Fault Detection of Re-Entry Vehicle Control Surface using Multiple Model Method

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Abstract: ***Over the last three decades, the growing demand for safety, reliability, maintainability and survivability in technical systems has drawn significant research in Fault Detection and Diagnosis (FDD). Such efforts have led to the development of many FDD techniques. Several review/survey papers on Fault Detection and Diagnosis have appeared since the 1990s.The present work is to detect the fault of the control surface of a Re-Entry Vehicle during its descent phase. Fault Detection study is carried out for the Longitudinal Plane. Model Based Method is implemented to detect the Fault in the Re-Entry Vehicle and the Detection Time is calculated based on the Probability Threshold. It is planned to develop the model based fault detection algorithm, applied to the longitudinal plane of the reentry vehicle.***

Keywords: Re-Entry Vehicle, Multiple Model Method, FTC, Longitudinal Plane, Process Noise, Measurement Noise.

1. Introduction

Detection and diagnosis of faults in complex plants is one of the most important task assigned to the system supervising that plant. The early indication of faults can help avoid major catastrophes, ones that could otherwise result in substantial material damage.

Fault detection is very important in airplanes, space vehicles, nuclear power plants, industrial plants. In the case of airplanes if an actuator or control surfaces fails to function as required, the vehicle may become uncontrollable. Similarly sensor failure would present incorrect action which can lead to instability. Thus, the timely detection of this kind of fault is essential to ensure safety of the system.

A significant amount of research on Fault Tolerant systems is motivated by aircraft designs. The goal is to provide "self repairing" in order to ensure a safe landing in the event of severe fault in the aircraft [1]. Such effort has been simulated partly by two commercial aircraft accidents in the late 1970s.

The passive fault tolerant control for systems subjected to failures is available in literature [2] - [7]. A state feedback output tracking adaptive control scheme for a linear system with unknown actuator failures (actuator stuck at unknown values at unknown times) is proposed in [2]. Despite the uncertainties in actuator failure and plant parameters, the plant output could track a given reference output asymptotically.

The active Fault Tolerant Control (FTC) identifies faults in real time and accommodates it either by controller reconfiguration or control reallocation. Thus, implementing active FTC requires a fault detection and isolation module in the first place.

There are mainly two approaches for fault detection and isolation namely,

1. Methods that do not need a plant model.
2. Methods that require the use of plant model.

Model free methods that were used mainly are,

1. Limit Checking: The plant measurements were compared against preset limits and exceeding the limit indicates failure.
2. Using Special Sensors: The special sensors were implemented limit checking in hardware.
3. Using multiple Sensors: The sensor failures could be detected using this approach. Multiple sensors were used to get same measurements and these measurements are compared.
4. Frequency analysis of plant measurements: Any deviation from normal behavior in the frequency analysis of measurements is an indication of a failure.
5. Expert system approach

Three methods of fault detection and isolation in Re-entry Vehicles are mainly available, which are,

- Multiple Model Based Methods
- Observer Based Methods
- Neural Network Based Methods

Observer based linearized aircraft model for residual generation and control reallocation scheme using control mixer approach was demonstrated in 1989 by Petros Ioannou and R.Rooney. It used a compensating input signal to accommodate the faults. This could estimate the control surface stuck position correctly and could detect multiple faults.

The fast active fault tolerant control using Adaptive Fault Diagnosis Observer (AFDO) is studied in [15]. A Fast Adaptive Fault Estimation (FAFE) algorithm was proposed to enhance the performance of fault estimation. Using the fault information, the observer based fault tolerant controller is designed to compensate for the loss of actuator effectiveness by stabilizing the closed loop system. This method has been successfully applied for the fault tolerant control of launch vehicle.

Multiple Model method uses multiple models of the system for Fault Detection and Isolation. One of the models represents the fault free case and all the others represents system model in case of a particular fault. The current state of the system is compared with the models and the model that has close relation with the state of the system will be used to represent the system. In case of multiple model method there will not be any interactions between the models. In Interactive multiple model method the different models will interact with each other to form.

