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Simulation of sensor failure accommodation in flight control system of transport aircraft: a modular approach *

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Abstract. Modeling and simulation plays a crucial role in design, development and testing of robust flight control systems (FCS). Simulation software has made it possible for the researchers to simulate complex behavior of FCS for design of sensor faults and accommodation techniques also. In this paper, a modular approach of simulation of sensor failure accommodation in FCS is developed for a transport aircraft. Sensor fault detection and accommodation (SFDA) system is developed and simulated for lateral dynamics of the aircraft model. Unlike black box models, all the parameters are accessible for control and verification purposes. Improvement in open loop response of lateral dynamics of 747 jet aircraft was achieved by pole placement technique. This closed loop aircraft control system was used for verification of SFDA. Failure of the sensors which measure and normally are also the aircraft states are simulated for the stuck fault scenarios. Fault detection is accomplished by evaluating any significant change in the behavior of the aircraft with respect to the fault-free behavior, which is estimated by using the Luenberger observer. Luenberger observer and feedback gain matrix were designed in MATLAB. Canberra metric is used as a signature for sensor fault detection. Simulation models of closed loop aircraft model, observer, Canberra metric, fault induction subsystem (including intermittent stuck fault) form SFDA system. Reconfiguration under faulty conditions is done by using the estimated state of the observer. The effectiveness of the proposed approach is in the field of modeling and simulation of accommodation of sensor failure in FCS. It is demonstrated by means of simulation results using MATLAB Simulink. The procedure described will be useful to researchers who like to simulate any engineering state space model for fault detection and reconfiguration. This approach may be useful for validation or implementation on DSP processors by using hardware in loop simulation.

Keywords: aircraft flight control system, lateral dynamics, sensor stuck fault, reconfiguration, luenberger observer, canberra metric, simulink, model based design, multi-level simulation

1 Introduction

Modeling and Simulation is playing a significant role in development of Aerospace electronics in various fields of avionics and FCS[4, 12]. It provides simulation environment ranging for atmosphere's variations to earth's gravity[7]. It plays a critical role in supporting sky thinking at the early stages of aircraft flight control systems design and validation[12]. Jang et al.[5] used simulation tool for Design and Analysis of Morpheus Lander FCS. Liu[9] used real time simulation for FCS development and validation. Saxena et al.[8] modeled damage propagation for Aircraft Engine Run-to-Failure Simulation. It has been used by many researchers for unmanned air vehicle (UAV)[2, 6] FCS design. References [1, 3, 13] and [14] simulated sensor fault accommodation system for FCS. Though modeling and simulation has been used by researchers extensively for varied applications in the field of FCS, there is a lack of procedural description of any simulation environment in

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the cited references. As sensor fault detection and accommodation is one of crucial area in FCS, an insight to Simulink based SFDA system is presented in this paper. SFDA in reliable feedback control systems could also lead to real-time implementation on DSP processors.

Sensors in FCS: Sensors are an important component in FCS as the measurements from sensors are used in the feedback loop of a control system. Sensor faults, if not detected and reconfigured in time, can lead to closed-loop instability and unrecoverable flight conditions. For sensor fault accommodation purposes, multiple physical redundancies are employed in many high performance military aircraft and commercial jetliners. However, an analytical sensor redundancy approach is more appealing as it comes with reduced complexity, lower cost, and weight optimization, depending on model accuracy.

Analytical redundancy implies the use of a validated mathematical model to generate signals that would otherwise be produced by redundant hardware. The presence of faults is detected by means of the residuals. Residuals are quantities that are over-sensitive to the malfunctions

The basic idea behind the observer or filter-based approach is to estimate the outputs of the system from the measurements by using either Luenberger observer(s) in a deterministic setting or Kalman filter(s) in a stochastic setting. Observers, Kalman filters and neural networks have been used extensively for FDI, particularly in the field of autonomous vehicles. In 1971, Luenberger proposed reconstructing unknown states using the available state and outputs. The reconstructed or estimated states are then available for feedback. Since Luenberger's proposal, observers have become widely used and play an important role in model-based analytical redundancy[14], especially for closed loop feedback control system.

The software package of MATLAB/Simulink is very efficient and convenient in modeling and simulation of dynamic systems, especially of control systems, signal processing system, etc. The users need to focus on developing algorithms, modeling, analyzing and visualizing simulations, customizing the simulation environment and defining parameters[7]. Models were developed for Boeing 747 jet aircraft lateral dynamics, controller, observer, fault induction and reconfiguration. All these five subsystems are configured together in main simulation model to demonstrate successful detection and reconfiguration of sensor fault in aircraft. Models can be developed using both top-down and bottom-up approaches as they are hierarchical. Main simulation model can be viewed at a high level, and then each subsystem blocks can be selected to see increasing levels of model detail. This approach provides insight into how a model is organized and how its parts, i.e. five subsystems interact. System at top level can be analyzed for interaction of its various subsystems. The number of levels increases with system's complexity.

Simulink is a block diagram environment for multi domain simulation and Model-Based Design for dynamic systems. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems. Any control algorithm can be modeled in Simulink if the physical system is described in terms of the equations of the models. However, any nonlinear equations should be linearized for solving. Simulink can be used to solve initial value problems for ordinary differential equations. "ode45" is used for simulation in this paper which suits for non-stiff type of problems and it has medium order of accuracy. Other 'ode' solvers can be used for different type of problems based on its type and required order of accuracy. It is integrated with MATLAB, enabling MATLAB algorithms into models and export simulation results to MATLAB for further analysis.

This paper focuses on the application of Luenberger observer for analytical redundancy for sideslip angle (β) sensor of lateral dynamics model of Boeing 747 jet aircraft. Observer will reconfigure with the remaining available sensor output of bank angle (ϕ). Stuck fault at '0' or less than zero (for specified input) can be detected by the fault detector of the model which uses Canberra metric. Reconfiguration with observer estimate for the failed sensor state will be done as soon as fault is detected. Contribution of this work is application of Luenberger observer for lateral dynamics of aircraft model for SFDA with complete modeling and simulation environment using MATLAB/Simulink.

