Prevention of Loss of Control in the event of Actuator Failure using MPC

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DECLARATION

We hereby *declare* that the Project Work Report entitled **Prevention of Loss of Control in the event of Actuator Failure using MPC** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** for the award of the Degree of Bachelor of Technology in **Mechanical Engineering** is a *bonafide report of the work carried out by us.* The material contained in this Project Work Report has not been submitted to any University or Institution for the award of any degree.

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ABSTRACT

Loss of Control is a serious problem and has been identified as the single largest cause for most number of aircraft accidents. It can be caused by various factors, one of which is actuator failure. Authors have developed a Model Predictive Control system to prevent the condition of LOC in the event of an actuator failure by returning the flight back to the trim conditions. Elevator jam has been demonstrated wherein MPC tracks the flight path angle to zero for stable level flight. MPC is applied to the six degrees-of-freedom twelve state nonlinear model of the F-18 HARV aircraft which was developed on MATLAB to validate the performance of the control system. The results obtained are shown and analysed.

Keywords: *Loss of Control, Model Predictive Control, Actuator Failure, Aircraft Control, Flight Dynamics*

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Nomenclature

Abbreviations

CAST Commercial Aviation Safety Team

CFIT Controlled Flight in Terrain

CICTT CAST/ICAO Common Taxonomy Team

HARV High Alpha Research Vehicle

ICAO International Civil Aviation Organization

JSAT Joint Safety Analysis Team

LOC-I Loss of Control - In Flight

MPC Model Predictive Control

NASA National Aeronautics and Space Administration

NTSB National Transportation Safety Board

PID Proportional Integral Derivative

PIO Pilot Induced Oscillations

Symbols

α Angle of attack, *rad* for computation, *deg* for display

$\bar{c}$ Mean Aerodynamic Chord, ft

$\bar{q}$ Dynamic Pressure, lbs/ft^2

$\bar{R}$ Tuning parameter diagonal matrix, *unit*

β Side slip angle, *rad* for computation, *deg* for display

ΔU Change in manipulated variable value, *unit*

δ_a Aileron control, *rad* for computation, *deg* for display

δ_e Elevator control, *rad* for computation, *deg* for display

δ_r Rudder control, *rad* for computation, *deg* for display

δ_T Thrust control, *lbs*

ϕ Roll angle, *rad* for computation, *deg* for display

ψ Yaw angle, *rad* for computation, *deg* for display

ρ Density, $slug/ft^3$

θ Pitch angle, *rad* for computation, *deg* for display

b Wing span, ft

g Gravitational constant, ft/s^2

h Altitude, ft

I_{xx} Roll Axis Moment of Inertia, $slug.ft^2$

I_{xz} Cross Product of Inertia about y axis, $slug.ft^2$

I_{yy} Pitch Axis Moment of Inertia, $slug.ft^2$

I_{zz} Yaw Axis Moment of Inertia, $slug.ft^2$

J Cost function, *unit*

m Mass, *slug*

p Roll rate, rad/s for computation, deg/s for display

pE Position East, ft

pN Position North, ft

q Pitch rate, rad/s for computation, deg/s for display

r Yaw rate, rad/s for computation, deg/s for display

R_s Reference vector, *unit*

S Wing area, ft^2

u Control input vector

V Total speed, ft/s

x State-vector of the 12-state F/A-18 full nonlinear flight dynamics model

Y Predicted manipulated variable value, $unit$

Chapter 1 Introduction

1.1 Loss of Control overview

The stability and control of an airplane has been a fascinating topic since the days of early aviation pioneers (late 19th century and early 20th century). They quickly understood that staying in air is a difficult task when compared to taking off from ground. Early inventors like Sir George Cayley and Alphonse Penaud were concerned about the inherent stability of the plane. Both of them included a tail at a specific angle such that the plane is inherently stable i.e when plane is departed from equilibrium, it comes back to that point. This notion of making the plane inherently stable stayed in aviation community until Wright Brothers came into the picture. Unlike others, Wright Brothers made their plane inherently unstable. This made a drastic change in the maneuverability of the plane. Even though the work of pilot increased, they could control their plane the way they want it and this helped them to keep the airplane in flight for longer duration. This example shows the importance of stability and control.

Coming to the present day, there has been a significant improvement in the understanding of flight dynamics and control. Also, there has been development of various types of control algorithms, aided by advances in the computational facilities and sensor technology (MEMS). This has lead to safer flights and brought the number of fatal accidents down but not to zero. The type of problem encountered now is significantly different from early inventors. This can be noted from the figure 1.1 that shows the number of commercial airplane accidents from 1959-2018 (Boeing 2019). The categories of accidents given in figure 1.1 is decided by the CICTT. It can be noted in figure 1.1 that the challenges like CFIT and LOC-I are faced by today's researchers which contribute heavy to the fatal accidents. Among them, LOC-I is the single largest cause for most number of fatalities and also accounts for most number of accidents. There are other stats presented by NTSB and ICAO which shows the same trend for LOC-I. Aviation community is faced by this serious problem of LOC-I.

As the number of accidents due to LOC on ground is very less, LOC will be used from now on instead of LOC-I. There are various definitions for LOC. But, it can be simply defined as the deviation from the intended flight path i.e. flying outside the normal flight envelope (CICTT 2011), (FAA 2017). Over the years, people have gained a good understanding of flight dynamics and control of a plane, but only within the flight envelope. The behaviour of the plane when it

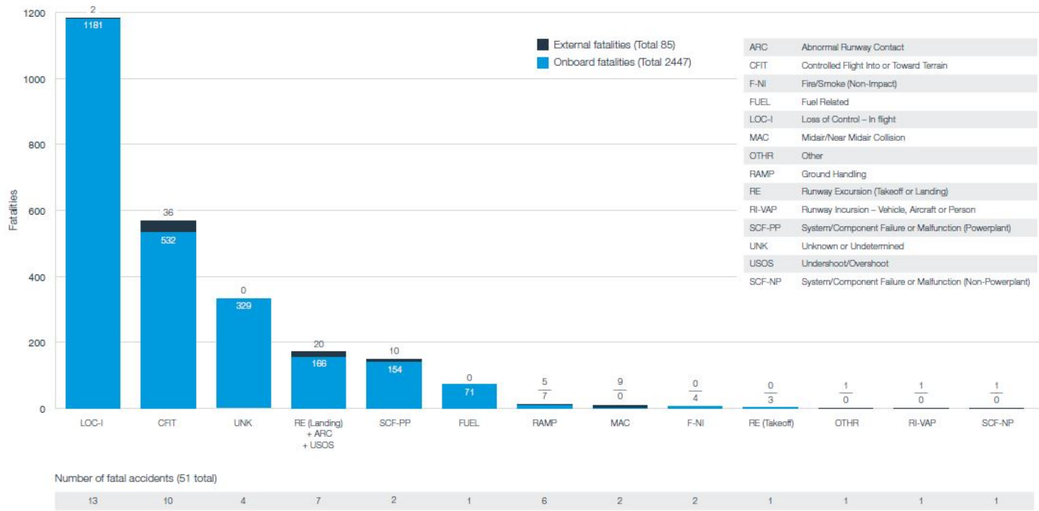

Figure 1.1: Commercial Airplane Accidental Data from 1959-2018 (Boeing 2019)

starts to move closer to the boundary of the envelope or out of it is not very well understood. This gives rise to a problem termed as LOC because it is difficult to control the airplane as one doesn't know how the plane will behave under such circumstances.

1.2 Motivation and Objectives

Authors are motivated to solve the problem of LOC outlined in the previous section by targeting a class of problem - Actuator Failures - that is a part of the chain that leads to the LOC. This is a challenging problem as it changes the dynamics of the system and also reduces the control authority making it difficult for the pilots to control the plane. Accident of Alaska Airlines Flight 261 is a perfect example of an actuator failure. Due to the unresponsive horizontal stabilizer, plane went into a deep dive and finally crashed into the pacific ocean killing everyone on board (NTSB 2002). It is important to note here that not all actuator failure events leads to fatal accidents. There have been numerous examples where pilots were able to recover the plane back or at least land safely. One such famous event is of US Airways Flight 1549 where the pilots had lost both the engines just after the take-off but still managed to land the plane on water without any casualties (NTSB 2010). Image 1.2 shows the passengers standing on the wing of the plane after landing on water.

This event shows that if a *correct* set of inputs is given to the plane quickly, then the plane can be prevented from entering LOC. Emphasis is placed on the word correct because many times it has been observed that pilots are not aware of the behaviour of the plane near LOC. And unintentionally they give a control input which worsens the situation. According to the analysis of Lambregts et al. (2008) of 74 LOC accidents, 10 were worsened by the faulty pilot inputs. So, when an actuator fails, it is of utmost importance to ensure that input to the plane

Figure 1.2: US Airways Flight 1549 after landing on water (NTSB 2010)

doesn't exacerbate the situation. This situation demands for a control algorithm to stabilize the plane as soon as failure of the actuator is detected. Authors are suggesting a method which employs tracking of flight angle using the MPC to stabilize the plane.

