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TWIN ACTIVE SIDE STICK CONFIGURATION MODEL AND PILOT-INDUCED OSCILLATIONS SUPPRESSION ALGORITHM

SIMULACE KOMBINACE DVOU KNIPLŮ ACTIVE SIDE STICK A ALGORITMUS POTLAČENÍ PILOTEM INDUKOVANÝCH OSCILACÍ

DIPLOMOVÁ PRÁCE
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Ředitel ústavu Vám v souladu se zákonem č.111/1998 o vysokých školách a se Studijním a zkušebním řádem VUT v Brně určuje následující téma diplomové práce:

Simulace kombinace dvou kniplů Active Side Stick a algoritmus potlačení pilotem indukovaných oscilací

v anglickém jazyce:

Twin Active Side Stick Configuration Model and Pilot-Induced Oscillations Suppression Algorithm

Stručná charakteristika problematiky úkolu:

V aplikacích řízení letadel systémy fly-by-wire, které nahrazují klasické mechanické propojení řídících ploch a kniplu pilota propojením elektronickým, může docházet k nedostatečné zpětné vazbě mezi letadlem a pilotem. Knipl Active Side Stick se tomuto snaží předcházet použitím motorů pro simulaci odezvy letadla a implementaci pokročilých funkcí řízení.
Cílem práce je vytvořit simulační model kniplu Active Side Stick v programu MATLAB Simulink s ohledem na jeho propojení se stejným kniplem kopilota a se simulačním modelem letadla. Model kniplu, případně reálný joystick se silovou zpětnou vazbou bude dále použit pro vývoj algoritmu pro potlačení pilotem indukovaných oscilací.

Cíle diplomové práce:

- Seznamte se s funkcí kniplu Active Side Stick firmy Honeywell.
- Sestavte model funkcí kniplu Active Side Stick pomocí programu MATLAB Simulink a realizujte propojení dvou shodných modelů.
- Seznamte se s problémem pilotem indukovaných oscilací a technikami jejich detekce a potlačení.
- Využijte model kniplu Active Side Stick, případně reálný joystick se silovou zpětnou vazbou k návrhu algoritmu potlačení pilotem indukovaných oscilací na základě silové zpětné vazby.

Seznam odborné literatury:

- Klyde, D. H. (1995). "Unified Pilot-Induced Oscillation Theory. Volume 1. PIO Analysis with Linear and Nonlinear Effective Vehicle Characteristics, Including Rate Limiting." DTIC Document.

Vedoucí diplomové práce: Ing. Ondřej Klusáček

Termín odevzdání diplomové práce je stanoven časovým plánem akademického roku 2011/2012.

V Brně, dne 27.10.2011

L.S.

prof. Ing. Jindřich Petruška, CSc. Ředitel ústavu	prof. RNDr. Miroslav Doupovec, CSc. Děkan fakulty

Anotace

Diplomová práce se zabývá představením, popisem a vytvořením modelu postranní řídicí páky pilota s aktivní silovou zpětnou vazbou firmy Honeywell International Inc. v prostředí MATLAB Simulink. Dále pak představením problému pilotem indukovaných oscilací a možnostmi jejich předcházení, detekce a potlačení. Model řídicí páky se silovou zpětnou vazbou je použit pro potlačení detekovaných oscilací v simulaci letounu.

Klíčová slova

aktivní postranní řídicí páka, knipl, aktivní silová zpětná vazba, fly-by-wire, pilotem indukované oscilace, MATLAB Simulink, Honeywell

Annotation

Diploma thesis is to present, describe and develop a MATLAB Simulink model of an active side stick controller by Honeywell International Inc. company. Second part of thesis deals with pilot-induced oscillation phenomena and methods to prevent, detect and suppress them. Active force feedback equipped side stick model is used to suppress oscillations detected during aircraft simulation.

Key Words

active side stick, pilot stick, active force feedback, fly-by-wire, pilot-induced oscillations, MATLAB Simulink, Honeywell

Bibliographic citation:

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Affidavit:

I declare, that the submitted thesis was written only by me with guidance from my supervisor and all used sources are referred bellow.

Filip Vadlejch ……………………………………….
Brno 2012 author's signature

Acknowledgement

I would like to thank all the people whose contribution helped me during my work and creation of this thesis. I especially appreciate help from my supervisor, Ing. Ondřej Klusáček, and advices in fields of aerodynamics, pilot-induced oscillations and active side stick design from Ing. Jan Tomáš, Ph.D., Ing. Pavel Hynek, Ph.D. and Ing. Petr Liškář.

Very special thanks goes to my family and friends who supported me through the whole time of my studies.