Model Based Methods can use either parameter estimation method or state estimation method. The parameter estimation method is used for systems that are subjected to multiplicative faults and State estimation methods are used for additive faults. State Estimation methods can be used for faults related to actuator, sensors etc. State estimation can be done using Kalman Filter or using an observer.

Organization of the Research paper is as follows: Mathematical Modeling of the Re-Entry Vehicle is studied in Section 2. Implementation of the Multiple Model Method and the Algorithm used for Implementation is briefed as part of Section 3. Section 4 covers the MATLAB implementation results of the entire study.

2. Mathematical Modeling of Re-Entry Vehicle

2.1 About Re-Entry Vehicle

A Re-Entry Vehicle refers to a vehicle which can be used for several missions. Once when a Re-Entry Vehicle completes a mission, it returns to the earth and can be used again whereas the Expendable Launch Vehicles (ELV) can be used only once. This is the main advantage of a Re-Entry Vehicle and this can be done at very low cost. Since the Re-Entry Vehicles are reused, the technical difficulties in designing such a system are immense. The flight control of reusable launch vehicles in various phases involve attitude maneuvering through a wide range of flight conditions, wind disturbances and plant uncertainties. Control of the dynamics of a Re-Entry Vehicle has gained importance owing to the improvement in its performance. Design of such control systems is not an easy task as their dynamics are highly nonlinear.

2.2 Flight Dynamics

The flight dynamics of a Re-Entry Vehicle are described by its equations of motion (EOM). The dynamics of Re-Entry Vehicle is similar to that of an Aircraft. The equations of motion for a flight vehicle usually are written in a body-fixed coordinate system. It is convenient to choose the vehicle centre of mass as the origin for this system, and the orientation of the system of coordinate axes is chosen by convention.

- The x-axis lies in the symmetry plane of the vehicle and points forward
- The z-axis lies in the symmetry plane of the vehicle, is perpendicular to the x-axis, and points down
- The y-axis is perpendicular to the symmetry plane of the vehicle and points out the right wing

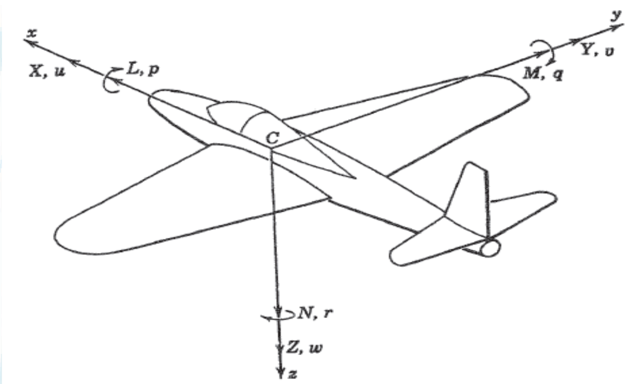

Figure 2.1: Body-Fixed Coordinate System of an Aircraft

Where,
p = Rotation rate about x-axis i.e. roll rate
q = Rotation rate about y-axis i.e. pitch rate
r = Rotation rate about z-axis i.e. yaw rate
X = Total Axial Force in the positive x-direction
Y = Total Side Force in the positive y-direction
Z = Total Normal Force in the positive z-direction
L = Total Rolling Moment in the positive p-direction
M = Total Pitching Moment in the positive q-direction
N = Total Yawing Moment in the positive r-direction
u = velocity in the x direction
v = velocity in the y direction
w = velocity in the z direction

An Re-Entry Vehicle has six degrees of freedom (if it is assumed to be rigid), which means, it has six paths it is free to follow: it can move forward, sideways, and down; and it can rotate about its axes with yaw, pitch, and roll. In order to describe the state of a system that has six degrees of freedom, values for six variables (unknowns) are necessary. To solve for these six unknowns, six simultaneous equations are necessary.