2 Basics of simulink

Fig. 1 shows a basic model developed in Simulink. This basic model consists of three blocks: Sine Wave, Gain, and Scope (one each for input and output signal). The Sine Wave is a Source Block from which a sinusoidal input signal originates. This signal is transferred through a line in the direction indicated by the arrow to the Gain Math Block. The Gain block modifies its input signal (multiplies it by a constant value, i.e. 3) and outputs a new signal through a line to the Scope block (output scope). The Scope is a Sink Block used to display a signal (much like an oscilloscope). Input is also displayed using input scope block. Further details of Simulink blocks and building models in Simulink can be seen in [7].

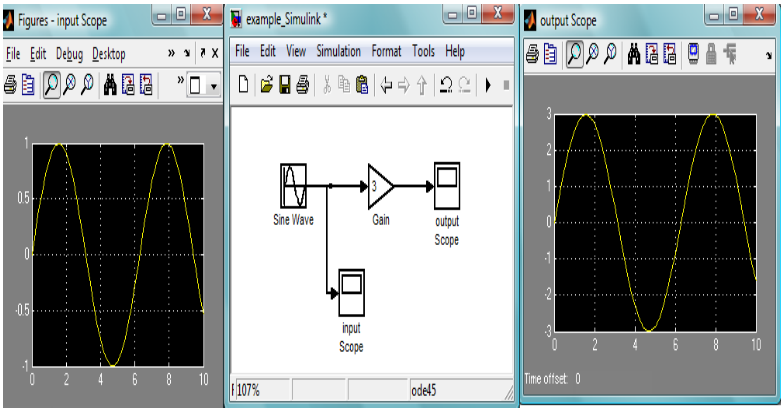

Fig. 1. Simulink basic model: an example

3 Modelling and simulation

Simulation has been carried out with lateral dynamics controller and observer of Boeing 747 jet aircraft model. The main simulation set-up model is shown in Fig. 2 which is simulated in MATLAB Simulink. It mainly consists of five subsystems which are discussed later in this section with complete specifications. The flow of simulation, from left to right, carried out is discussed below:

(1) There are two inputs (rudder and aileron), out of which only rudder input is actuated by a command of '0.3' radian for $20s$ for the simulation. Aileron input is grounded. Aileron input or both the inputs can be excited, if required.

(2) The two inputs are multiplexed together to form input signal for 'Boeing 747 Jet aircraft lateral dynamics' subsystem and observer subsystem.

(3) Boeing 747 Jet aircraft lateral dynamics takes the input and provides 'x' (see Sec 4.1 for details of 'x' state vector). Two of the four states, i.e. β & ϕ are the outputs of the sensors of the aircraft. Out of the two sensors, 'ϕ' is always considered as fault free, and shown as one of the outputs of aircraft. 'β' sensor failure will be simulated and analyzed in rest of the subsystems of the model. 'x' vector is passed to 'Fault Induction' subsystem (details in Sec 4.3) for further simulation. 'β' can also be considered as fault free, and 'ϕ' may be considered as faulty for analysis.

(4) Stuck fault is the fault where sensor gets stuck at one position and erroneously gives a constant output. This output is the last value of the sensor at the time instant when it got stuck and failed. 'Fault Induction' subsystem is used for induction of stuck fault of 'β' sensor only. 'β' state is extracted out of the four states of x for fault induction. Fault Introducer (N Sample switch, details in Sec 4.3) forces β sensor to become '0' at any selected value of time. Fig. 11 shows fault induction at 10 sec. Faulty 'β' sensor along with other three healthy states is multiplexed in 'Fault Induction' subsystem to form xFaulty state vector as shown in Fig. 2 and 5. In Fig. 2, 'controller' subsystem receives xFaulty, the faulty state vector in feedback loop.

(5) 'Observer' subsystem estimates the two sensor outputs, 'βO' and 'ϕO'. It uses healthy sensor state 'ϕ' from 'Boeing 747 Jet aircraft lateral dynamics subsystem for estimating the two sensor states.

(6) Reconfiguration block provides the estimated signal (from redundant hardware or mathematical model) instead of faulty sensor signal in the feedback loop. This is modeled by 'Reconfiguration' subsystem of Fig. 2 which is used for two purposes. First purpose is to detect and indicate fault in Scope named 'Fault Indicator'. This is done by comparing aircraft sensor output (β) with observer estimate of 'β' (βO) in 'Reconfiguration'

subsystem. The second purpose is switching over to observer estimate 'βO' instead of faulty sensor output 'β' as soon as fault is indicated.

(7) 'Controller' subsystem is also used for two tasks. First task is to provide control law (Kx) in the feedback loop of 'Boeing 747 Jet aircraft lateral dynamics' subsystem as shown in Fig 2. In case of fault, xFaulty state vector replaces x state vector and fault propagates with control law ($K \times x$Faulty) signal in feedback loop and creates closed loop instability in all the elements of 'x' state vector. Second task is to incorporate reconfigured 'β' state in the feedback loop which is received from 'Reconfiguration' subsystem.

In case of 'no fault' scenario 'Reconfiguration' subsystem continues to keep 'β' (aircraft sensor output) in feedback loop through 'controller' subsystem.