Few decades ago, CFIT was the cause for the most number of fatalities. But due to continuous improvements, number of accidents due to CFIT has come down. With the dedicated efforts of various institutions to tackle the problem of LOC, authors hope that same fate is achieved by LOC. Main objectives of this work are:

- To understand the general equations of motion of a fixed wing airplane, concept of stability derivatives, and various longitudinal and lateral modes.
- To understand what LOC is and how it can be prevented.
- To get familiar with the concept of flight path angle tracking, and Model Predictive Control.
- To implement a tracking/regulation stabilizing control algorithm and later compare the outputs of this with that of MPC.
- To develop a Model Predictive Control system to control the flight path angle of the airplane.

Chapter 2 gives a background of LOC and the work that has been done to characterize LOC. It also summarizes the work that has been done for the prevention of LOC in the event of actuator failures. Chapter 3 gives a description of testing platform (F-18 HARV), explains about trim point calculation and talks about Tracking/Regulation Stabilizing Control and MPC design. Chapter 4 talks about the results obtained from both the controllers and compares them. Chapter 5 concludes the work done and suggests a few possible extensions for this work.

Chapter 2 Literature Survey

Before developing methods to prevent/mitigate LOC, it is important to understand and characterize LOC. In the 1990s, LOC was identified as a major concern for commercial air travel safety. In 1997, CAST was formed to categorize LOC and suggest methods to prevent it. After CAST identified LOC as a major contributor to fatal accidents, JSAT was formed to study the various LOC accidents and suggest methods to reduce the number of accidents attributed to LOC (Russell and Pardee 2000).

Defining LOC is the first step towards developing methods for mitigating / preventing it. LOC is qualitatively defined as flight outside the normal flight envelope, unchanged by the pilot inputs, inability to maintain the heading and characterized by the nonlinear effects, abnormal attitudes, airspeed, and acceleration (Wilborn and Foster 2004), (CICTT 2011), (FAA 2017). But, these definitions won't help in developing methods for LOC prevention / mitigation explicitly. In 2000, Boeing and NASA Langley Research Center jointly developed a method to quantitatively characterize LOC using a set of 5 quantitative metrics. Using these metrics, one can decide whether an event can be considered as LOC or not. If two metrics are exceeded, then the plane is nearing LOC and if three metrics are violated, then the plane has entered LOC (Wilborn and Foster 2004).

As LOC is a complex event comprising of various factors, quantitative metrics method, in which standard limits are used, might not be enough. Belcastro and Foster (2010) conducted an extensive analysis of 126 LOC related accidents. The output of the analysis identified various causal factors just before LOC and divided them broadly into three categories. Those categories are (Belcastro and Foster 2010):

- Adverse On-board Conditions: Includes vehicle impairment, system faults and failures, inappropriate crew response (PIO), and vehicle damage to airframe and engines.

- External Hazards and Disturbances: Includes poor visibility, wake vortices, wind shear, turbulence, thunderstorms, snow and icing conditions, and sudden maneuvers for obstacle avoidance or collisions.

- Abnormal Dynamics and Vehicle Upsets: Abnormal attitude; abnormal airspeed, angular rates, or asymmetric forces; abnormal flight trajectory; uncontrolled descent and stall departures.

Another important outcome of the analysis is the identification of a causal sequence preceding LOC that resulted in 88.9% of the accidents. The causal sequence usually includes first step as an external hazard or disturbance and ends with vehicle upsets. Belcastro and Jacobson (2010) outlines the causal sequence which is shown in figure 2.1.

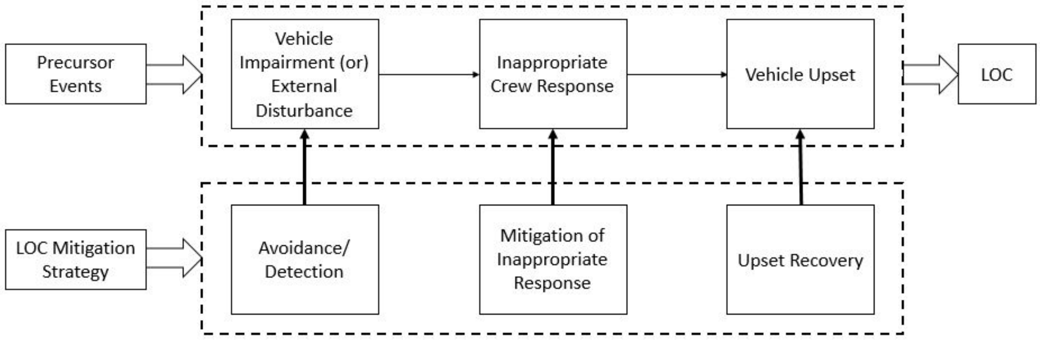

Figure 2.1: Causal Sequence and LOC mitigation strategies (Belcastro and Jacobson 2010)

Belcastro et al. (2014) analysed the worst case combination of the causal factors which also lead to a similar sequence. Belcastro and Jacobson (2010) also gives recommendations for counteracting LOC which is shown in figure 2.1. The strategy is divided into three broad categories one for each category of causal factors. Avoidance and detection usually deals with identifying whether the plane is near LOC or not and if it is, then it should be avoided. Detection can be done using Fault Detection, Isolation, and Reconfiguration algorithms. Hwang et al. (2010) provides a very good survey of algorithms in this category. Once it is detected that the plane is approaching LOC, pilot can be alerted using visual or aural cues (Stepanyan et al. 2016).

Second stage is mitigation of inappropriate response. This category usually deals with the situation in which vehicle impairment or external hazard wasn't avoided and the sequence towards LOC has been initiated. This can be done using Fault Tolerant Control Algorithms. Actuator failure problems are dealt in this category by reconfigure the controller online as the dynamics of the system changes. Authors firmly believe that it is better to prevent LOC in this stage only. Review of work done in the event of actuator failure is done later in this section. Third and final step for preventing the plane from going into LOC is Upset Recovery. This category is comprised of highly nonlinear motion of the plane and requires developing various analysis tools such as Bifurcation and Continuation methods. Algorithms used for upset recovery usually include Linear methods such as Feedback Linearization Techniques which includes Linear Parametric Varying Control (Dongmo 2012), and nonlinear controllers like Nonlinear Smooth Feedback Regulators (Dongmo 2016), High-Order Sliding Mode Control (Dongmo 2012), Receding Horizon Optimal Control, Nonlinear Smooth Trackers (Dongmo 2015). More rigorous review of LOC is done by Harrison (2018) in his PhD thesis wherein, he develops a method for mitigating LOC for general aviation aircraft, which are found to be more prone to LOC.

Actuator failure problem belongs to the second category as mentioned in the previous paragraph. Actuator failure has to be dealt with correct control inputs within small window of time frame. There has been a significant amount of work done to develop the algorithms to tackle the problem of actuator failure. Few of them are listed below:

- Ochi and Kanai (1995) implemented feedback linearization technique to reconfigure the control.

- Joosten et al. (2008) developed a MPC coupled with nonlinear dynamic inversion to reduce the computational complexity of the plant. Hennig and Balas (2008) also suggested a MPC based Supervisory Flight Control to address aircraft damage and faults.

- Kasnakoglu and Kaynak (2012), Şeyma Akyürek et al. (2016) uses loop shaping techniques to control the airplane after the actuator failure.

- Strube et al. (2012) generates a complete flight trajectory plan to guide the airplane to its landing site after actuator failure.

- Gunes et al. (2019) developed a Sliding Mode Control to prevent LOC in a UAV with a rudder jam.

- Chowdhary et al. (2013) developed a state-dependent guidance logic to control airplanes under actuator failures and severe structural damage.

- Caglayan et al. (1988) developed a robust flight control system tolerant of low-level surface damage, a hierarchical failure detection, isolation, and estimation (FDIE) system identifying actuator failures and moderate-to-serve surface damage, and a reconfiguration logic in which the pseudo surface resolver (PSR) is reconfigured after impairment to recover performance and minimize transients.

- Cunha Jr and Doncescu (2011) used non linear inverse control technique to control the thrust of a multi engine transport aircraft with complete hydraulic loss.

- Hu et al. (2000) employed H_∞ approximation I/O linearization formulation and μ-synthesis to design a non linear controller for a longitudinal flight control problem.

- Weiss and Hsu (1987) examined the complementary capabilities of several restructurable flight control system (RFCS) concepts through its integration into a complete system.

- Looze et al. (1985) employs a robust control system design for an unfailed aircraft to minimize the effects of failed surfaces and to extend the time available for restructuring the Flight Control System.

- Ostroff and Hueschen (1984) uses a discrete multivariable control law using four controls for the longitudinal channel of a B-737.
- Chang et al. (2001) designs a set of regulator controllers for all possible actuator failures and a switching mechanism to determine which controller to step in to address the specific actuator failure.
- Bajpai et al. (2002) employs nonlinear regulator theory to address the persistent disturbance caused by jammed actuators.
- Zhenyu Yang and Hicks (2002) utilizes the mixer control method to recover the input/output functionality in the event of an actuator failure and recover the system back to desired performance.
- GAO and ANTSAKLIS (1991) gives us insight on the pseudo-inverse method of re-configurable control methods and how it can be implemented.
- Bodson and Groszkiewicz (1997) compares three different multi variable adaptive control algorithms to compensate for actuator failures or surface damage.
- Ahmed-Zaid et al. (1991) developed a control system augmented with a hybrid adaptive linear quadratic control scheme to accomodate drastic changes in flight dynamics due to surface damage or hardware failure.
- Boskovic and Mehra (1999) propose a new parametrization for the modeling of control effector failures in flight control applications
- Tao et al. (2001) developed direct adaptive-state feedback control schemes for linear time-invariant plants with actuator failures.
- Tang et al. (2007) designed a adaptive failure compensation controller which is capable of accommodating uncertainties in actuator failure time instants, values and patterns.
- Zhang et al. (2019) proposes a fault tolerant control system for distributed parameter systems. The proposed controller is designed by using the Lyapunov's direct method and adaptive control strategies.
- Burken et al. (2001) outlines two reconfigurable flight control methods: robust servomechanism and control allocation when one or more control surfaces are jammed.