In order to simplify the flight dynamics equations, there are few assumptions that need to be made, they are,

- Earths curvature is zero.
- Aircraft has constant mass (dm/dt = 0).
- Aircraft is a rigid body.
- Turbulence and gusts are ignored.
- Aircraft is symmetric.
- There are no rotating masses.

The full aircraft equations of motion reflect a rather complicated relationship between the forces and moments on the aircraft, and the resulting aircraft motion. The derivation of the equations, however, follows a very simple pattern starting from Newton's second law for translational and rotational motions.

Newton's Second law for translational motion is [31],

$$\bar{F} = \frac{d}{dt}(m\bar{v})$$

Where $\bar{F}$ is the sum of externally applied forces and $m\bar{v}$ is the linear momentum.

Newton’s Second law for rotation motion is [31],

$$\bar{M} = \frac{d}{dt}(\bar{H})$$

Where $\bar{M}$ is the sum of externally applied moments and $\bar{H}$ is the angular momentum.

$\bar{F}$ And $\bar{M}$ are both vector quantities which can each be represented by three component equations (corresponding to three dimensional spaces). The translational equation, therefore, describes the aircraft with respect to its three translational degrees of freedom, while the rotational equation describes the aircraft with respect to its three rotational degrees of Freedom. Newton's second law, therefore, yields six equations for the six degrees of freedom of a rigid body.

2.3 Longitudinal Equations of Motion

$$F_X = m(\dot{u} + qw - rv)$$
$$F_Z = m(\dot{w} + pv - qu)$$
$$\bar{M} = \dot{q}I_y - pr(I_Z - I_X) + (p^2 - r^2)I_{ZX}$$

2.4 Nonlinear equations of motion in Longitudinal Plane

Although the force acting on the y direction is assumed as zero, this is not the case with the linear velocity along the y direction and hence the same will have some effect on the total vehicle velocity.

The nonlinear equations of motion of the Re-Entry Vehicle in longitudinal plane is described by the a set of four equations, namely, $\dot{u}, \dot{w}, \dot{\theta}$ and $\dot{q}$.

$$\dot{u} = F_x/m + rv - qw + g_{xb}$$
$$\dot{v} = F_y/m + pw - ru + g_{yb}$$
$$\dot{w} = F_z/m - pv + qu + g_{zb}$$

where,

$$\begin{bmatrix} g_{xb} \\ g_{yb} \\ g_{zb} \end{bmatrix} = [ItoB] \begin{bmatrix} g_{xI} \\ g_{yI} \\ g_{zI} \end{bmatrix}$$

where,

g_{xb}, g_{yb}, g_{zb} - Gravitational acceleration components in body axis

ItoB - Inertial to Body axis transformation

g_{xI}, g_{yI}, g_{zI} - Gravitational acceleration components in earth axis

The rate of pitch angle can be represented as,

$$\dot{\theta} = (q\cos\phi - r\sin\phi)/\cos\varphi$$

2.5 Observation Equations

The measurement or observation equations are as below,

$$V_R = \sqrt{u_a^2 + v_a^2 + w_a^2}$$

The angle of attack , α is given by,

$$\alpha = \arctan\left(\frac{w_a}{u_a}\right)$$

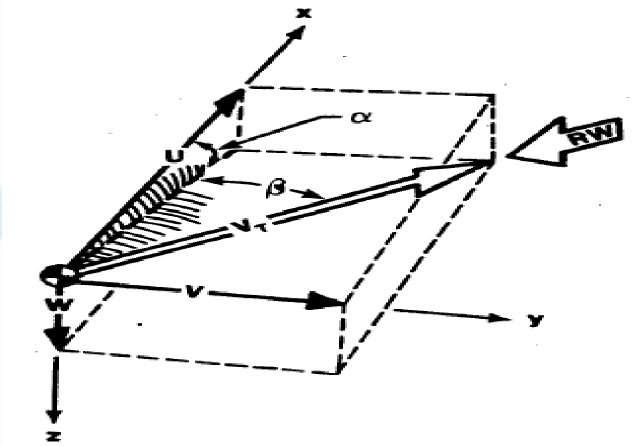

Figure 2.4: Velocity Components and Aerodynamic Orientation Angles

$$\begin{bmatrix} u_a \\ v_a \\ w_a \end{bmatrix} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} - (ItoB)(\Omega \times r)$$

where,

r- Vehicle location with respect to the earth frame

Ω - Angular rotation speed of earth given by,

$$\Omega = [0.0 \quad 0.0 \quad 7.292115E-5]\,rad/s$$

The measurements of θ and q are available directly.