Table of Contents

List of Symbols

A	state matrix of state space	$[-]$
B	input matrix of state space	$[-]$
$\bar{c}$	mean geometric chord	$[m]$
$\bar{c}_e$	elevator surface mean geometric chord	$[m]$
C	stick friction constant	$[Nms/rad]$
C_D	drag coefficient	$[-]$
C_{D_0}	drag coefficient for zero conditions	$[-]$
C_{D_α}	AOA contribution coefficient to drag	$[rad^{-1}]$
$C_{D_{i_h}}$	HS position contribution coefficient to drag	$[rad^{-1}]$
C_{D_δ}	surface deflection contribution coefficient to drag	$[rad^{-1}]$
C_{h_α}	surface hinge moment contribution from AOA	$[rad^{-1}]$
C_{h_δ}	surface hinge moment contribution surface deflection	$[rad^{-1}]$
C_L	lift coefficient	$[-]$
C_{L_0}	lift coefficient for zero conditions	$[-]$
C_{L_α}	AOA contribution coefficient to lift	$[rad^{-1}]$
$C_{L_{i_h}}$	HS position contribution coefficient to lift	$[rad^{-1}]$
C_{L_q}	airplane angular velocity contribution coefficient to lift	$[rad^{-1}]$
C_{L_δ}	surface deflection contribution coefficient to lift	$[rad^{-1}]$
C_M	pitching moment coefficient	$[-]$
C_{M_0}	pitching moment coefficient for zero conditions	$[-]$
C_{M_α}	AOA contribution coefficient to pitching moment	$[rad^{-1}]$
$C_{M_{i_h}}$	HS position contribution coefficient to pitching moment	$[rad^{-1}]$
C_{M_q}	airplane ang. velocity contribution coeff. to pitching moment	$[rad^{-1}]$
C_{M_δ}	surface deflection contribution coefficient to pitching moment	$[rad^{-1}]$
d_T	distance of thrust line to center of gravity	$[m]$
E_D	energy of damping	$[J]$
E_K	kinetic energy	$[J]$
E_P	potential energy	$[J]$
$F(p)$	open loop system transfer function	$[-]$
F_{A_x}	aerodynamic force in X body fixed axis	$[N]$
F_{A_z}	aerodynamic force in Z body fixed axis	$[N]$
F_{T_x}	thrust generated force in X body fixed axis	$[N]$
F_{T_z}	thrust generated force in Z body fixed axis	$[N]$
F_S	stick force	$[N]$
G	gearing gain	$[-]$
i	armature current	$[A]$
i_h	horizontal stabilizer (HS) position	$[rad]$
I	grip’s moment of inertia	$[kg\ m^2]$
k	spring stiffness	$[N/m]$
K_m	torque constant	$[Nm/A]$
l_k	spring position	$[m]$

L	terminal inductance	$[H]$
M_A	aerodynamic moment along Y body fixed axis	$[Nm]$
M_M	motor moment	$[Nm]$
M_T	thrust generated moment along Y body fixed axis	$[Nm]$
M_f	friction moment	$[Nm]$
p	Laplace operator	$[-]$
P	work of outer forces	$[J]$
q	airplane angular velocity	$[rad/sec]$
$\bar{q}$	airplane dynamic pressure	$[kg/m^2]$
$\bar{q}_h$	dynamic pressure on tail surfaces	$[kg/m^2]$
R	terminal resistance	$[\Omega]$
$R_i(p)$	current regulator transfer function	$[-]$
S	airplane area	$[m^2]$
S_e	elevator surface area	$[m^2]$
T	engines thrust	$[N]$
V_p	airplane airspeed	$[m/s]$
α	aircraft angle of attack	$[rad]$
δ	control surface deflection	$[rad]$
ε	downwash angle	$[rad]$
θ, γ	pitch attitude angle	$[rad]$
φ	stick deflection	$[rad]$
τ_σ	EC motor current time constant	$[s^{-1}]$

List of Abbreviations and Acronyms

AC	alternating current
AOA	angle of attack
BLDC	brushless DC motor
DC	direct current
EC	electrically commutated
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FBW	fly-by-wire
FCS	flight control system
FF	force feedback
HS	horizontal stabilizer
PIO	pilot-induced oscillation
PR	pitch rate
RVDT	rotary variable differential transformer
SAAB AB	Svenska Aeroplan Aktiebolaget

1. Introduction

Evolution of flight control systems led to use of hydraulic circuits and digital signal processing. Although this system is without question advantageous removing the mechanical linkage causes loss of natural force feedback in cockpit controls. The purpose of this thesis is to sum up methods of introducing force feedback into pilot cockpit controls artificially to restore haptic situation awareness and to present active side stick assembly and its features. Force feedback controls are necessary in fly-by-wire aircraft control applications where direct mechanical linkage between pilot and aircraft control surfaces is removed. Active force feedback allows authentic reproduction of aerodynamic forces induced on control surfaces into cockpit controls and thus significantly reduces pilot workload and improves air transport safety.