Chapter 3 Methodology

3.1 F-18 Model Description

F-18 HARV is used as a test platform for the demonstration of the control algorithm. The reason for this is the easy availability of the stability and control derivatives in open literature. It is developed by McDonnell Douglas Corporation (now The Boeing Company) based on US Navy's F/A-18. It is a high performance, single seat, twin tail aircraft powered by two General Electric F404-GE-400 turbofan engines equipped with afterburner, which is capable of producing 16,100 lbs of uninstalled static thrust at sea level. F-18 HARV was used by NASA's Dryden Flight Research Center for investigating flights in high angle of attack region, usefulness of thrust vectoring, and actuated leading edge strakes (NASA 2014). Figure 3.1 shows F-18 HARV in flight.

Figure 3.1: F-18 High Alpha Research Vehicle (NASA 1991)

The aircraft parameters are listed in Table 3.1. This data is for F/A-18 and is referred from Buttrill and Arbuckle (1992), wherein they developed a mathematical model and associated computer program in FORTRAN to simulate F/A-18. Here, it is assumed that the values of the parameters for F-18 HARV are similar to F/A-18.

The following control surfaces are present on the F-18 HARV: pairs of Eleva-

Variable	Value
b	37.42 ft
S	400 ft^2
$\bar{c}$	11.52 ft
m	1034.5 slug
I_{xx}	23,000 slug ft^2
I_{yy}	1,51,293 slug ft^2
I_{zz}	1,69,945 slug ft^2
I_{xz}	-2971 slug ft^2

Table 3.1: F-18 Parameters (Buttrill and Arbuckle 1992)

tors, Aileron, Rudder, Leading Edge Flaps and Trailing Edge Flaps. There is also a thrust vectoring mechanism, but is not included in the simulation for simplicity purpose. Also, Leading Edge and Trailing Flaps are not included in the simulation as they are used during take-off and Landing. Longitudinal Control is achieved using the elevator and thrust, while lateral control is achieved through rudder and aileron. Various characteristics of all four actuators are presented in table 3.2. Characteristics of elevator, rudder, and aileron are referred from (Buttrill and Arbuckle 1992), and (Chang et al. 2016) is referred for thrust.

Actuator	Saturation Limits	Rate Limits	Dynamics
δ_{ele}	$-24°$ to $10.5°$	$-40°/s$ to $40°/s$	$\frac{30}{s+30}$
δ_{ail}	$-25°$ to $25°$	$-100°/s$ to $100°/s$	$\frac{48}{s+48}$
δ_{rud}	$-30°$ to $30°$	$-61°/s$ to $61°/s$	$\frac{40}{s+40}$
δ_T	0 to 20,000 lbs	-	$\frac{30}{s+30}$

Table 3.2: F-18 Actuator Characteristics

Equation 3.1 represents a general form of state space representation of a dynamical system, where f is a nonlinear function in x and u.

$$\dot{x} = f(x, u) \tag{3.1}$$

$$x = \begin{bmatrix} V & \beta & \alpha & p & q & r & \phi & \theta & \psi & pN & pE & h \end{bmatrix}^T \tag{3.2a}$$

$$u = \begin{bmatrix} \delta_{ele} & \delta_{ail} & \delta_{rud} & \delta_T \end{bmatrix}^T \tag{3.2b}$$

Motion of F-18 HARV is represented in the form of equation 3.1 using 12 states and 4 control inputs which are shown in equation 3.2. Refer equation 5.1 given in Appendix 5.1 for the function f. It can be observed from the equation 5.1 that aerodynamic forces and moments (equation) are an essential part which govern the motion of a plane.

Modeling theses forces and moments is a challenge in itself, as they are non-linearly dependent on α, β, δ_{ele}, δ_{ail}, δ_{rud}, p, q, and r (Equation 3.3). Techniques of Parameter Identification like Maximum Likelihood Method are used for this purpose. (Napolitano et al. 1996a) and (Napolitano et al. 1996b) shows the method applied for F-18 HARV. Aerodynamic model for F-18 HARV is adopted from (Chakraborty et al. 2011), wherein they have used the model to show the usefulness of linear analysis methods in examining the revised control laws for F/A-18. Refer Appendix 5.2 for the calculation of aerodynamic coefficients in equation 3.3. Developed model is accurate enough to depict the motion of airplane in high alpha region and near LOC points. The complete mathematical model of F-18 HARV is built on MATLAB and Simulink.

$$D = \bar{q}SC_D(\alpha, \beta, \delta_{ele}) \tag{3.3a}$$

$$Y = \bar{q}SC_Y(\alpha, \beta, \delta_{ail}, \delta_{rud}) \tag{3.3b}$$

$$L = \bar{q}SC_L(\alpha, \beta, \delta_{ele}) \tag{3.3c}$$

$$l = \bar{q}SbC_l(\alpha, \beta, \delta_{ail}, \delta_{rud}, p, r, V) \tag{3.3d}$$

$$M = \bar{q}S\bar{c}C_m(\alpha, \delta_{ele}, q, V) \tag{3.3e}$$

$$N = \bar{q}SbC_n(\alpha, \beta, \delta_{ail}, \delta_{rud}, p, r, V) \tag{3.3f}$$

3.2 Trim Calculation and Analysis

Trim point is those combinations of values of u for which the $\dot{x} = 0$. Calculation of the value of the control input to trim the airplane is of essential importance. At trim position, the value of net force and moment is zero. They are used to check whether the states are converging to the desired trim for a given location of elevator jam.

Simple technique of force and moment balance has been used to calculate the trim values for stable level flight during elevator failure. First step is to decide a range of values of α for which the plane has to be trimmed. Then for selected values of α, value of δ_{ele} is computed for which the C_m (equation 5.3b) is zero. Using the values of α and δ_{ele}, coefficient of lift and drag is calculated (equation 5.2c and 5.2a). Then, forces are balanced in X and Z direction as shown in figure 3.2 to get equation 3.4. Note the Y direction forces are zero as there is no motion in that direction during stable level flight during an elevator failure.

$$L + Tsin\theta = W \tag{3.4a}$$

$$Tcos\theta = D \tag{3.4b}$$

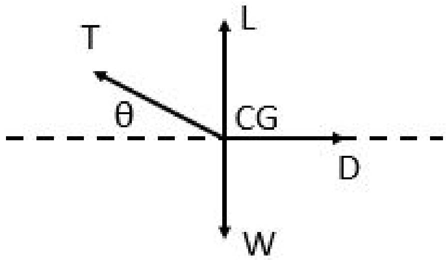

Figure 3.2: Force Balance in X and Z direction for level flight

Equation 3.4 represents two equations in two variable. One of the obvious variables is T. Other variable is V as it governs the amount of lift and drag. Equation 3.4 is solved for thrust and velocity. Note that for our case θ is equal to α. This will give a combination of state values for which the aircraft will be in level flight. This data should be used only within the saturation limits of control surface values given in table 3.2. Results obtained are shown in figure 3.3-3.5. Here, the range of α considered for calculation is from $1°$ to $37°$. Below the alpha of $1°$, the lift generated is negative and elevator reaches its saturation limit for alpha values beyond $37°$. These trim values can also be calculated using trim function given in MATLAB