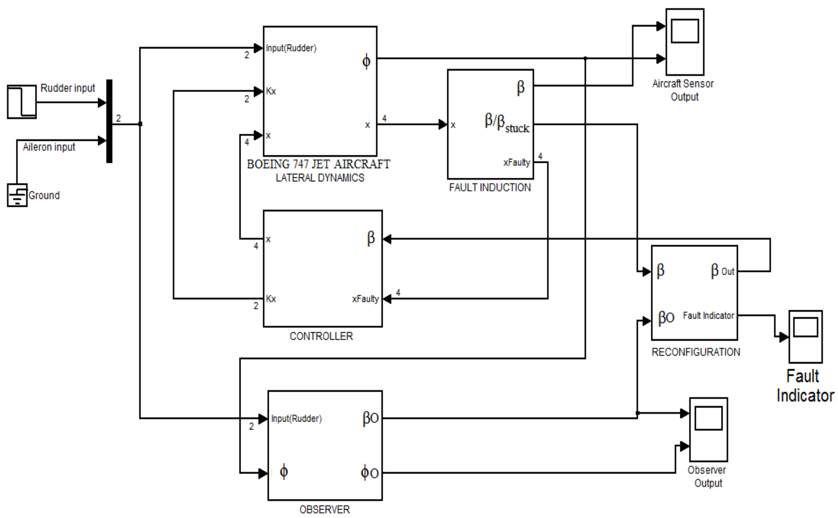

Fig. 2. Simulink model for the sensor fault detection and accommodation (SFDA) in FCS

4 Subsystem implementation in simulink

4.1 Boeing 747 jet aircraft lateral dynamics subsystem

The Boeing 747 jet transport aircraft model has four states ($\beta, \psi, \theta, \phi$), two inputs (rudder, aileron) and two outputs (β, ϕ). The simplified trim state space model of the aircraft during cruise flight at $MACH = 0.8$ and $H = 40,000ft$, is given in Eqs. (1) and (2)[10]. 'x' is the state vector, $x = [\beta, \psi, \theta, \phi]^T$, β: sideslip angle (rad), ψ: yaw rate (rad/s), θ: roll rate (rad/s), ϕ: bank angle (rad).

$$\dot{x} = Ax + Bu, \qquad y = Cx + Du, \tag{1}$$

$$A = \begin{bmatrix} -0.0558 & -0.9968 & 0.0802 & 0.0415 \\ 0.598 & -0.115 & -0.0318 & 0 \\ -3.05 & 0.388 & -0.465 & 0 \\ 0 & 0.0805 & 1 & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} 0.0729 & 0 \\ -4.75 & 0.00775 \\ 0.153 & 0.143 \\ 0 & 0 \end{bmatrix}, \tag{2}$$

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad D = 0.$$

Eq. (1) and (2) of Boeing 747 jet transport aircraft used in ref [11] shows two outputs (yaw (ψ), bank angle (ϕ) as indicated by 'C' matrix. However, for this work, all the four aircraft states (x) are required and two (β, ϕ) of the four states are taken as sensor output. Eq. (1) modifies to form Eq. (3) and Eq. (2) will have only A and B matrices.

$$\begin{aligned} \dot{x} &= Ax + Bu, \\ y &= x. \end{aligned} \tag{3}$$

Therefore, C and D matrices are not required and aircraft model is formed with only A and B matrices as shown in Fig. 3. 'Boeing 747 Jet aircraft lateral dynamics model' subsystem shown in Fig. 3 has two inports, namely 1 (Rudder), 2 (Kx) and one outport ('x'). Two matrix gains are used for multiplication of $B \times u$ and $A \times x$ as required in Eq. (3). Input 'u' is the difference of two inputs, i.e. rudder input and control law (Kx) originating from controller subsystem (more details in Sec 4.5). Output 'x' vector consists of 4 states of aircraft. To observe all the four states, one multiplexer can be connected at output as done in Fig. 4.

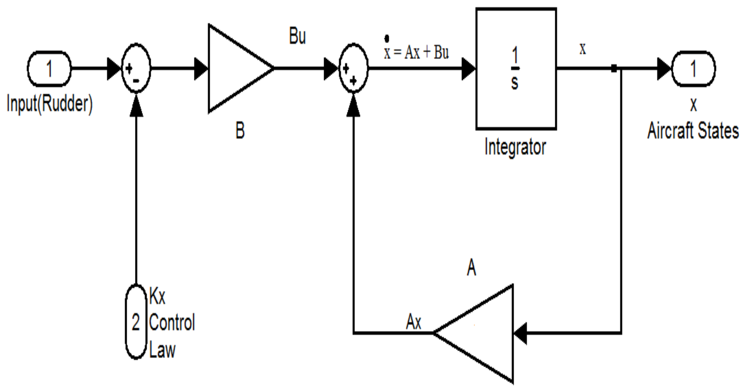

Fig. 3. Simulink model of jet aircraft model

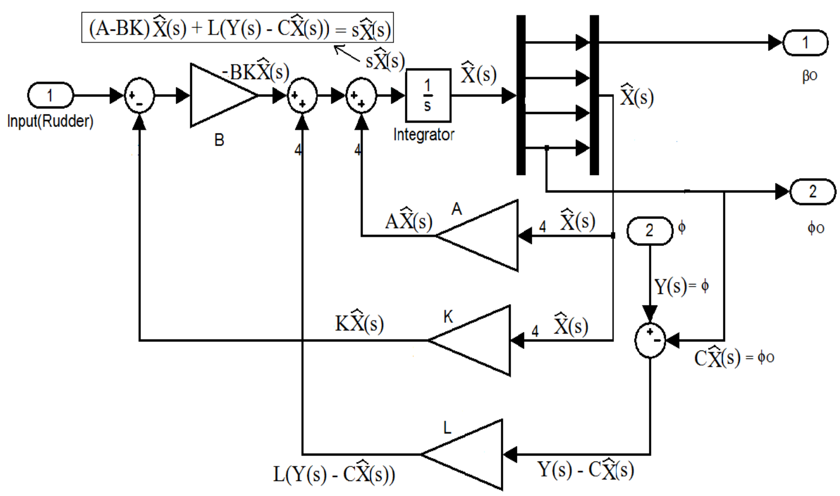

Fig. 4. Simulink model of observer

4.2 Observer subsystem

4.2.1 Definition and derivation

The observer is basically a copy of the plant; it has the same input and almost the same differential equation. An extra term compares the actual measured output y to the estimated output; $\hat{y}$ which will cause the estimated states '$\hat{x}$' to approach the values of the actual states x asymptotically. The error dynamics of the observer are given by the poles of (A-LC), where L is observer gain.