Thesis is divided into two main parts. First part deals with active side stick introduction (chapter 2) and development of a simulation model (chapter 3). A MATLAB Simulink model is developed to demonstrate force feedback mechanism and cooperation of two interconnected active side sticks. Aircraft simulation is used to determine adequate forces to be presented into the side stick. A simple pilot behavior model is used to control the aircraft closed loop system.

Second part of the thesis deals with pilot-induced oscillations phenomena, sums up oscillations categories and their respective causes (chapter 4) and focuses on prevention, suppression and mitigation of oscillations originating from surface rate or position limiting in combination with disproportional pilot responses during high demanding tasks (chapter 6). Several suppression schemes are presented, advantages and disadvantages of individual schemes are described and results from simulations are compared. Next, an oscillations detection algorithm is reproduced and used in combination with oscillations suppression methods to confirm its effectiveness. Active force feedback side stick model is then connected to aircraft simulation (described in chapter 5) and force feedback is used for pilot-induced oscillations suppression.

2. Flight Control Systems

A flight control system (FCS) is a device or set of devices providing coupling between the pilot and the aircraft allowing the pilot to control aircraft movement. A conventional FCS for fixed-wing aircrafts consists of aircraft control surfaces (primary control surfaces commonly including ailerons, elevators and rudder; secondary control surfaces may include flaps, slats, spoilers or lift dumpers, trim tabs, etc.), cockpit control mechanism and linkages providing connection between cockpit controls and control surfaces. Also engines and engine controls are considered as part of the FCS as they influence overall behavior of the aircraft.

During the first controlled gliding flights (the earliest well-documented controlled flights were performed by Otto Lilienthal near year 1891) the movement of the plane was controlled only by shifting pilot's body, i.e. relocating the center of gravity, which can be hardly considered as a FCS from today's point of view. The first attempts to control aircraft movement by deflecting a control surface have also been performed by Otto Lilienthal [1]. The control system of Lilienthal's gliders was obviously designed as a purely mechanical assemblage. The aileron control surface, for example, was end part of the wing, which could be wrapped downwards changing the wing's airfoil and angle of attack of the curved part of wing, thus increasing lift force on one part of the wing. The control parts of surfaces were connected by a set of wires to a hoop actuated by pilot. This layout was then adopted by all other aircraft manufacturers and developed further. Lilienthal's hoop became a stick and the control surfaces were separated from the wing body for easier movement. However the evolution of mechanical connection assembly was not as distinctive. Although in a way much more complex than couple of wires and pulleys the mechanical connection between cockpit controls and control surfaces is common in all small aircrafts these days.

As the aircrafts became larger (due to required larger transport capacity) the control systems became more complicated, more parts were needed for the connection and the weight of the parts rise. Also the aerodynamic forces generated on control surfaces enlarged due to higher speeds, larger control surfaces and added friction in control mechanism and controlling of such large aircraft became more difficult or even impossible. To decrease forces present in cockpit controls a hydraulic circuit was added. With hydraulic actuation pilot controls only the hydraulic valves which then move the control surface to desired position.