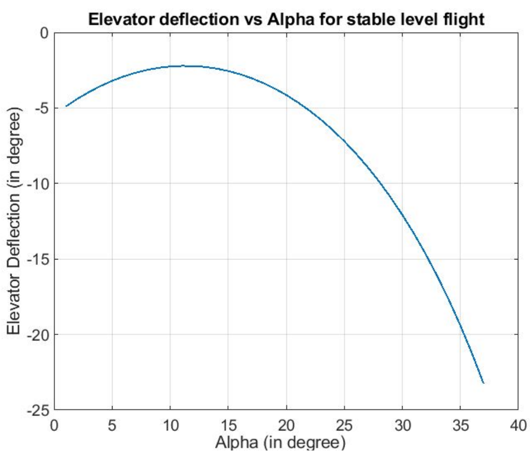

Figure 3.3: Variation of Elevator position with Alpha for level flight

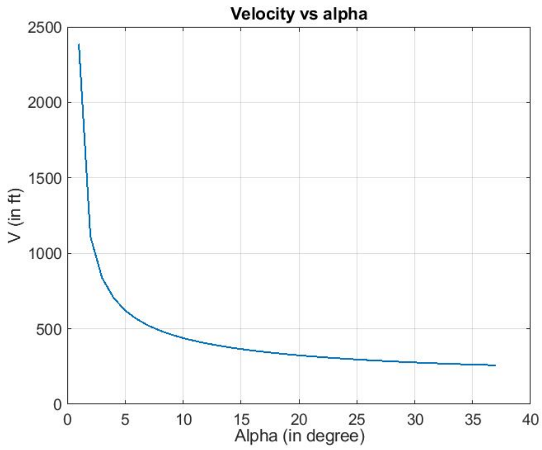

Figure 3.4: Variation of Velocity with Alpha for level flight

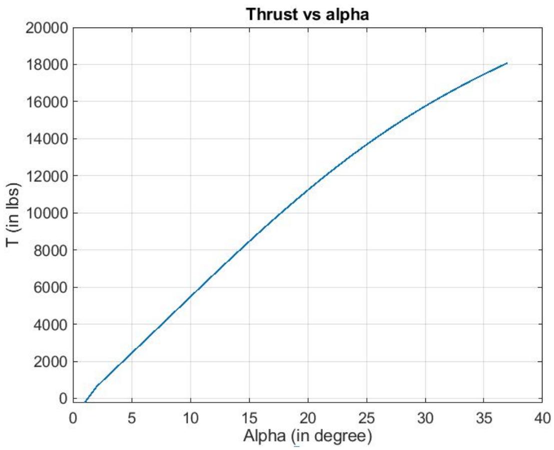

Figure 3.5: Variation of Thrust with Alpha for level flight

To test whether the values obtained are correct or not, the trim combination of thrust and elevator are input into the F-18 model without any controller (Chang et al. 2016). Initial condition of the model is given in equation 3.5. Order of the states is same as given in equation 3.2.

$$x = \begin{bmatrix} 350ft/s & 20^\circ & 40^\circ & 10^\circ/s & 0^\circ/s & 5^\circ/s & 0^\circ & 0^\circ & 0^\circ & * & * & * \end{bmatrix}^T \tag{3.5}$$

* is replaced for the values of pN, pE, and h as those states are not of primary importance. Figure 3.6 shows the results obtained by giving inputs to dynamic model as shown in equation 3.6. This value of u corresponds to 37° of alpha (figure 3.3 and 3.5). It can be noted from figure 3.6 that plane achieves stable level flight and converges to the value calculated using method described above.

$$u = \begin{bmatrix} -23.26^\circ & 0 & 0 & 18078.86lbs \end{bmatrix}^T \tag{3.6}$$

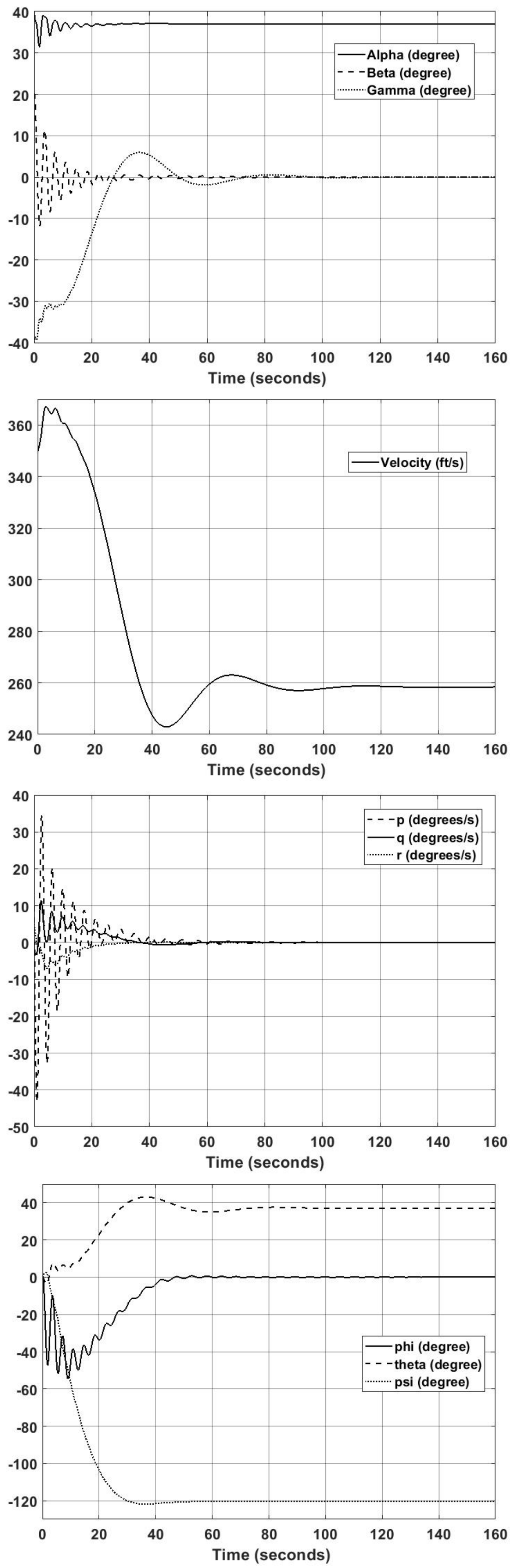

Figure 3.6: For elevator at $-23.26°$

For the δ_{ele} values below $-2.3°$, the states doesn't converge to what is calculated. The reason for this can be found by linearizing the model below this δ_{ele} position and construct a pole-zero diagram. A for the linearized model is 12X12 matrix. So, there are twelve roots, out of which 4 are zero. Out of the remaining 8, 2 are for Phugiod, Short Period and Dutch Roll Mode each. Remaining two are for spiral and roll. From figure 3.7, it can be noted that one of the roots is in right half of the plane. Therefore, the trim point is unstable. Thus, the system doesn't converge to that in open loop system. The Pole-Zero Map is created using the Linear Analysis Tool in MATLAB.

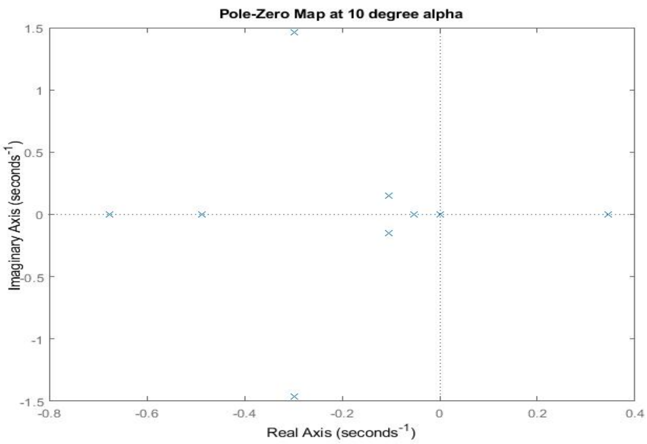

Figure 3.7: Pole-Zero Diagram at 10° alpha (Elevator at $-2.25°$)

3.3 Control System

As stated previously, the crux of this project is to prevent loss of control in the aircraft, and to accomplish this, we have to look at designing the appropriate control system which will enable the flight to never reach a state of loss of control. We considered the case of an actuator jam to demonstrate possible LOC condition in the aircraft and designed the control system to return the aircraft back to trim condition despite the actuator jam. The different control systems which were implemented are the following:

1. Tracking/Regulation Stabilizing Control System: This system was referenced from (Chang et al. 2019) to demonstrate the validity of our model and to set a reference point for our implementation of the control system.

2. Model Predictive Control System: This system was implemented by us to prevent LOC condition in the aircraft in the event of an actuator failure.

3.3.1 Tracking/Regulation Stabilizing Control

Tracking/regulation stabilizing control is a method of determining the feasible straight level flight trim for a given set of conditions. The control problem that arises during an unanticipated actuator failure is very different from the conventional type of problems where the mathematical model of the system to be controlled is usually available. This controller attempts to stabilize the aircraft to a trim state which includes the actuator impairment without wasting time on re-trim and controller redesign computations.

The main objective of the controller is to neutralize the effect of the persistent disturbance and stabilize the flight path angle at zero. The control structure used is a double-loop state feedback with an internal model integrator which is included to ensure robust flight path angle tracking. The state feedback matrices are designed to stabilize the closed loop system and optimize the transient response subject to control input constraints based on the H_2 optimal control approach.

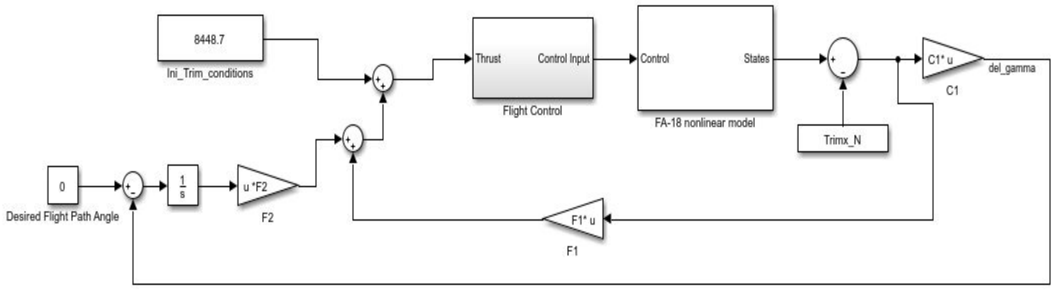

Figure 3.8: Simulink Model of Tracking/Regulating Stabilizing Controller

3.3.2 Model Predictive Control

Model predictive control (MPC) is an advanced method of process control that is used to control a process while satisfying a set of constraints. MPC is based on iterative, finite-horizon optimization of a mathematical model of the plant. MPC predicts the values of the state of the plant for different values of the manipulated variables and optimizes the state values in a closed loop to enable the plant to follow a fixed reference. The main advantage of MPC is the fact that it allows the current time-slot to be optimized, while keeping future time-slots in account. This is achieved by optimizing a finite time-horizon, but only implementing the current time-slot and then optimizing again. It also has the following advantages which make it suitable for our application:

1. It can handle multiple manipulated variables and manipulated outputs

2. Constraints can be imposed on the manipulated variables and manipulated outputs so that they remain within the aircraft's envelope.

