ is used for simulation. Here, input vector is used as $\mathbf{u}=\begin{bmatrix}1\\ 1\end{bmatrix}$. Sensor fault vector is used as $f_S=\begin{bmatrix}0\\ 1\end{bmatrix}$ after roll rate sensor fault is occurred.

To obtain fault detection and isolation scenarios, Reduced Order Observer coefficient must be found. Firstly, $H=\begin{bmatrix}-0.7697 & -0.2256\\ 0.3714 & 1.1174\end{bmatrix}$ is used as arbitrary. Choosing H matrix, $T=\begin{bmatrix}1.8629 & -0.6381 & -1.2141 & -0.0068\\ 0.7379 & -1.04 & -1.1135 & 1.5326\end{bmatrix}$, $D=\begin{bmatrix}1 & 0\\ 0 & 1\\ 1.5308 & -0.5272\\ 0.6307 & 0.2955\end{bmatrix}$, $F=\begin{bmatrix}-0.4064 & 0.0761\\ -1.1244 & 0.0579\end{bmatrix}$, $G=\begin{bmatrix}-1.4873 & 0.3155\\ 0.4043 & 1.5912\end{bmatrix}$, $L=\begin{bmatrix}-0.099 & 0.5094\\ -0.1545 & 0.3873\end{bmatrix}$ are found. Choosing H matrix, founded F matrix must be stable. Here eigenvalues' of the F matrix are $\{-0.1743 \pm i0.178\}$. It means founded F matrix is stable.

Using DOS method, Reduced Order Observer residuals are obtained as shown in Figure 5.

By checking residuals, it is seen that after 250th iteration, r2, increased while r1 did not change. Here, the fault is caused by roll rate sensor.

Here, to use GOS method will not usable because of the only 2 residuals information.

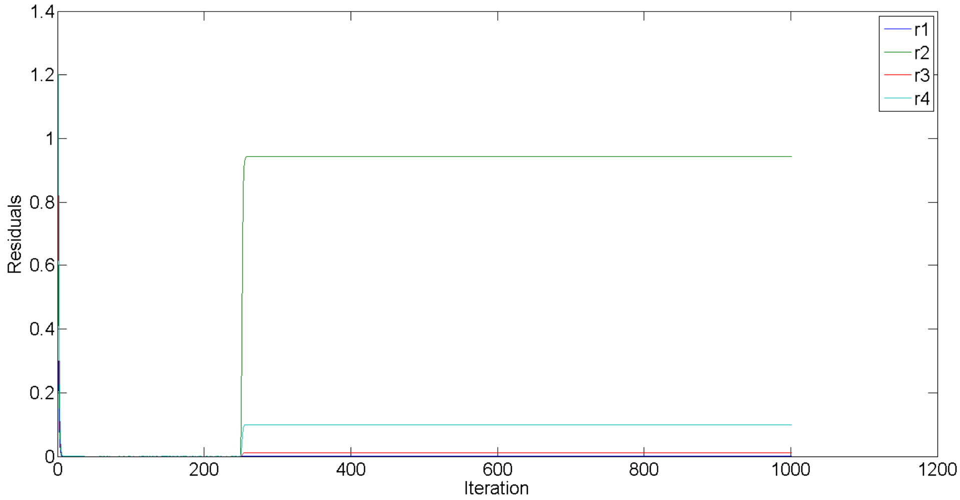

Figure 2. Residuals with Full Order Observer Using DOS.

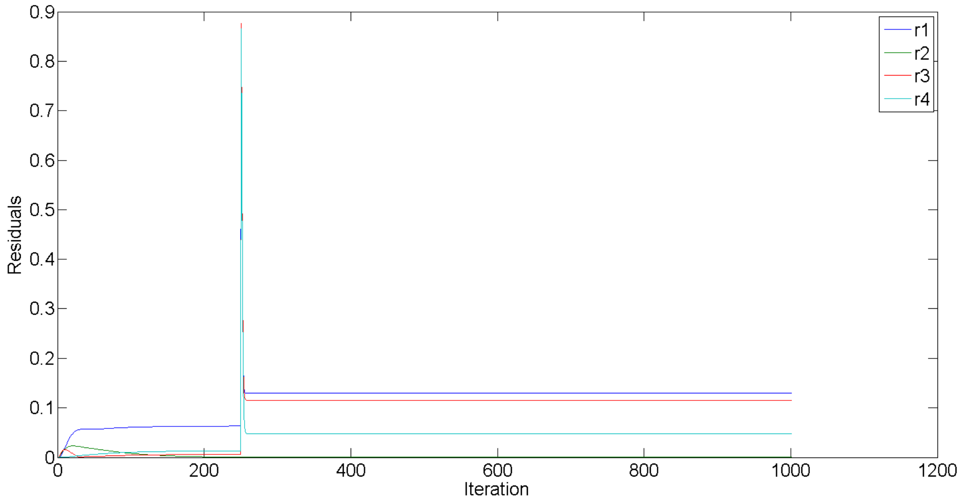

Figure 3. Residuals with Full Order Observer Using GOS.