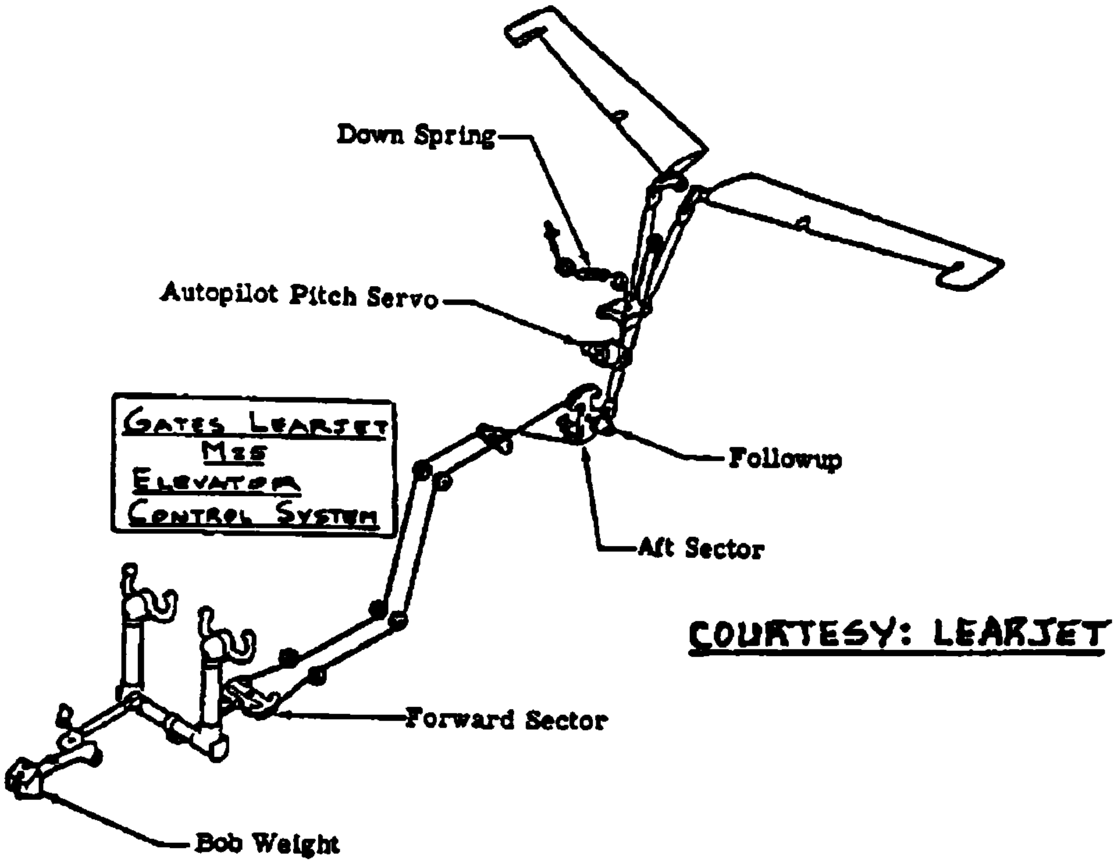

Figure 2-1: Example of Reversible Flight Control System [2]

2.1. Fly-by-wire

The hydro-mechanical FCS solved only one of issues preventing of building larger aircrafts. There still was a mechanical circuit inclinable to breakages or jamming, with weight and complexity unacceptable in modern aircraft. For these reason the whole connection between cockpit controls and surfaces was replaced by an electrical interface. The pilot's actions on the cockpit control are converted via set of sensors to electrical signals which are then processed by a computer and passed to actuators deflecting the control surfaces (either by opening hydraulic valve or moving an electric actuator). Communication between all parts of such FCS is done by electrical wires, hence the term fly-by-wire (FBW).

This solution brings many advantages. Apart from the weight and mechanical complexity reduction mentioned above, maintenance time of such system is reduced as the system can check its connection itself, without a technician required to inspect the linkages. Processing the signals by a computer also allows the manufacturers to equip the plane with functions reducing pilot's workload and improving aircraft handling qualities. The computer can modify aircraft flight characteristics and with high rate of operations per second is able to control the aircraft even when it is dynamically instable. The FBW FCS can also provide warnings for dangerous maneuvers (stall, over bank …) or can even limit pilot’s actions due to flight envelope protection reasons. Time required for training a pilot for a new airplane type can be also significantly reduced if FBW systems of several airplanes make their dynamics similar to each other. The computer can host or elaborate the autopilot function and other high level functions and control laws. Price of such system is then limited mainly by price of the software development.

The disadvantages of the FBW FCS come mainly from dependability of the computer and the sensors. For safety reasons the system must be redundant, so in case of failure its functionality is not compromised. The computers, all wires, sensors and also actuators are doubled or tripled to prevent any malfunction and system must detect any failure and bypass or vote out the faulty hardware. This multiplication partially vitiates the weight reduction but is necessary for safety reasons. With implementation of system monitors, advanced controllers and regular maintenance reliability of modern FBW systems improved so drastically that it is commonly used in civil air transport and the manufacturers can focus on other issues caused by removing the mechanical linkage between pilot and aircraft.

2.2. Cockpit controls

Cockpit controls undergone a rather gentle evolution contrary to the flight control systems. Lilienthal experimented with different controls designs and probably all of them were revised during the history of controlled flight. Wright brothers for example used a lever for elevation control; many later designs were using a control wheel. Experiments with cockpit controls shape generally led to three basic designs used today:

- A **center stick** is truly widespread in small aircrafts, both civil and military. Center stick is basically a lever placed between pilot’s legs (hence “center” stick). Pilot controls elevation by pushing or pulling the stick in longitudinal direction and banking by moving the stick in lateral direction. The center stick can be hold by left or right hand based on cockpit controls layout and often carries several buttons and switches so pilot doesn’t have to release the controls when for example communicating over radio.
- A **control column** with control **wheel** is a larger version of center stick. It is also placed in front of pilot and elevation control is performed by pushing and pulling the column as well. The difference lies in the control wheel. Pilot operates the banking by turning a wheel similar to car’s wheel, so there is no lateral motion of the column. The wheel itself has many shapes, from a full hoop to U, V or W shaped “yoke”. This design is used in larger aircrafts where larger control forces are required.