3. There is little to no time delay when it is implemented as it takes into account future time-slots while optimizing the manipulated variables.

As shown in the figure 3.9, the mathematical model helps predict the future states of the plant and the optimizer helps minimize the cost function while taking into account the constraints on the manipulated variables. The cost function is

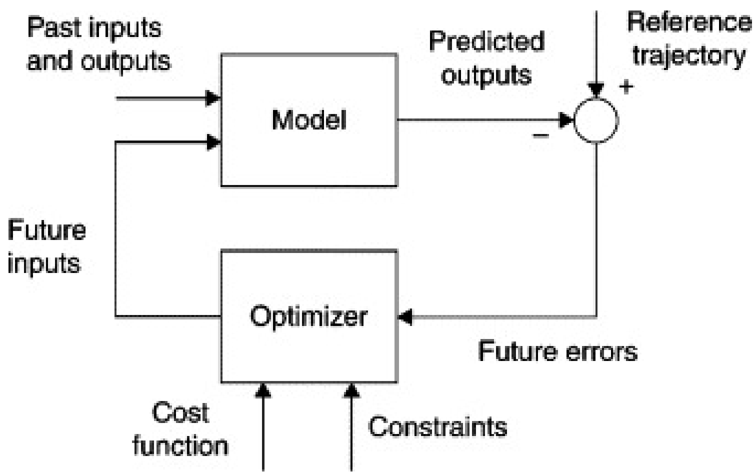

Figure 3.9: Basic Structure of Model Predictive Control (Alnaizy et al. 2013)

defined as the following (Wang 2009):

$$J = (R_s - Y)^T (R_s - Y) + \Delta U^T \bar{R} \Delta U \tag{3.7}$$

where the first term is minimizing the error between the predicted outputs and the reference and the second term is giving consideration to the change in the manipulated variable values. $\bar{R}$ denotes the tuning parameter which decides the weightage given to the second term. Higher the value of $\bar{R}$, smoother will be the response but the response may be delayed and vice-versa.

We designed the MPC with the help of Simulink module in MATLAB which takes care of the control algorithm implementation. Considering our case of actuator jam, considering only longitudinal control, the manipulated variable will be the *thrust* and the manipulated output of the system will be γ. The trim condition calculated previously will act as the reference since we want to get the plant back to the trim condition. The actuator jam position δ_{ele} will act as an external disturbance. Here, δ_{rud} and δ_{ail} are kept at zero all the time. The figure 3.10 shows the simulink model of MPC developed by us to mitigate LOC in the event of an actuator failure. Linear MPC block was used for this purpose and tuned parameter values are given in table 3.3. The block trims the model at the stable level flight conditions with which the plane was flying before the elevator jam and uses that to generate trajectory for various combinations of control input during optimization.

Parameter	**Value**
Sample Time	0.1 seconds
Prediction Horizon	15 seconds
Control Horizon	1 second

Table 3.3: MPC Parameters

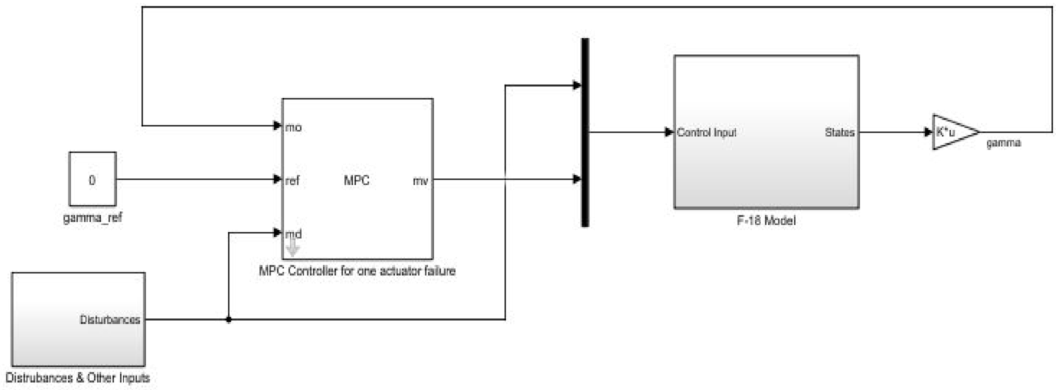

Figure 3.10: Simulink Model of MPC to mitigate LOC for one actuator failure

Chapter 4 Results

MPC is tested at two different elevator jam position to demonstrate its robustness. Those results are also compared with Tracking/Regulating Stabilizing Controller. Equation 4.1 and 4.2 shows the stable level flight trim values for elevator jam position of $-5°$ and $-23°$ respectively, which are calculated using the method described in methodology section. Figure 4.1 and 4.2 shows the variation of states with time since the jam of elevator from zero seconds. Figure 4.3 and 4.4 shows the variation of states with time for MPC. In all the results, the plane is flying stable level flight with an α of $15°$ before the elevator jam. It is important to note here that the performance of the MPC is highly dependent upon the parameters listed in table 3.3.

For Elevator jammed at $-5°$:

$$\begin{gathered} x = \begin{bmatrix} 313.7ft/s & 0° & 21.7° & 0°/s & 0°/s & 0°/s & 0° & 21.7° & 0° & * & * & * \end{bmatrix}^T \\ u = \begin{bmatrix} -5° & 0 & 0 & 12094lbs \end{bmatrix}^T \end{gathered} \tag{4.1}$$

For Elevator jammed at $-23°$:

$$\begin{gathered} x = \begin{bmatrix} 258.62ft/s & 0° & 36.87° & 0°/s & 0°/s & 0°/s & 0° & 36.87° & 0° & * & * & * \end{bmatrix}^T \\ u = \begin{bmatrix} -23° & 0 & 0 & 18040lbs \end{bmatrix}^T \end{gathered} \tag{4.2}$$

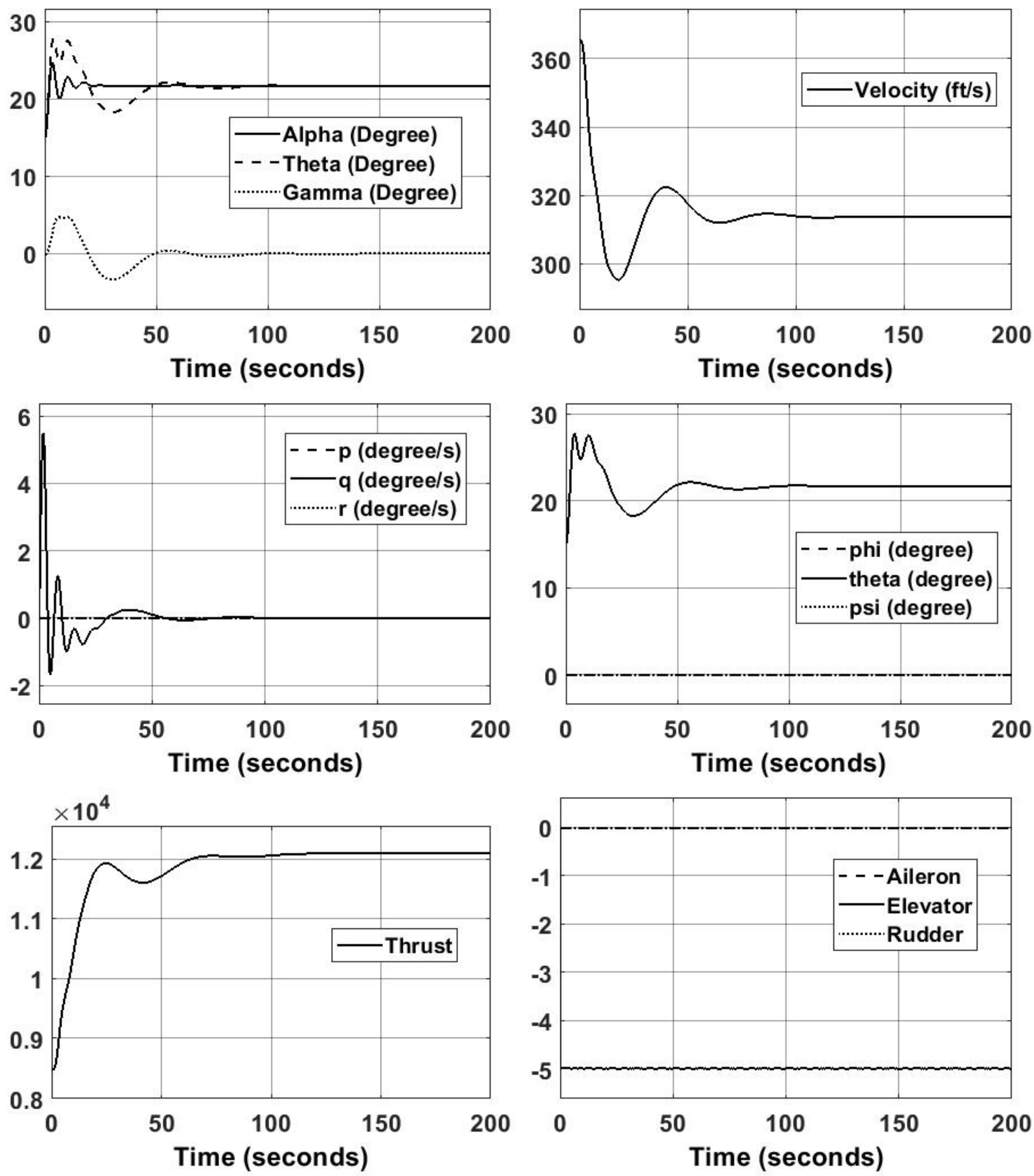

Figure 4.1: For elevator jam at $-5°$ with Tracking/Regulating Stabilizing Control