The plant model needs to be completely controllable and observable for the observer design. A system is called completely controllable if it is possible to transfer the system state from any initial state to any desired state in specified time by a control input. A system is called completely observable if every state can be completely identified by measurements of the outputs over a finite time interval. Controllability matrix and observability matrix of a state space system can be calculated using following MATLAB functions. After finding the matrices, their rank can also be calculated using following MATLAB function.

$$co = ctrb(A, B),\ ob = obsv(A, C),\ rank(co),\ rank(ob).$$

Rank of both controllability and observability matrix was found to be four which is same as rank of 'A' matrix. It proves that the plant model used here is completely controllable and observable. Sensor failure reduces rank of observability matrix and hence system becomes unobservable. SFDA system avoids this problem by providing estimate for failed sensor.

Observer for lateral dynamics of aircraft is designed and simulated in this work based on [14]. Observer design for longitudinal dynamics of F-8C aircraft was discussed in [14]. The reader may refer same for further details of observer design and simulation.

An approximation of lateral dynamics of Boeing 747 jet aircraft has been taken as the plant for the design of the controller and observer. Open loop response of the aircraft model was marginally stable with pole location at

$$p = [-0.0329 + 0.9467i - 0.0329 - 0.9467i - 0.5627 - 0.0073].$$

An Optimal controller was designed for the Boeing 747 jet aircraft model in [11] which was useful as efficient yaw damper. However, for this work feedback gain matrix K is designed using pole placement technique. Improvement in open loop response of aircraft was achieved by providing this feedback control law. The following MATLAB command was used for placing the poles of closed loop system at

$$pc = [-1.5108 - 1.2390 + 1.2861i - 1.2390 - 1.2861i - 1.0141],$$

$$[K, \text{prec}, \text{message}] = \text{place}(A, B, pc).$$

The feedback gain matrix (K) of Eq. (3) provides stable closed loop control system which is used for verification of SFDA.

$$K = \begin{bmatrix} 0.1453 & -0.5235 & -0.1598 & -0.1981 \\ -7.3737 & -6.3740 & 13.5923 & 12.5915 \end{bmatrix}. \tag{4}$$

Full order observer design was also done in MATLAB which can estimate the failed sensor state. If the observer and system states are $\hat{x}$ and x, then the difference between the outputs of the observer and system will be $C(\hat{x}(t) - x(t))$, so that the observer is given by

$$\dot{\hat{X}} = (A - LC)\hat{x}(t) + Bu(t) + Ly(t), \tag{5}$$

L is chosen such that (A-LC) has stable Eigen values placed further away (negatively) from the eigen values of A. The poles of (A-LC) are placed at $po = [-14.977 - 0.6350 + 0.8909i - 0.6350 - 0.8909i - 0.8200]$.

It can be observed that po is multiple times away from p. This was done for faster estimation by observer. As there is duality between controllability and observability, pole placement technique can be used to find the observer gain (L) matrix. If po is the desired set of poles, the following function is used to obtain the matrix L in '$.m$' file of MATLAB.

L =place (A', C', po). Using MATLAB function, L is found to be

$$L = \begin{bmatrix} -5.1977 \\ -1.8303 \\ 22.3035 \\ 16.4313 \end{bmatrix}. \tag{6}$$

The observer is realized by obtaining the Laplace transform of Eq. (4) and substituting $u = -K\hat{x}$, K being the control law given in Eq. (3). Observer equation in Laplace domain is thus given by Eq. (6) where, $Y(s)$ and $C\hat{X}(s)$ are the system and observer outputs for the available healthy sensor state.

$$s\hat{X}(s) = (A - BK)\hat{X}(s) + L\big(Y(s) - C\hat{X}(s)\big). \tag{7}$$

4.2.2 Modelling and simulation

The sensor output of 'Boeing 747 jet aircraft lateral dynamic model' consists of β and ϕ. When β sensor fails, it affects the ϕ state also as shown in Fig. 11. 'ϕ' state is affected because of faulty state vector, 'xFaulty' present in feedback loop.

Observer design is based on the assumption that at least one of the sensor outputs, viz ϕ is healthy and available to estimate the failed sensor signal. Observer uses affected ϕ state [$Y(s)$] from the plant to estimate β state as shown in Fig. 4. Thus the observer has two outputs as estimated states (βO & ϕO) and two inputs (Rudder input & affected 'ϕ' sensor output from aircraft model).

Eq. (6) is simulated in Fig. 4 with the help of blocks from Simulink library browser. Modelling of Observer requires A, B matrices of aircraft, control law K of controller and L matrix designed for observer. The flow of signals and signal at each node can be seen in Fig. 4 to understand the simulation of observer Eq. (6). As $\hat{x}(s)$ has four states, demux is required to extract four state signals separately. Out of these four signals, 'βO' and 'ϕO' are the two outputs of observer. Mux is required to bring the four states together as required for feedback.

4.3 Fault induction subsystem

Fig. 2 shows induction of stuck fault where 'x' state vector is taken from 'Boeing 747 Jet Aircraft Lateral Dynamics' subsystem to fault induction subsystem. In fault induction subsystem, 'β' state is extracted out of 'x' state vector using demux as shown in Fig. 5. 'β' sensor signal is passed through fault introducer and faulty signal 'β' is multiplexed back with other three healthy sensor states using mux to form xFaulty. Signal xFaulty is erroneous state which is fed from fault induction subsystem to rest of the subsystems. Induction of stuck fault is done at 10 s as shown below:

$$\text{Output} = \begin{cases} \text{aircraft sensor output,} & t < 10s, \\ \text{stuck sensor signal,} & t \geq 10s. \end{cases} \tag{8}$$

Fault induction is done with the help of N-sample switch as shown in Fig. 5. It is explained with the following if-else statement.

If $t < 10s$, output = up input port (healthy signal) else output = down input port (stuck signal, '0')

The sample time is 0.02 s in the model and $N = 500$ in N sample switch. Fig. 5 shows 'β' sensor stuck at value of '0' at 10 s i.e. (0.02×500). This forces β sensor value to get stuck at '0' after $t \geq 10$ s. Fault can be induced at any time and for any value using this N sample switch block of Simulink tool.