- A **side stick** is again similar to the center stick. Apart from the previously mentioned solutions side sticks are located on the side console of the pilot, either on the left or right side. This design is typically found on aircrafts equipped with fly-by-wire FCS.

All of described elevation and banking control designs are complemented by pedals for yaw control and engine controls in powered planes.

In non-FBW applications where physical link is present, pilot is alerted of aircraft response by force generated in the control stick by aerodynamic forces present on deflected surfaces. Removing of the physical link causes a need for artificial feel devices to simulate the aircraft response. There are several ways with different complexity being used to generate the force feedback in cockpit sticks:

- The easiest approach to present a force making pilot aware of a stick deflection is to include a spring mechanism centering the stick into neutral position. This approach, commonly named as **passive stick** approach, has a general advantage in its mechanical essence. No electrical power is needed for the centering spring. The main disadvantage is the lack of response to changes of aerodynamic forces generated on control surfaces. The dependency between airspeed and stick forces, for example, is not presented into the passive stick.
- Spring centering with electrically modified force gain can be used to simulate dependency between airspeed and stick forces. An actuator (perhaps a servomotor) is used to preload the centering spring when the airspeed increases. Such approach is sufficient to simulate airspeed force gain but can’t reliably accommodate advanced functions as the pilot – copilot stick coupling and may not be satisfactory while performing high demanding tasks such as airborne refueling or landing. Also the number of springs and related actuators needs to be relatively high to modify stick characteristics independently in both axes [3].
- The newest solution to implement the artificial feel of aircraft responses is to present the surface generated forces into the stick directly by an actuator. The centering force of the spring is replaced by a torque generated by a servomotor or hydraulic valve. Such stick is called an **active stick**, due to active effect of the actuators to the pilot’s force feedback. The magnitude of inserted force may be computed either from force sensors implemented in surface actuators or from a mathematical model of the airplane. The force produced by the copilot on his stick can be summed with the aircraft response forces creating a simple implementation of pilot – copilot stick coupling. Pilot – copilot coupling means not only presenting forces from one stick to the other but also mutual position tracking. This is the main difference from passive stick as there is no way the passive stick can change its position to track either second stick deflection, autopilot actions or control surfaces movements. Next with sufficient stick actuator torque and response speed of the actuators advanced function can be easily implemented to prevent stall, expeditious stick deflections or various oscillations. The overall magnitude of forces presented in stick may be tunable so the pilot can adjust the haptic feedback to suite his expectations.

2.3. Honeywell Active Side Stick

Honeywell International Inc. (Honeywell) described and developed several versions on the active stick assembly in a side stick design. Honeywell registered a patent describing Active Control Stick Assembly [4]. The patent describes several versions of active stick assembly where the most elaborated one incorporates two rotary actuators, one for each axis, producing their torque to the stick body by cables (Figure 2-2). The stick support (84) is housed in a crane (88) guiding the support’s spherical bottoms surface in a manner such that the longitudinal axis of the support rotates with respect to one or both rotational axes. One centering spring (92) passively biases control stick support body toward a null position, creating a backup mechanical feedback device in case of power supply or actuator failure. The rotary actuator (94) is mechanically linked to control stick support body via cables (96 and 98). During operation the rotary actuator instructed by a controller selectively retracts and lets out cables to generate controlled torque about a rotational axis and thereby provide haptic force feedback to control stick [4].