The nonlinear model of reentry vehicle in longitudinal plane is obtained with the states as q, V_R, θ, α are chosen as measurement variables and the observation equations are also selected.

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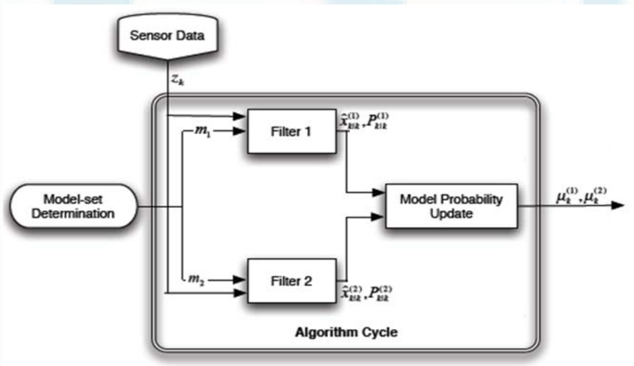
3. Implementation of Multiple Model Method

Multiple Model Algorithm use more than one model to estimate the current state of the system. Each model will be assigned a probability based on the current state of the system. The model having the highest probability at any given time will be considered as the current state of the system.

3.1 Multiple Model Method Algorithms:

Time Update	
Model Filtering	
Predicted State	$\hat{x}^{(i)}_{k\|k-1} = F^{(i)}_{k-1}\hat{x}^{(i)}_{k-1\|k-1}$
Predicted Covariance	$P^{(i)}_{k\|k-1} = F^{(i)}_{k-1}P^{(i)}_{k-1\|k-1}(F^{(i)}_{k-1})' + Q^{(i)}_{k-1}$
Measurement Residual	$\tilde{z}^{(i)}_k = z_k - H^{(i)}_k\hat{x}^{(i)}_{k\|k-1}$
Residual Covariance	$S^{(i)}_k = H^{(i)}_k P^{(i)}_{k\|k-1}(H^{(i)}_k)' + R^{(i)}_k$
Filter Gain	$K^{(i)}_k = P^{(i)}_{k\|k-1}(H^{(i)}_k)'(S^{(i)}_k)^{-1}$
Update State	$\hat{x}^{(i)}_{k\|k} = \hat{x}^{(i)}_{k\|k-1} + K^{(i)}_k\tilde{z}^{(i)}_k$
Update Covariance	$P^{(i)}_{k\|k} = P^{(i)}_{k\|k-1} - K^{(i)}_k S^{(i)}_k (K^{(i)}_k)'$
Model Probability Update	
Model Likelihood	$L^{(i)}_k \overset{assume}{=} \mathcal{N}(\tilde{z}^{(i)}_k;0,S^{(i)}_k)$
Model Probability	$\mu^{(i)}_k = \frac{\mu^{(i)}_{k-1}L^{(i)}_k}{\sum_j \mu^{(j)}_{k-1}L^{(j)}_k}$