Once error is induced at any predefined time, the output states (β and ϕ) cross the specified limits of safe operation as seen in Fig. 11. The state 'x' vector also becomes faulty (xFaulty) which goes from fault induction block to controller block in Fig. 13. Fig. 6 shows the modified fault induction subsystem which is capable of inducing intermittent stuck fault. This is done with the help of two N-Sample switches. The flow of signal can be analyzed in the diagram which induces stuck fault between 6 to 10 s. SFDA plot is shown in Fig. 16.

4.4 Reconfiguration subsystem

The fault detection and reconfiguration is done with the help of an observer and signature using Canberra metric[14]. The value of 'βO' is obtained from the observer estimated output and is compared with 'β' sensor value of aircraft. For detecting β sensor failure, the signature Canberra metric S is used which is given by Eq. 7. Here 'T' is the sampling interval.

$$S(t) = \frac{\beta(t) - \beta O(t)}{\beta(t) + \beta O(t)},\ t = nT(T; \text{Sampling period}), \tag{9}$$

$$\frac{S + (\frac{2}{T})}{\frac{s(2-W)}{W} + \frac{z}{T}} = \frac{s + 100}{9s + 100}. \tag{10}$$

Eqs. (7) and (10) are simulated along with 'switch' and 'Abs' block to form Reconfiguration subsystem as shown in Fig. 6. Reconfiguration subsystem is explained below:

(1) Eq. (7) is simulated in Reconfiguration subsystem's Canberra metric block and its detailed simulation model is shown in Fig. 8 which is self-explanatory. It compares 'β' from 'Boeing 747 jet aircraft lateral dynamics' and estimated 'βO' from 'observer' and generates signal S.

(2) Signal S is smoothened using "Filter" block of 'Reconfiguration' subsystem which follows Eq. (10).

(3) Simulation of the filter is done by using transfer function block of Simulink which implements Eq. (10).

(4) The output of 'Abs' block of the subsystem gives absolute value of the input. This is the threshold value which is used to indicate the fault in fault indicator scope. Threshold value of more than '0.8' of 'Abs' block indicates fault occurrence.

(5) The fault indicator signal is also used as control signal for reconfiguration in switch as shown in Fig. 7. This control signal of Switch is the output of 'Abs' block. Switch operates the following equation.

$$\beta out = \begin{cases} \beta, & |Abs| < 0.8, \\ \beta O, & |Abs| \geq 0.8. \end{cases} \tag{11}$$

It is executed with the following if-else statement in Simulink switch block.

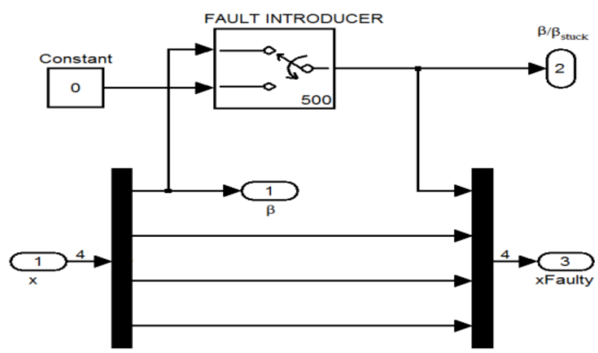

Fig. 5. Simulink model of fault induction subsystem

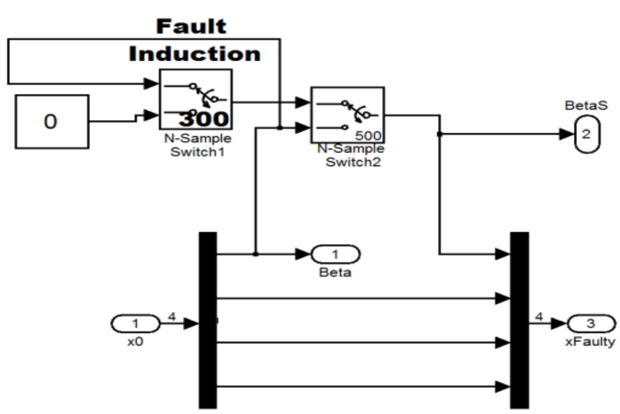

Fig. 6. Intermittent stuck fault model

If $|Abs| \geq 0.8$, $\beta out = \beta O$, else $\beta out = \beta$; Reconfiguration is done as soon as fault is detected by switching over to estimated 'βO' from 'Observer' subsystem.

4.5 Controller subsystem

Controller subsystem is used to provide control law in the feedback loop of the plant. Design of control matrix K was discussed in Section 4.2.1 and K matrix is given in Eq. (3). 'Controller' subsystem has two inputs (βOut & xFaulty) and two outputs (x & Kx) as shown in Fig. 2 and 9. Detailed simulation diagram of 'Controller' subsystem is given in Fig. 9. It is performing two tasks:
(1) It provides feedback gain matrix K (control signal) which is designed using MATLAB script file and given in Eq. (3). State vector 'x' is matrix multiplied with feedback gain matrix K and forms one of the outputs of 'Controller' subsystem at outport 2.
(2) Controller also performs the task of reconfiguring corrected β (βOut) which is used to correct faulty state vector 'xFaulty' in case of fault. This is done by using demux to extract four signals from xFaulty as shown in Fig. 9. Reconfigured β Out is multiplexed with other three healthy states of xFaulty to form corrected state vector 'x', which is then fed back to 'Boeing 747 Jet Aircraft lateral dynamics' subsystem and forms outport 1. The 'β' sensor state from xFaulty is terminated using Terminator block.