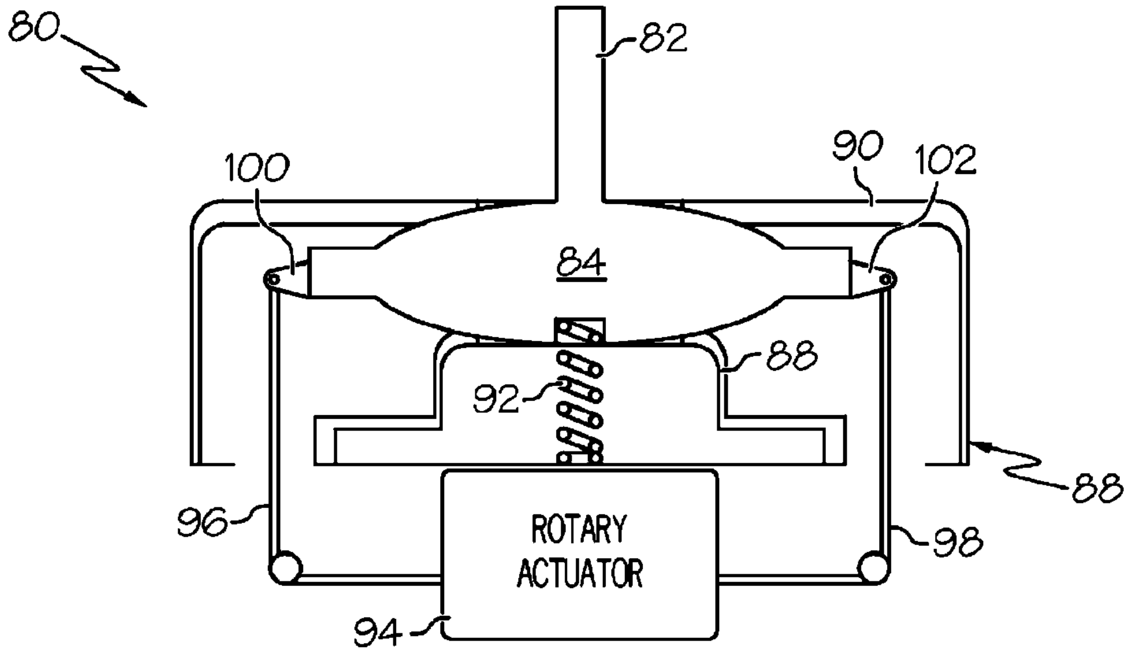

Figure 2-2: Honeywell Active Control Stick Design

Honeywell side stick incorporates a force sensor measuring the force pilot is producing to the stick. The measured force is used as a feedback to the rotary actuator controller so the correct force magnitude against or along with the pilot action is generated. The generated force itself is computed to simulate aircraft response as described above. In case when two sticks are connected in a pilot – copilot dual stick operation the generated force is summed with force measured by the opposite stick force sensor to produce the copilot actions into the pilot’s stick and vice versa.

The goal of this thesis is to produce a simulation model of the Honeywell active side stick in MATLAB Simulink to prove this force feedback concept. Let’s review some of the side stick’s features.

2.4. Active Side Stick Functionality

The general function of the active side stick is the same as of all other pilot sticks – to provide **interface between pilot and the aircraft**. This means there has to be several sensors to measure pilot command. Common approach is to have separated sensor groups for the two axes of stick rotation, the pitch axis and the roll axis. (pitch axis, i.e. longitudinal axis controls elevation, pushing the stick in forward direction moves aircraft nose downwards for descending, pulling the stick backward moves nose up; roll axis, i.e. lateral axis controls bank angle, left deflection causes counterclockwise rotation, right deflection causes clockwise rotation of the aircraft along longitudinal axis). These sensor groups are essential for aircraft control and thus the safety of flight and are multiplied for this reason to conserve control redundancy in case of any sensor failure. The common number of sensors for one axis is 4 to 6. More sensors are simply harder to place in limited area reserved for cockpit controls, less sensors are inclinable for lowering handling qualities in case of one sensor failure (let’s consider the case of two sensors: in case of one sensor failure there are two sets of data received for one axis deflection without confirmation which set of data is valid; minimal number of sensors per axis is therefore 3 to vote out the corrupted one).

Number of sensors corresponds to type of sensors used. More durable sensors are less likely to fail and thus lower number of such sensors is required to meet safety requirements. There is variety of angular position sensors available, but only several types are suitable for an aircraft application. In gaming joysticks which imitate real cockpit controls we can find virtually every imaginable sensor from low cost potentiometers which degrade quite rapidly to Hall effect sensors in pricier devices. Hall effect sensors and different types of encoders may be too bulky to mount higher number of them in aircraft side stick assembly. Common approach uses Rotary Variable Differential Transformers (RVDT) due to sensors small size, sturdiness, low sensitivity to temperature, voltage and frequency variations and simple and therefore reliable control electronics [5]. Operating range of RVDTs is about ±30 degrees with great accuracy which is sufficient for stick position monitoring. Output from all RVDTs is then compared and potentially faulty sensors are voted out, the rest of data is averaged and enters the actuator control units.