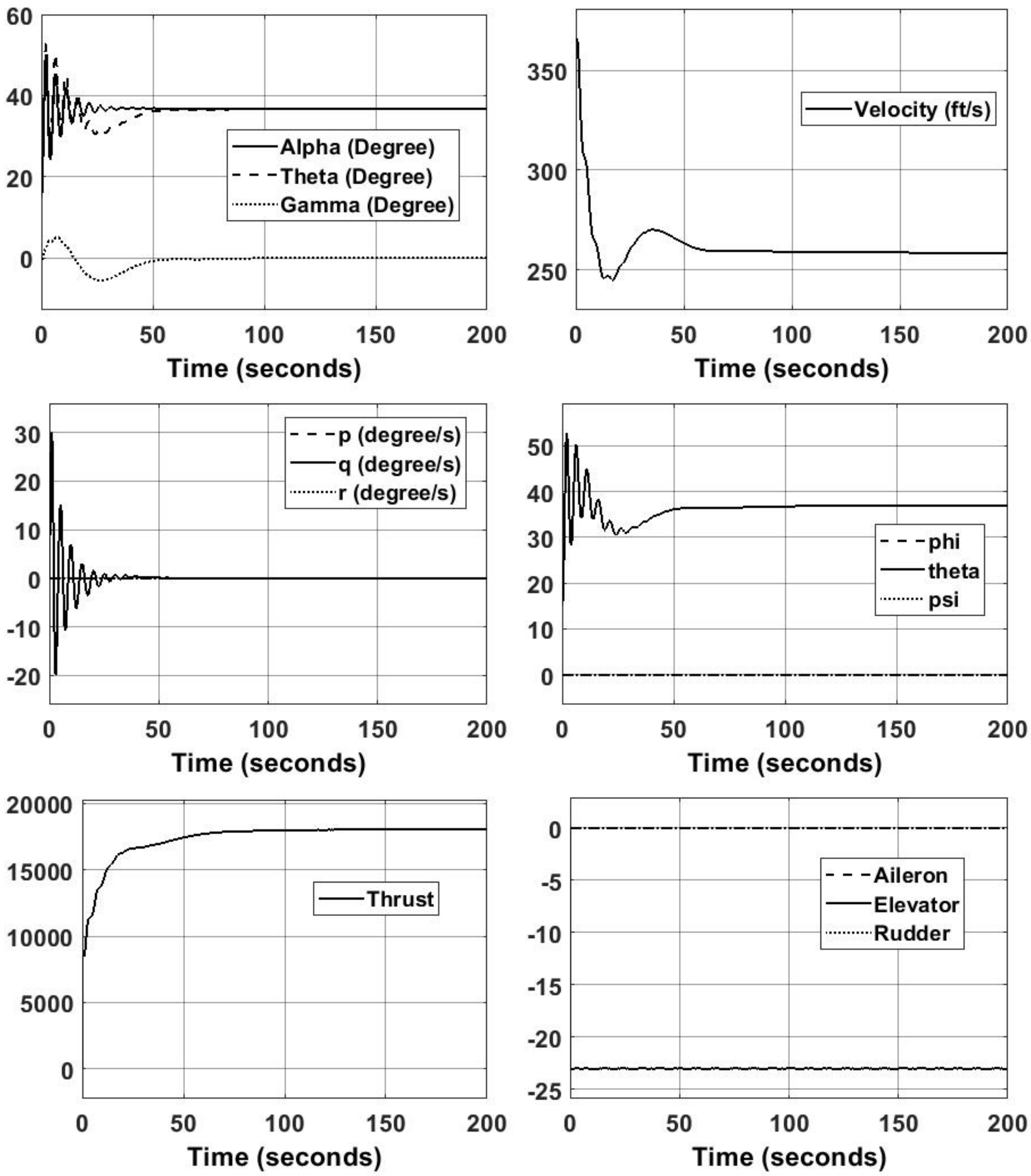

Figure 4.2: For elevator jam at -23° with Tracking/Regulating Stabilizing Control