3.2 Block Diagram of Multiple Model Method Implementations



4. Simulation Results and Discussions

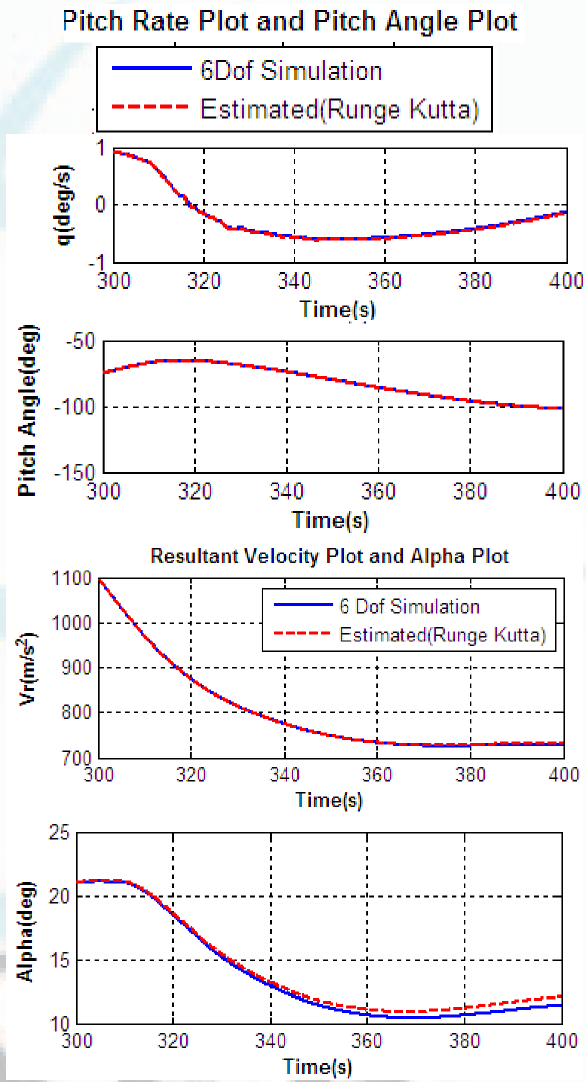
In order to implement the model based methods, the longitudinal plane mathematical model is implemented in MATLAB. Fourth order Range Kutta Method with a sample time of 0.02s is used for integration in MATLAB. The response obtained is then compared six Degree of Freedom Simulation Software.

Simulation Results include the following plots:

- Pitch Rate Comparison
- Pitch Angle Comparison
- Resultant Velocity Comparison
- Angle of Attack Comparison

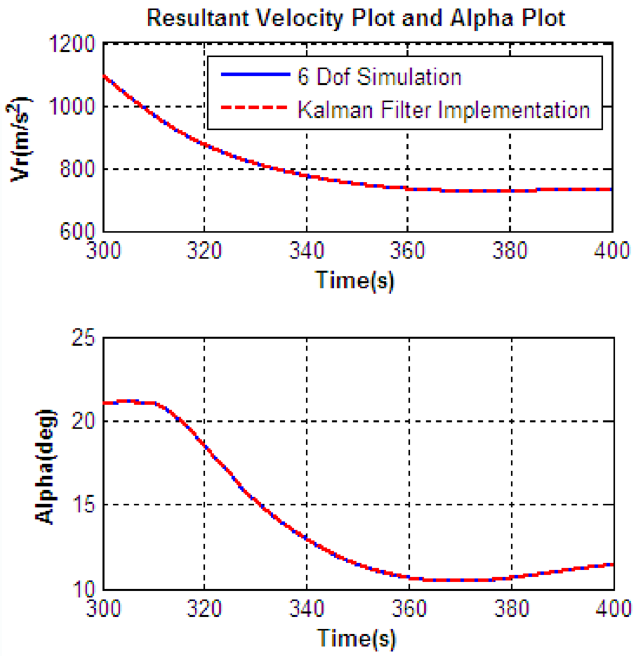
The below simulation Result are obtained for the interval 200s to 800s

4.1 Simulation Results of Runge Kutta Implementation



From the above Alpha plot it can be observed that the estimated is not very close to the Software Simulated data. Hence using Kalman Filter the above offset can be eliminated.