The other critical half of pilot to aircraft interface is a **feedback from aircraft to pilot**. As mentioned above pilot should be aware of stick deflection in order to reliably control the aircraft. Studies shows [6], [7] that force feedback is more natural to pilot and does not increase the pilot's workload. The feeling is natural and pilot is aware of situation without excessive delays compared to for example visual feedbacks. This is the main active side stick's advantage. The aircraft response is generated in stick with high fidelity, similar to real response of mechanically interconnected flight control systems. The force magnitude is computed from current data from aircraft and can thus quickly respond to changes in airspeed, angle of attack or normal acceleration. Forces presented to active side stick are of course not the real forces at the control surfaces but are normalized not to exceed some defined maximal amplitudes so even larger aircrafts are easy to control. It is very important that the maximum amount of force artificially generated in stick is not too high to allow proper handling. Pilot should be always able to achieve necessary stick position by applying greater force even when motor is pushing in opposite direction. FBW equipped aircrafts often use functions to reduce pilot authority to avoid some rapid maneuvers. These functions however include algorithms to restore pilot authority when necessary, for example when pilot is using full stick deflection. Similar algorithm can be used for the active feedback making the stick softer when in corner positions if limiting force feedback would to be generated.

As stated in Honeywell active side stick patent [4], there are several ways to introduce active force feedback into the stick. Required change in force magnitude can sometimes be very steep. For this reason only several ways are considerable for sufficient force feedback. We can rule out pneumatic and hydraulic systems for both slowness and large required area. The best solution appears to be an electric actuator. Again because the space available in side stick assembly AC motors are not applicable. In addition most aircrafts power supply is DC [8] so there would be a need for additional electronics occupying more space. Current DC motors on the other hand are very durable and powerful even in small sizes. With DC motor we can achieve a high starting torque which is necessary for side stick application where the motor doesn't really turns but most of the time presents torque to stick held in place by the pilot. More on the plus side, DC motors can be momentarily highly overloaded to generate peak of force in the side stick and have relatively small mechanical time constant [9].

If we consider a nominal voltage about 20 volts DC and current up to 5 amperes we can find number of suitable motors within sizes desirable for aircraft industry [10]. With a planetary gearheads the motor is able to produce moments above 45 Nm which (for a common 15 centimeter long stick grip) corresponds to 300 N of pilot force applied. This is highly over recommended values for maximum control forces defined by FAA (see Table 2-1).

Maximum Cockpit Control Forces Allowed			
Cockpit control forces are given in newton [N] as applied to the stick, control wheel or rudder pedal(s)	Pitch	Roll	Yaw
a) For temporary application:			
Stick	270	135	
Wheel (applied to rim)	330	270	
Rudder pedal(s)			670
b) For prolonged application:	45	25	90

Table 2-1: Maximum Cockpit Control Forces Allowed by FAR 23 and FAR 25 (FAA Federal Aviation Regulations), taken from [2].

As in the case of position sensors there is also required reliability and small demand after service of the electric motors. This calls for use of brushless motors to enlarge period of service caused by need to check and/or switch the worn brushes. It can be assumed the side stick assembly will have brushless DC motor (BLDC for brushless DC or also EC for electrically commutated).

If an electric motor is included in the assembly its sensors (if there are any) can be used also for sensing the stick handle movement or position. Although the motor should be primarily torque regulated it should always follow the stick position as there is a fixed mechanical connection through the gearing.

Regarding the motor to stick connection it is obvious that there needs to be a **non-slipping connection** to guarantee the required torque will be presented into the stick grip. Honeywell patent again describes several possibilities [4]. The easiest solution coming to mind is a set of gears between motor axis and stick's grip axis of rotation. In this case the two axes should be placed as close to each other as possible to reduce number and size of gears required otherwise the efficiency of such connection will decrease rapidly. For a farther relative placement of the axes set of cables described above (Figure 2-2) seems to have an advantage in efficiency over the gearing. A combination of both methods is use of synchronous belt drive, which will guarantee efficiency of a close range gearing with possibility to place motor away from the stick assembly as with use of cables. This is essential so the motors can be mounted on a fixed, non-moving part of assembly to reduce moment of inertia of the stick's grip.

In all described variants there can be introduced an additional gearing from the motor's output shaft to stick rotational axis by changing the diameter of gear wheels or pulleys. This way we can further modify the motor torque characteristics, so the manner of connection needs to be considered during drive design.

Another fundamental part of the active side stick assembly is a **force sensor**. Measuring the force applied by pilot is essential for almost all force feedback features (except for stick shaker functions providing different warning annunciations). There are basically two ways of gaining the force value – by measuring or by computing from other variables. Once again the two methods can be combined to gain a certain redundancy which however in this application is not as vital as in case of stick deflection measuring.