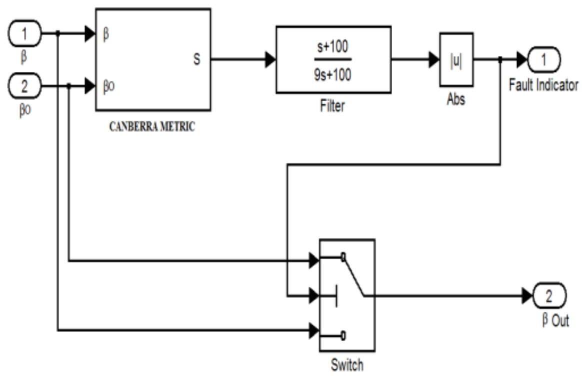

Fig. 7. Reconfiguration subsystem

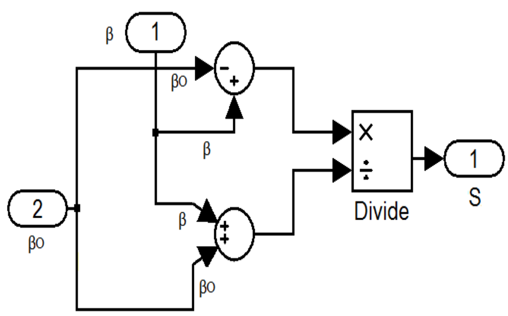

Fig. 8. Canberra metric model

5 Discussion of results

Out of the two inputs, only rudder is actuated with command of '0.3'radians amplitude for $20s$ as seen in main simulation model of Fig. 2. Rudder input command function is as follows:

$$\text{Rudder Input} = \begin{cases} 0.3\,rad, & 0 \leq t \leq 20s, \\ 0\,rad, & t \geq 20s. \end{cases} \quad (12)$$

The stable sensor output (β & ϕ) with rudder input command is shown in Fig. 10 for healthy scenario.

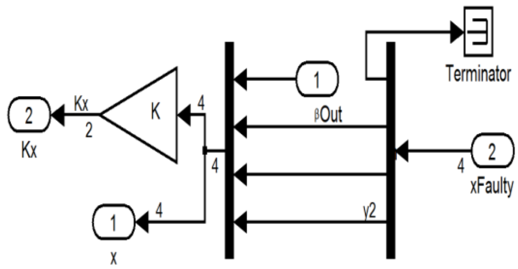

Fig. 9. Controller subsystem

For the simulation, Fault is introduced for sideslip angle sensor ‘β’. ‘Reconfiguration’ subsystem will accommodate this fault with the help of ‘Observer’ and ‘Controller’ subsystem. Stuck fault of ‘0’ and less than zero stuck faults (for specified input) can be detected by the fault indicator of the model.

Stuck fault of ‘0’ is introduced at 10 s using ‘Fault Induction’ subsystem. Fig. 11 shows the scenario when the fault is not addressed to. If detection of fault and reconfiguration does not take place, aircraft crosses the limits of safe operation. It can be seen that stuck fault in β sensor affects ϕ sensor also. This is because of faulty state vector, ‘xFaulty’ in feedback loop through controller. This explains that sensor fault accommodation should be done in time. Otherwise, it can lead to closed-loop instability and unrecoverable flight conditions. ‘Observer’ subsystem successfully estimates the two sensor outputs for input rudder command. Fig. 12 shows the estimated observer states with rudder command of ‘0.3’ rad.

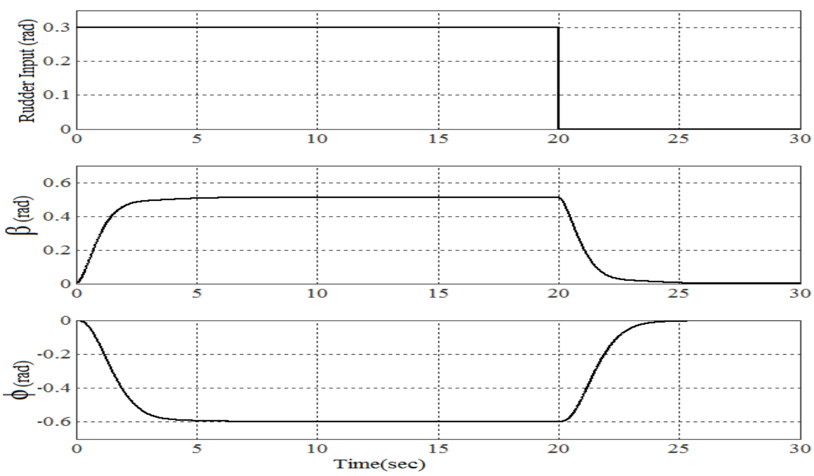

Fig. 10. Healthy scenario

First plot of Fig. 13 shows that stuck fault of ‘0’ was introduced at 10 s. Fault is successfully detected as shown in second plot. Fault reconfiguration for failed sensor is shown in third plot. Forth plot of Fig. 13 shows that with proper accommodation of fault, the other aircraft sensor output (ϕ) also remain in stable region of operation. Reconfiguration is clearly seen in Fig. 13 as there is slight shift in the stable state around 10 s. Fig. 14 shows the SFDA system for stuck fault of ‘-0.1’. Fig. 15 shows input, fault introduction at 10 s, reconfigured state and estimated observer state together in the same scope. Fig. 16 shows SFDA plot for Intermittent stuck fault from 6 to 10 s. SFDA system works for stuck faults at any time instants and for stuck value of ‘0’ and lesser than zero values.