4.2 Results of Kalman Filter Implementation



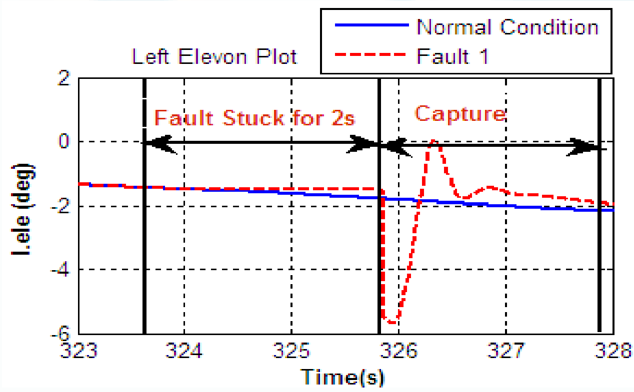
Results after Kalman Filter implementation for various values of Process Noise and Measurement Noise are found to match closely with the 6DoF Simulation Software.

4.3 Implementation of Multiple Model Method

Multiple Model Method Implementation is studied for the 2 Model System. Model 1 is considered as the Normal Model and Model 2 is considered as the Faulty Model. The Fault is injected into the system using the 6 DoF Simulation Software.

Faulty Condition considers Left elevon to be stuck at -1.5 at 323.8th second and the elevon is stuck for 2 seconds.

The Faulty Condition Characteristics are shown below.



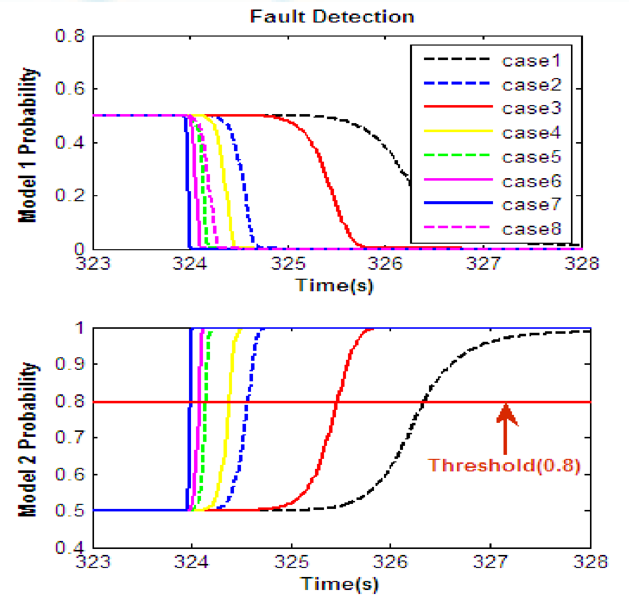
Multiple Model Method is implemented to detect the above fault in the system.

Fault Detection Time is calculated for various values of Process Noise and Measurement Noise.

Below are some of the cases considered for the Study.

- Case 1: Q=I, R=0.1 and higher
- Case 2: Q=I, $R=(0.001)^3I$
- Case 3: Q=(0.1)I, R=0.001
- Case 4: Q=(0.1)I, $R= (0.001)^3I$
- Case 5: $Q=(0.01)^2I$, $R= (0.001)^3I$
- Case 6: $Q=(0.01)^2I$, $R= (0.001)^4I$
- Case7: $Q= (0.001)^2I$, R=0
- Case8: Q=0, $R= (0.001)^2I$

Where,
- Q – Process Noise Covariance Matrix
- R – Measurement Noise Covariance Matrix



- Case **1** and **2** considers the Q matrix as identity matrices and hence are not realistic.
- Cases **7** and Case **8** considers Q Matrix to be zero and R Matrix to be zero respectively, which is not so in real case.
- Considering Cases **3** to Case **6**, it can be concluded that the least time required for detecting the elevon stuck failure is at **324.08s** ,i.e. with a delay of **0.28s**

5. Conclusion

The study of basics of Re-Entry Vehicle, System dynamics of Re-Entry Vehicle and implementation of the system dynamics in MATLAB are successfully completed in this study. Multiple Model Method implementations is carried out to detect the fault in the system and it is found that the fault can be detected within 0.28s of its occurrence.

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