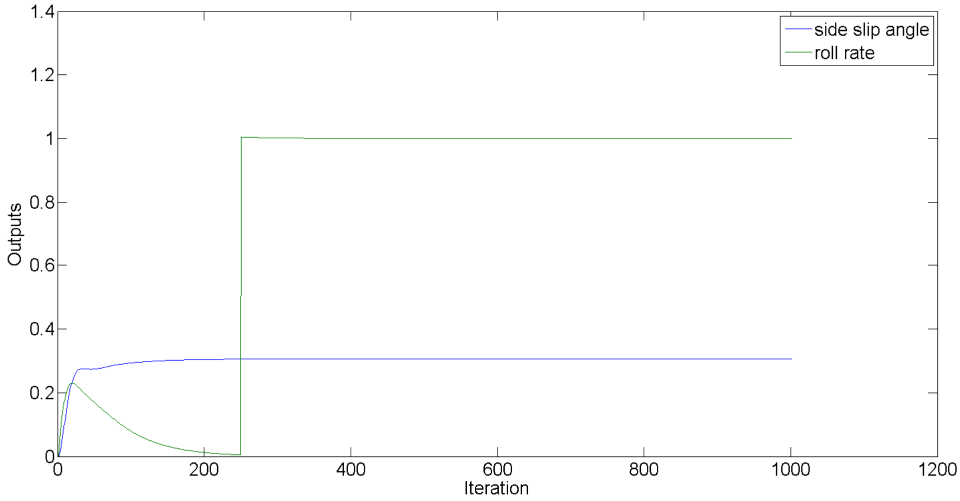

Figure 4. Outputs of the System.

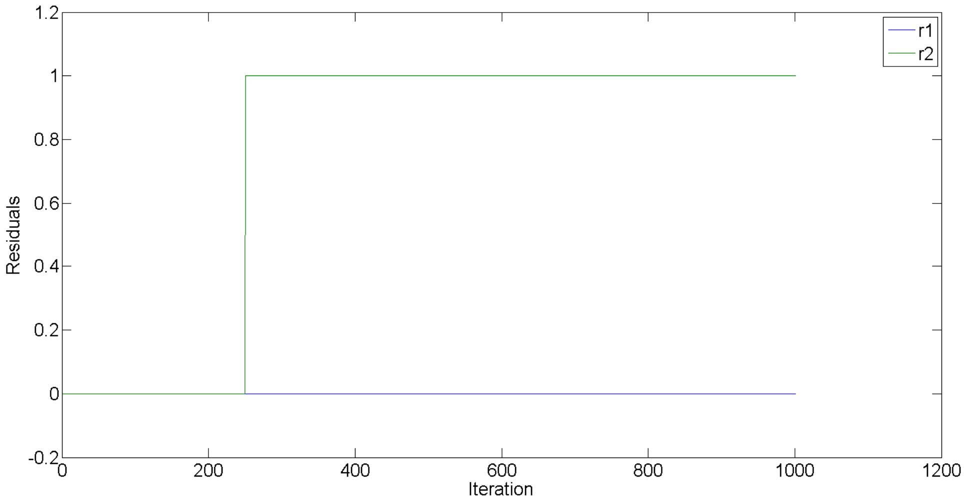

Figure 5. Residuals with Reduced Order Observer Using DOS.

4. CONCLUSION

In this study, using model based approaches, sensor fault detection and isolation is obtained on an aircraft lateral flight control. Firstly, Full Order Observer can be used for sensor faults. A failure simulation prepared in one sensor at any time and using DOS and GOS methods, sensor faults are isolated. By checking residuals with DOS method, after sensor fault, almost residuals increased but the biggest rise is the faulty sensor residual. It is seen that if the threshold is not chosen suitable, sensor fault is not isolated correctly. By checking residuals with GOS method, after sensor fault, three residuals increased while one residual did not change. Here, unchanged residual information points to sensor fault. GOS method is more appreciate because of more residual information. Secondly, Reduced Order Observer can be used for sensor faults. A failure simulation prepared in one sensor at any time. Here, it is accepted some outputs are not measurable. Even if some outputs are not obtained, using DOS method, after sensor fault, one residual increased but other did not change. Here, changed residual information points to sensor fault.

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VITAE

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He was born in 1978 in Eskisehir, Turkey. He graduated from Civil Aviation School Department of Avionics in 2001, and received a MSc degree from the Anadolu University in 2003. He received a PhD degree from the Anadolu University in 2008. His PhD degree is from Anadolu University with the thesis titled "Sensor and Actuator Fault Detection, Isolation and System Reconfiguration in Flight Control System Using Unknown Input Observers". He is currently an assist. Prof. of Faculty of Aeronautics and Astronautics since 2008.

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