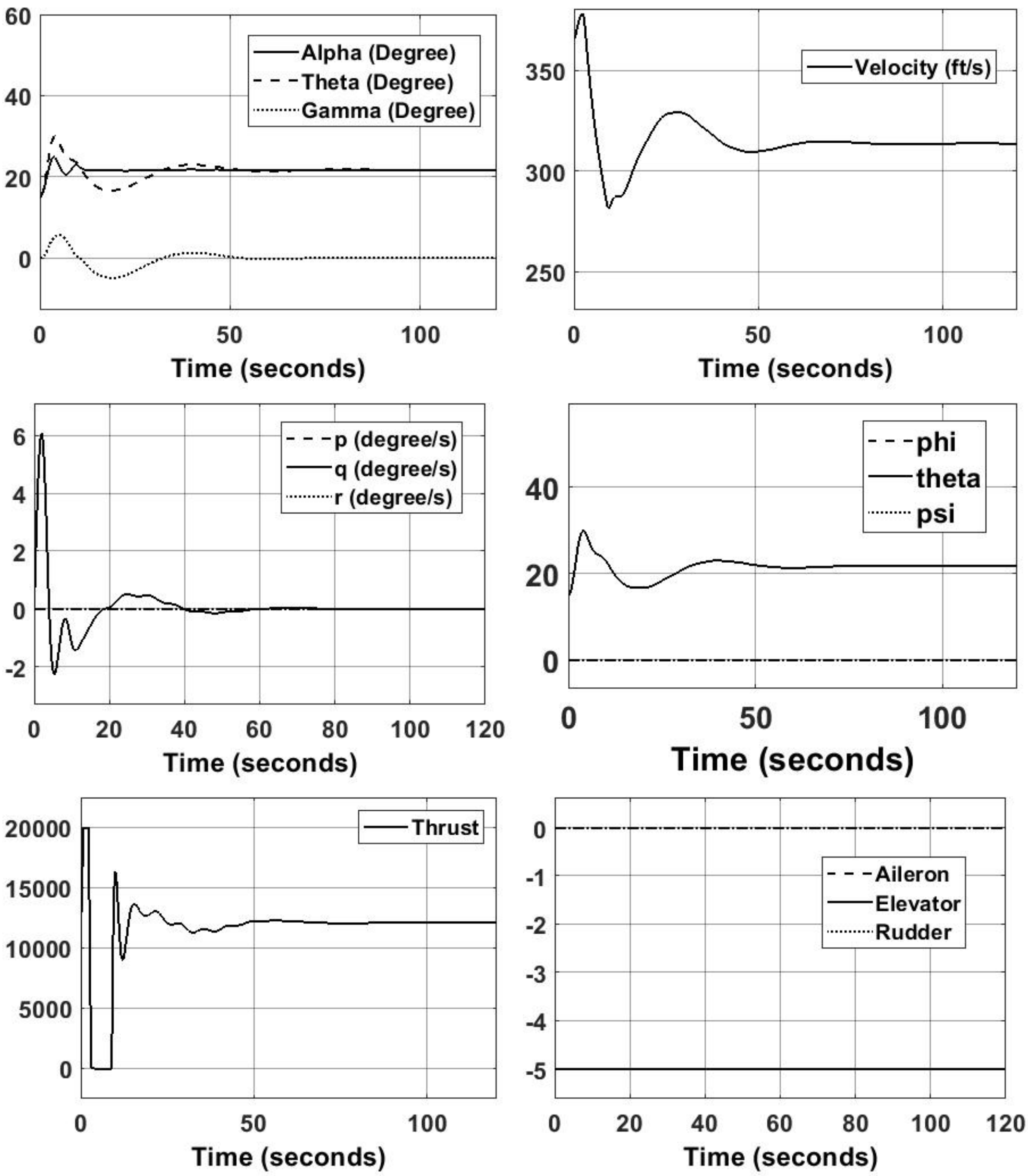

Figure 4.3: For elevator jam at $-5°$ with MPC

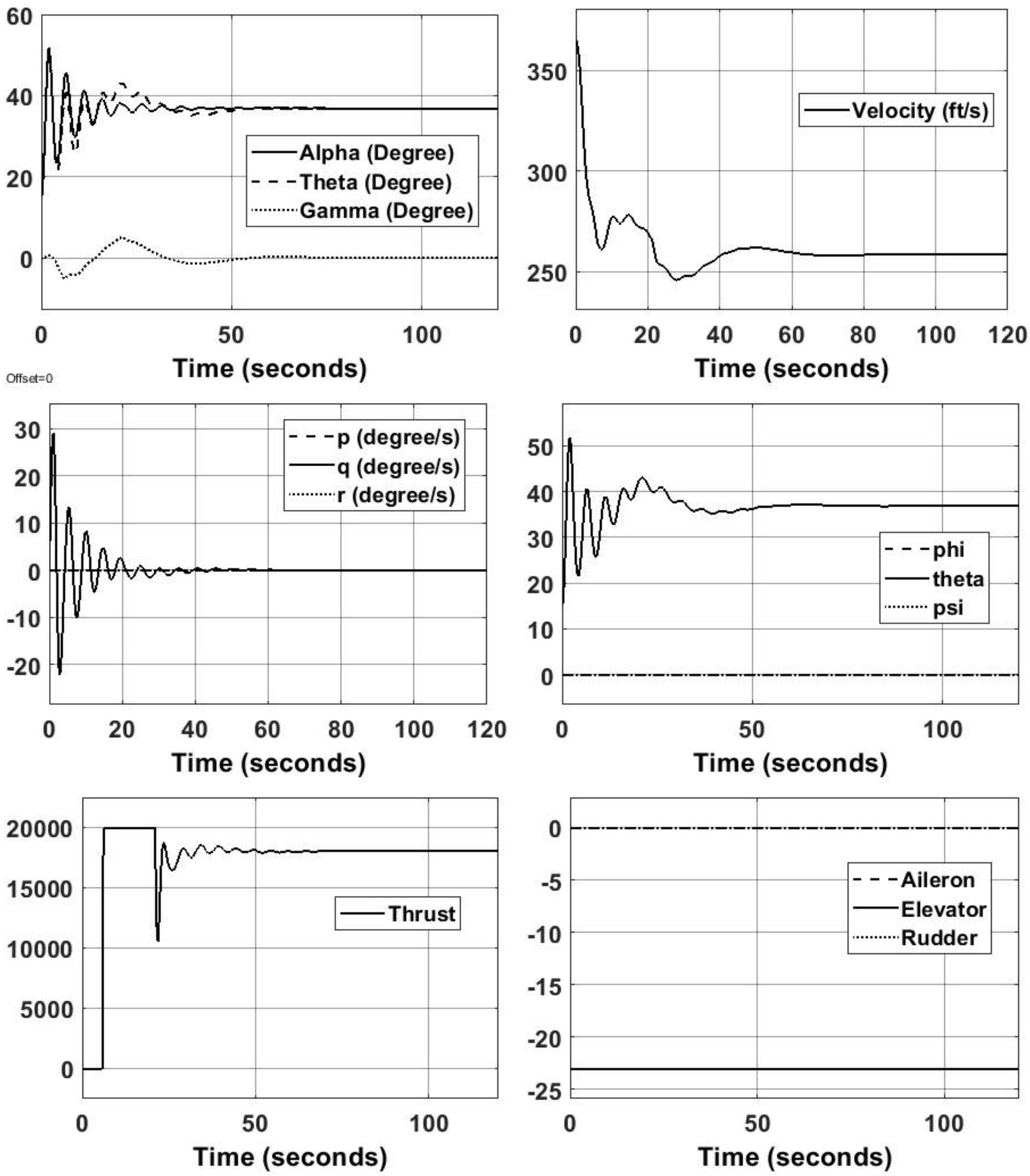

Figure 4.4: For elevator jam at $-23°$ with MPC

Chapter 5 Conclusion

Based on the results obtained, one can conclude that MPC works as well as the tracking/regulation stabilizing control for tracking γ to zero and getting the flight back to trim condition. Authors find the model predictive control better than tracking/regulation stabilizing control in the following ways:

- Physical constraints for the actuators and manipulated variables can be inherently added to the MPC system, where as for the tracking/regulation stabilizing control, they must be added separately. The provision for adding soft or hard constraints is a big advantage when MPC system is considered.
- MPC tuning is more simple when compared to Tracking/Regulation stabilizing control and can be made more aggressive or passive based on the requirement of the situation.

The major disadvantage of the Model Predictive Control system is the need for high computing power. This is rendered moot when we consider the case of an aircraft which already possesses the required computational prowess. Few suggestions from authors for future work:

- Extend the MPC for multiple actuator failure such as elevator plus rudder jam. This scenario can take place for an attack or fighter aircraft when the tail of the plane is badly damaged. This can be done by tracking ψ along with γ to zero.
- As MPC provides a provision for constraints to be included, envelope protection can be included in the constraints itself. One such example can be including constrains over normal load factor. This can be especially useful for a commercial airplane so that the passenger inside the plane doesn't have to experience high g's during the prevention of LOC.

Appendix

5.1 Equations of Motion

General equations of motion governing the motion of a conventional fixed wing airplane is shown in equation 5.1. More information on these equations can be found in (Stevens and Lewis 1992), (Nelson 1998), (Cook 2013).

$$\begin{aligned}\dot{V} = -\frac{1}{m}\bar{q}S(Dcos\beta - Ysin\beta) + g(cos\phi cos\theta sin\alpha cos\beta + sin\phi cos\theta sin\beta \\ - sin\theta cos\alpha cos\beta) + \frac{T}{m}cos\alpha cos\beta\end{aligned} \tag{5.1a}$$

$$\begin{aligned}\dot{\beta} = \frac{1}{mV}\bar{q}S(Ycos\beta + Dsin\beta) + psin\alpha - rcos\alpha + \frac{g}{V}cos\theta sin\phi cos\beta \\ + \frac{sin\beta}{V}(gcos\alpha sin\theta - gsin\alpha sin\phi cos\theta + \frac{T}{m}cos\alpha)\end{aligned} \tag{5.1b}$$

$$\begin{aligned}\dot{\alpha} = -\frac{1}{mVcos\beta}L + q - tan\beta(pcos\alpha + rsin\alpha) \\ + \frac{g}{Vcos\beta}(cos\phi cos\theta cos\alpha + sin\alpha sin\theta) - \frac{Tsin\alpha}{mVcos\beta}\end{aligned} \tag{5.1c}$$

$$\begin{aligned}\dot{p} = ((I_{zz}L + I_{xz}N - (I_{xz}(I_{yy} - I_{xx} - I_{zz})p \\ + (I_{xz}^2 + I_{zz}(I_{zz} - I_{yy}))r)q)/(I_{xx}I_{zz} - I_{xz}^2))\end{aligned} \tag{5.1d}$$

$$\dot{q} = ((M + (I_{zz} - I_{xx})pr + (r^2 - p^2)I_{xz})/I_{yy} \tag{5.1e}$$

$$\begin{aligned}\dot{r} = ((I_{xz}L + I_{xx}N + (I_{xz}(I_{yy} - I_{xx} - I_{zz})r \\ + (I_{xz}^2 + I_{xx}(I_{xx} - I_{yy}))p)q)/(I_{xx}I_{zz} - I_{xz}^2))\end{aligned} \tag{5.1f}$$

$$\dot{\phi} = p + (qsin\phi + rcos\phi)tan\theta \tag{5.1g}$$

$$\dot{\theta} = qcos\phi - rsin\phi \tag{5.1h}$$

$$\dot{\psi} = (qsin\phi + rcos\phi)sec\theta \tag{5.1i}$$

$$\begin{aligned}\dot{p_N} = cos\theta cos\psi Vcos\beta cos\alpha + (sin\phi sin\theta cos\psi - cos\phi sin\psi)Vsin\beta \\ + (cos\phi sin\theta cos\psi + sin\phi sin\psi)Vcos\beta sin\alpha\end{aligned} \tag{5.1j}$$

$$\begin{aligned}\dot{p_E} = cos\theta sin\psi Vcos\beta cos\alpha + (sin\phi sin\theta sin\psi + cos\phi cos\psi))Vsin\beta \\ + (cos\phi sin\theta sin\psi - sin\phi cos\psi)Vcos\beta sin\alpha\end{aligned} \tag{5.1k}$$

$$
\begin{aligned}
\dot{h} = sin\theta V cos\beta cos\alpha - sin\phi cos\theta V sin\beta \\
- cos\phi cos\theta V cos\beta sin\alpha
\end{aligned}
\tag{5.1l}
$$

5.2 F-18 HARV Aerodynamic Model and Coefficient

Chakraborty et al. (2011) fitted the curves on the flight test data of stability and control derivatives of F-18 HARV available in open literature to get the equations 5.2 and 5.3. Coefficients needed for the calculations are given in table 5.1 and 5.2. Note that the model is restricted to be used in the range of 0° to 60° of angle of attack. This is due to the type of data used during fitting.