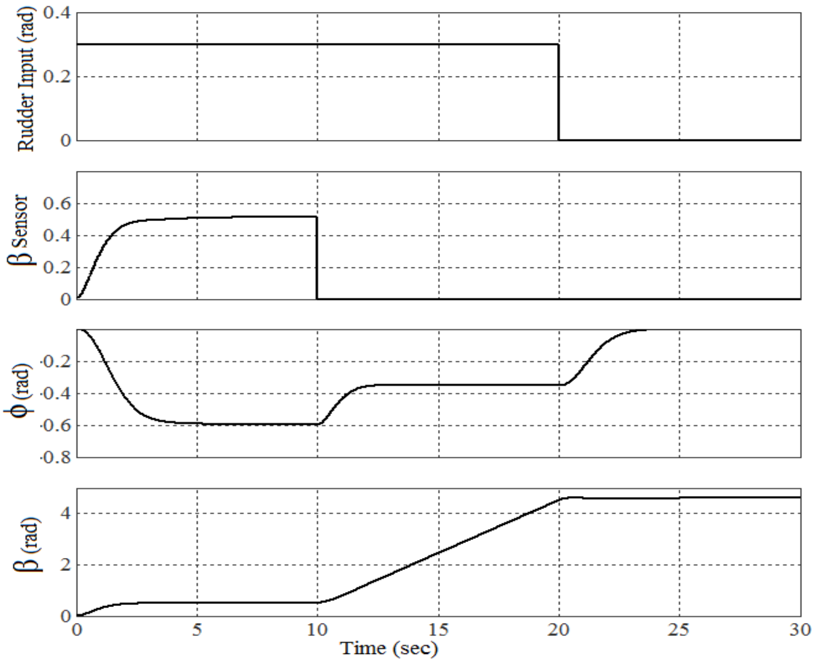

Fig. 11. Fault without reconfiguration

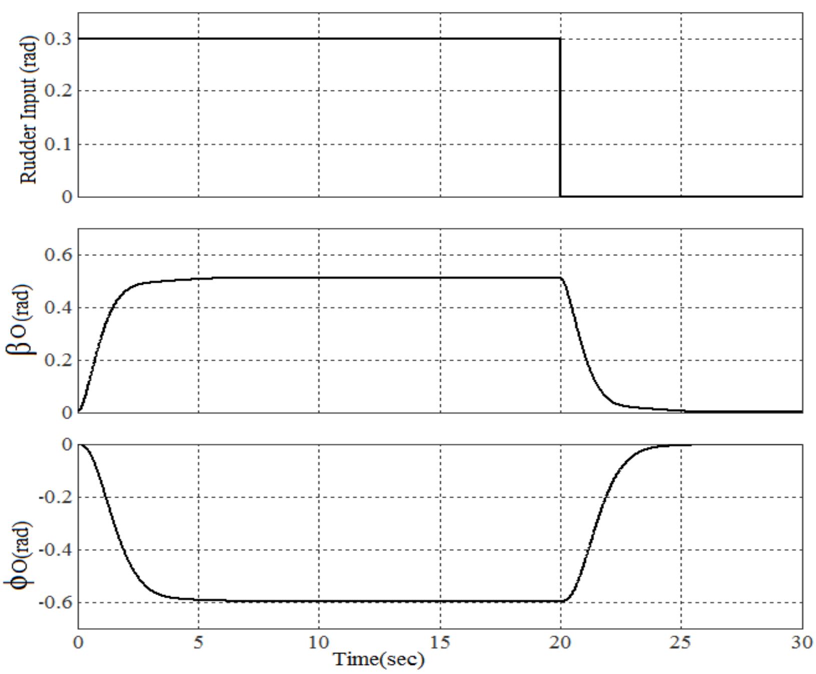

Fig. 12. Observer estimated states

6 Conclusion

Modelling and simulation software plays a significant role in the development of sensor fault accommodation in FCS. Therefore, an insight to SFDA system using Simulink for a transport aircraft is presented. SFDA is developed for lateral dynamics of Boeing 747 jet aircraft. Models were developed for 'Boeing 747 jet aircraft lateral dynamics', 'Controller', 'Observer', 'Fault Induction' and 'Reconfiguration' subsystems. Controller was developed using pole placement method and Observer was developed using Luenberger's method in MATLAB. Canberra metric was used for fault detection.