Drag Force Coefficient:

$$
\begin{aligned}
C_D = (C_{D_{\alpha_4}}\alpha^4 + C_{D_{\alpha_3}}\alpha^3 + C_{D_{\alpha_2}}\alpha^2 + C_{D_{\alpha_1}}\alpha + C_{D_{\alpha_0}})cos\beta \\
+ C_{D_0} + (C_{D_{\delta_{ele_3}}}\alpha^3 + C_{D_{\delta_{ele_2}}}\alpha^2 + C_{D_{\delta_{ele_1}}}\alpha + C_{D_{\delta_{ele_0}}})\delta_{ele}
\end{aligned}
\tag{5.2a}
$$

Side Force Coefficient:

$$
\begin{aligned}
C_Y = (C_{Y_{\beta_2}}\alpha^2 + C_{Y_{\beta_1}}\alpha + C_{Y_{\beta_0}})\beta \\
+ (C_{Y_{\delta_{ail_3}}}\alpha^3 + C_{Y_{\delta_{ail_2}}}\alpha^2 + C_{Y_{\delta_{ail_1}}}\alpha + C_{Y_{\delta_{ail_0}}})\delta_{ail} \\
+ (C_{Y_{\delta_{rud_3}}}\alpha^3 + C_{Y_{\delta_{rud_2}}}\alpha^2 + C_{Y_{\delta_{rud_1}}}\alpha + C_{Y_{\delta_{rud_0}}})\delta_{rud}
\end{aligned}
\tag{5.2b}
$$

Lift Force Coefficient:

$$
\begin{aligned}
C_L = (C_{L_{\alpha_3}}\alpha^3 + C_{L_{\alpha_2}}\alpha^2 + C_{L_{\alpha_1}}\alpha + C_{L_{\alpha_0}})cos(\frac{2\beta}{3}) \\
+ (C_{L_{\delta_{ele_3}}}\alpha^3 + C_{L_{\delta_{ele_2}}}\alpha^2 + C_{L_{\delta_{ele_1}}}\alpha + C_{L_{\delta_{ele_0}}})\delta_{ele}
\end{aligned}
\tag{5.2c}
$$

Rolling Moment Coefficient:

$$
\begin{aligned}
C_l = (C_{m_{\beta_4}}\alpha^4 + C_{l_{\beta_3}}\alpha^3 + C_{l_{\beta_2}}\alpha^2 + C_{l_{\beta_1}}\alpha + C_{l_{\beta_0}})\beta \\
+ (C_{l_{\delta_{ail_3}}}\alpha^3 + C_{l_{\delta_{ail_2}}}\alpha^2 + C_{l_{\delta_{ail_1}}}\alpha + C_{l_{\delta_{ail_0}}})\delta_{ail} \\
+ (C_{l_{\delta_{rud_3}}}\alpha^3 + C_{l_{\delta_{rud_2}}}\alpha^2 + C_{l_{\delta_{rud_1}}}\alpha + `C_{l_{\delta_{rud_0}}})\delta_{rud} \\
+ \frac{bp}{2V}(C_{l_{p_1}}\alpha + C_{l_{p_0}}) + \frac{br}{2V}(C_{l_{r_2}}\alpha^2 + C_{l_{r_1}}\alpha + C_{l_{r_0}})
\end{aligned}
\tag{5.3a}
$$

Drag Force		**Side Force**		**Lift Force**	
Coefficient	Value	Coefficient	Value	Coefficient	Value
$C_{D_{\alpha_4}}$	1.4610	$C_{Y_{\beta_2}}$	-0.1926	$C_{L\alpha_3}$	1.1645
$C_{D_{\alpha_3}}$	-5.7341	$C_{Y_{\beta_1}}$	0.2654	$C_{L\alpha_2}$	-5.4246
$C_{D_{\alpha_2}}$	6.3971	$C_{Y_{\beta_0}}$	-0.7344	$C_{L\alpha_1}$	5.6770
$C_{D_{\alpha_1}}$	-0.1995	$C_{Y_{\delta_{ail_3}}}$	-0.8500	$C_{L\alpha_0}$	-0.0204
$C_{D_{\alpha_0}}$	-1.4994	$C_{Y_{\delta_{ail_2}}}$	1.5317	$C_{L_{\delta_{ele_3}}}$	2.1852
C_{D_0}	1.5036	$C_{Y_{\delta_{ail_1}}}$	-0.2403	$C_{L_{\delta_{ele_2}}}$	-2.6975
$C_{D_{\delta_{ele_3}}}$	-3.8578	$C_{Y_{\delta_{ail_0}}}$	-0.1656	$C_{L_{\delta_{ele_1}}}$	0.4055
$C_{D_{\delta_{ele_2}}}$	4.2360	$C_{Y_{\delta_{rud_3}}}$	0.9351	$C_{L_{\delta_{ele_0}}}$	0.5725
$C_{D_{\delta_{ele_1}}}$	-0.2739	$C_{Y_{\delta_{rud_2}}}$	-1.6921	-	-
$C_{D_{\delta_{ele_0}}}$	0.0366	$C_{Y_{\delta_{rud_1}}}$	0.4082	-	-
-	-	$C_{Y_{\delta_{rud_0}}}$	0.2054	-	-

Table 5.1: Force Coefficients (Chakraborty et al. 2011)

Pitching Moment Coefficient:

$$\begin{aligned} C_m &= (C_{m_{\alpha_2}}\alpha^2 + C_{m_{\alpha_1}}\alpha + C_{m_{\alpha_0}}) \\ &+ (C_{m_{\delta_{ele_2}}}\alpha^2 + C_{m_{\delta_{ele_1}}}\alpha + C_{m_{\delta_{ele_0}}})\delta_{ele} \\ &+ \frac{\bar{c}q}{2V}(C_{m_{q_3}}\alpha^3 + C_{m_{q_2}}\alpha^2 + C_{m_{q_1}}\alpha + C_{m_{q_0}}) \end{aligned} \tag{5.3b}$$

Yawing Moment Coefficient:

$$\begin{aligned} C_n &= (C_{n_{\beta_2}}\alpha^2 + C_{n_{\beta_1}}\alpha + C_{n_{\beta_0}})\beta \\ &+ (C_{n_{\delta_{rud_4}}}\alpha^4 + C_{n_{\delta_{rud_3}}}\alpha^3 + C_{n_{\delta_{rud_2}}}\alpha^2 + C_{n_{\delta_{rud_1}}}\alpha + C_{n_{\delta_{rud_0}}})\delta_{rud} \\ &+ (C_{n_{\delta_{ail_3}}}\alpha^3 + C_{n_{\delta_{ail_2}}}\alpha^2 + C_{n_{\delta_{ail_1}}}\alpha + C_{n_{\delta_{ail_0}}})\delta_{ail} \\ &+ \frac{bp}{2V}(C_{n_{p_1}}\alpha + C_{n_{p_0}}) + \frac{br}{2V}(C_{n_{r_1}}\alpha + C_{n_{r_0}}) \end{aligned} \tag{5.3c}$$

Rolling Moment		**Pitching Moment**		**Yawing Moment**	
Coefficient	Value	Coefficient	Value	Coefficient	Value
$C_{l_{\beta_4}}$	-1.6196	$C_{m_{\alpha_2}}$	-1.2897	$C_{n_{\beta_2}}$	-0.3816
$C_{l_{\beta_3}}$	2.3843	$C_{m_{\alpha_1}}$	0.511	$C_{n_{\beta_1}}$	0.0329
$C_{l_{\beta_2}}$	-0.3620	$C_{m_{\alpha_0}}$	-0.0866	$C_{n_{\beta_0}}$	0.0885
$C_{l_{\beta_1}}$	-0.4153	$C_{m_{\delta_{ele_2}}}$	0.9338	$C_{n_{\delta_{ail_3}}}$	0.2694
$C_{l_{\beta_0}}$	-0.0556	$C_{m_{\delta_{ele_1}}}$	-0.3245	$C_{n_{\delta_{ail_2}}}$	-0.3413
$C_{l_{\delta_{ail_3}}}$	0.1989	$C_{m_{\delta_{ele_0}}}$	-0.9051	$C_{n_{\delta_{ail_1}}}$	0.0584
$C_{l_{\delta_{ail_2}}}$	-0.2646	$C_{m_{q_3}}$	64.7190	$C_{n_{\delta_{ail_0}}}$	0.0104
$C_{l_{\delta_{ail_1}}}$	-0.0516	$C_{m_{q_2}}$	-68.5641	$C_{n_{\delta_{rud_4}}}$	0.3899
$C_{l_{\delta_{ail_0}}}$	0.1424	$C_{m_{q_1}}$	10.9921	$C_{n_{\delta_{rud_3}}}$	-0.898
$C_{l_{\delta_{rud_3}}}$	-0.0274	$C_{m_{q_0}}$	-4.1186	$C_{n_{\delta_{rud_2}}}$	0.5564
$C_{l_{\delta_{rud_2}}}$	0.0083	-	-	$C_{n_{\delta_{rud_1}}}$	-0.0176
$C_{l_{\delta_{rud_1}}}$	0.0014	-	-	$C_{n_{\delta_{rud_0}}}$	-0.0780
$C_{l_{\delta_{rud_0}}}$	0.0129	-	-	$C_{n_{p_1}}$	-0.0881
$C_{l_{p_1}}$	0.2377	-	-	$C_{n_{p_0}}$	0.0792
$C_{l_{p_0}}$	-0.3540	-	-	$C_{n_{r_1}}$	-0.1307
$C_{l_{r_2}}$	-1.0871	-	-	$C_{n_{r_0}}$	-0.4326
$C_{l_{r_1}}$	0.7804	-	-	-	-
$C_{l_{r_0}}$	0.1983	-	-	-	-

Table 5.2: Moment Coefficients (Chakraborty et al. 2011)

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