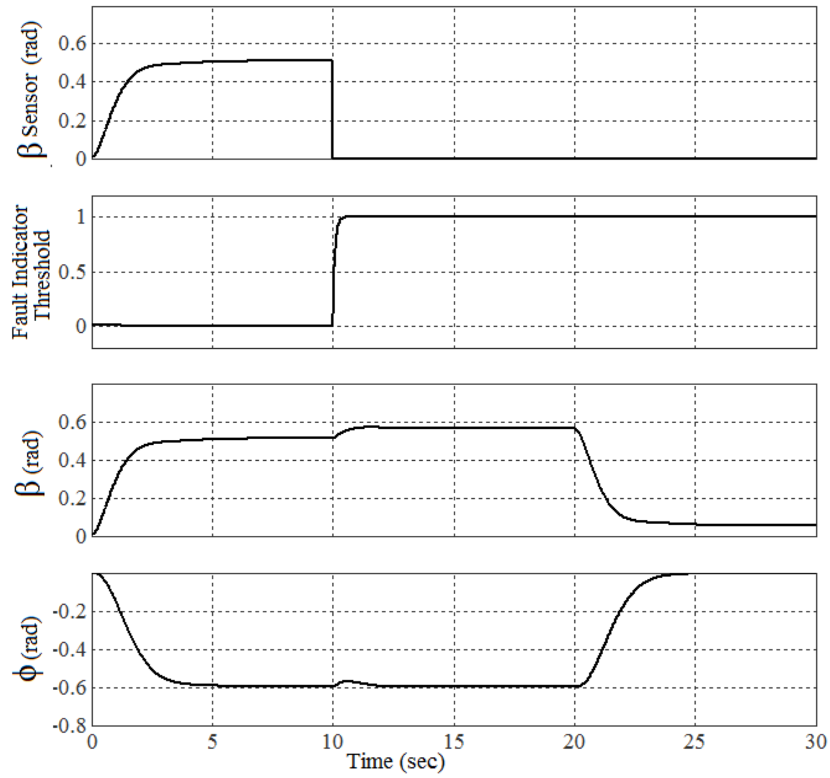

Fig. 13. SFDA for stuck '0' fault

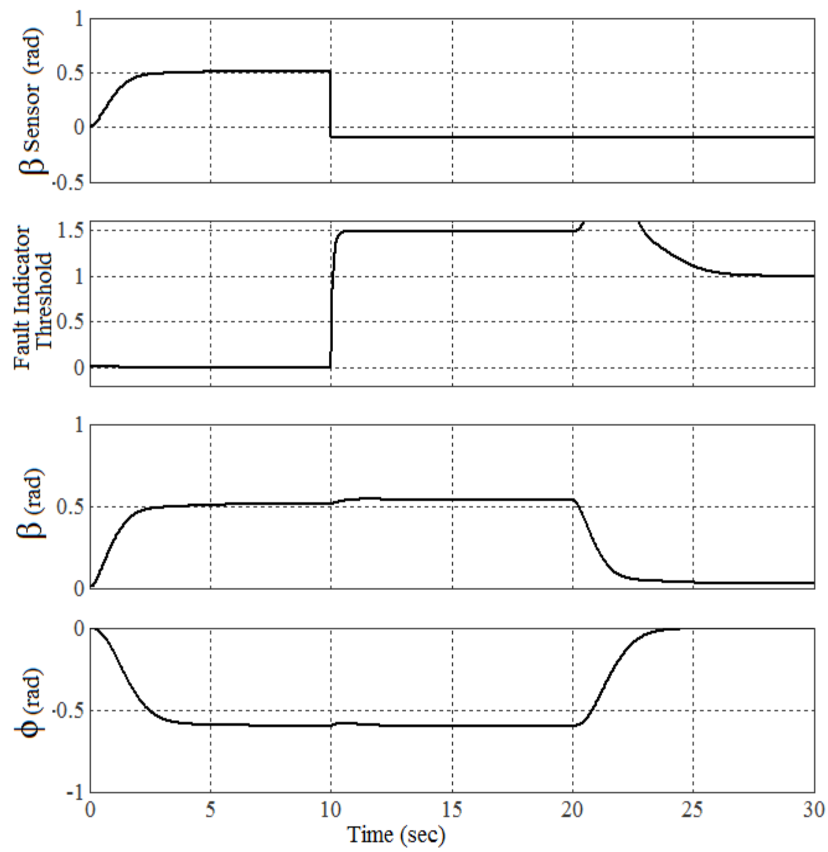

Fig. 14. SFDA for stuck '-0.1' fault

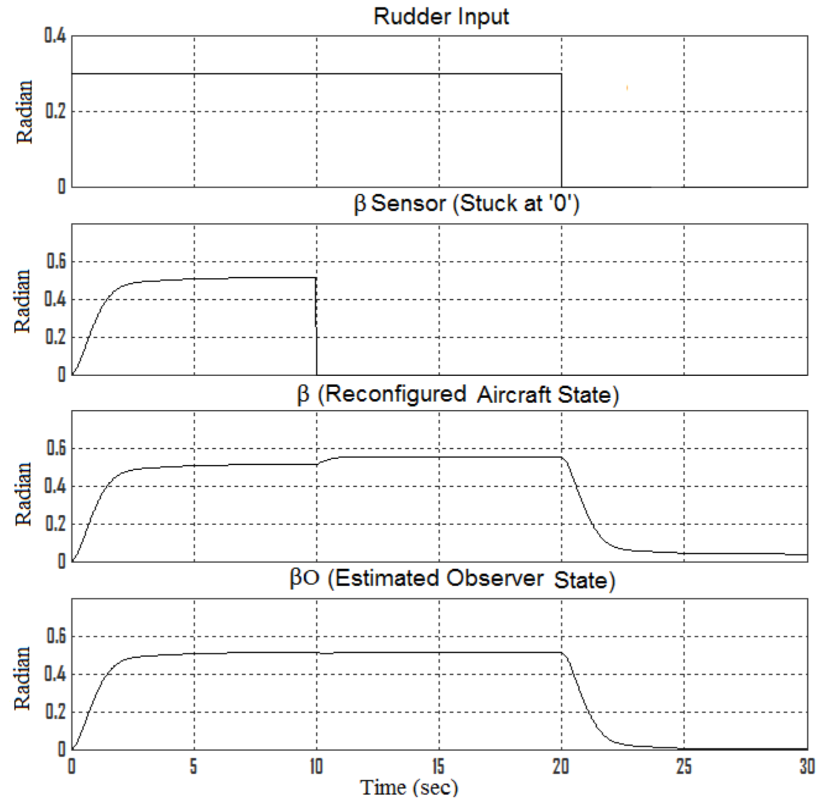

Fig. 15. SFDA and observer states

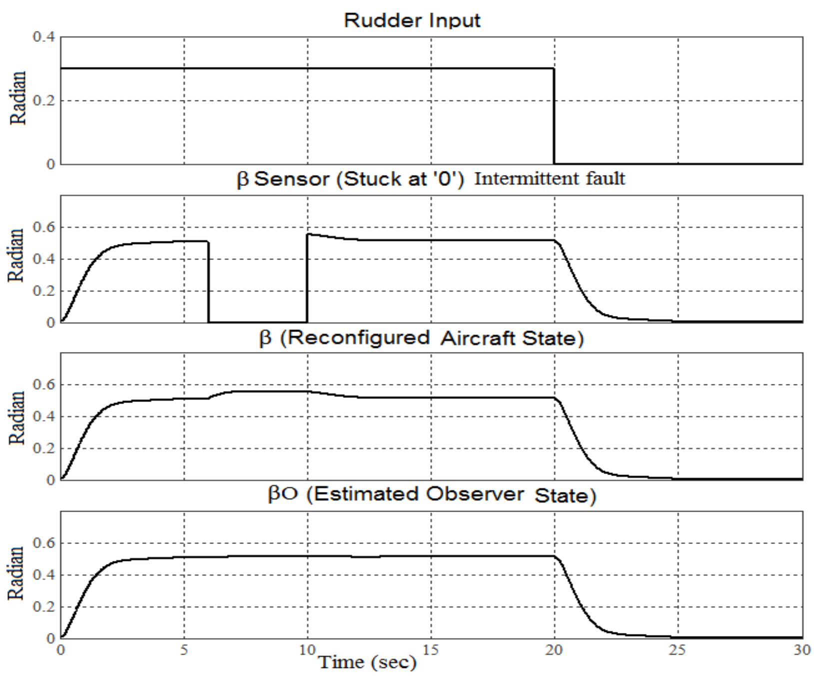

Fig. 16. Intermittent stuck fault

Luenberger observer developed was used for analytical redundancy for sideslip angle (β) sensor of lateral dynamics model of Boeing 747 jet aircraft. Observer reconfigure with the remaining available sensor output of bank angle (ϕ) which is considered to be healthy.

The five subsystems are developed and configured together in main simulation model to show the complete system of sensor fault tolerant FCS. Stuck fault induction and its reconfiguration in FCS were simulated to demonstrate successful implementation of SFDA system. This approach may be useful for validation or implementation on DSP processors by using hardware in loop simulation.

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