Both methods need to obtain not only force magnitude but also the force direction, so we need at least one value per axis. Computing the force from other variables can be implemented in motor controller as the motor should be torque regulated it is only matter of gearing constants to compute force applied on stick's grip in given axis. However due to the gearing there can be a certain delay, even a drift caused by gearing elasticity. Measuring the force directly in the stick's grip by strain gauges or special force sensors [11] will give us the exact applied force. Another plus of using sensors is that we can position multiple sensors in different directions so the force applied under certain angle from axes of rotation is measured accurately.

2.5. Two Side Sticks Coupling

In side stick applications there are always two same sticks present – the pilot's stick and the copilot's stick. On a non-FBW aircraft there is a mechanical connection between the two sticks making them move together as one body and also transferring forces applied on one stick into the second stick. When removing the mechanical link between sticks and surfaces we usually remove also the link between the two sticks. In case of center sticks and columns there can be some mechanical interlock preserved but for the side sticks the connection mechanism would be overly complicated. The lack of pilot and copilot's sticks coupling gives us second reason to use a force algorithm.

Let's analyze this deeper. From the first flights during training the pilot is used to have a direct mechanical connection to his instructor through the stick interconnection. When advancing to larger aircrafts with FBW but still with stick interconnection the same awareness of second pilot actions is present. In situations where the pilots decide to deflect their sticks in opposite directions they are immediately notified by abnormally increasing force in the stick. If we consider both pilots pushing/pulling with the exact same force magnitude in opposite directions the resulting stick deflection will be null in both sticks thus the output command will also be null. For these cases such systems must have a mechanism which allows disconnection of the sticks to allow pilots to take over the control.

If the same situation occurs with a passive side stick equipped cockpit both pilots would command certain opposite deflections getting only the passive feedback generated by centering spring. When the takeover switch gives the same priority to both pilots FCS would average command from both stick units giving a null command to actuators. Pilot may consider the aircraft not responding and further increase stick deflection without realizing the reason for such behavior. When a force feedback coupling is introduced to side sticks pilots are aware of the other pilot's actions and may use the takeover switch when needed.

Similar reasoning can be applied for overall in-flight situation awareness. Per pilots experiences [12] the passive side stick with automatic centering doesn't provide any information about the aircraft position and state. When the aircraft is trimmed for a steady flight with elevator deflection using a horizontal stabilizer the sticks should remain in deflected position when no pilot's force is applied. Pilot can then tell the attitude of such aircraft only by looking at the cockpit controls. To overcome this disadvantage side sticks used these days are in fact not control columns but rather attitude and bank angle "selectors" [12]. Pilot doesn't command control surface deflection but deflect the stick to gain a desired state (let's say pulling the stick to gain a climbing rate) and then releases it to center position. FCS is then in command of the control surfaces to keep the selected state. Deflection of the stick therefore doesn't represent the control surface deflection but rate of control surface deflection instead (note this scheme is mainly implemented on Airbus airplanes, Boeing airplanes are usually equipped with passive center sticks with stick shakers for warning providing purposes and classical deflection selector approach).

3. MATLAB Simulink Model of Active Side Stick

A MATLAB Simulink simulation model of side stick with active force feedback was developed to demonstrate capabilities of this concept. Per functionalities discussion (chapter 2.4) a system with following characteristics was modeled:

- 15 centimeter long stick grip
- centering spring for passive force feedback
- EC motor for active force feedback
- torque control of the motor
- force sensors

The size of stick was chosen to approximate the real side stick being used. A gaming joystick was used to gain estimation of stick weight and consequently the inertia moment (grip is assumed to be a rod with rotation axis at one end). Centering spring stiffness was set to produce a nominal force defined in Table 2-1 for respective axes. The passive feedback provides force feel of magnitude for temporary application when a full stick deflection is applied. Stick deflection is limited to ±30 degrees in both axes by simulated mechanical stops.

A simplified model of EC motor was used for simulation as there is no need to design the exact controller for specified motor type. Motor is connected to stick rotation by a gearing ratio with some given efficiency. Defining the exact type of connection will only result in updating gearing ratio and efficiency therefore it is not necessary to go deeper into modeling torque transition.

Model is equipped with simulated sensorics to produce necessary data. The number of “sensed” variables is reduced to minimum in order to model real application with limited area to place sensors. An artificial noise added to “sensed” variables.

3.1. One Axis Design

In following section the model will be described in more details. As both pitch and roll axes of the stick are highly similar only one will be analyzed. Let’s choose pitch axis as most of further functions will be regarding this axis. Both axes should be separated from sensorics and power drive point of view hence can be considered independent. In other words it is assumed a deflection in pitch axis would not cause any change in roll axis.

Side stick model can be divided into several subsystems per provided functions. Data flow among the subsystems represents the fundamental idea of active side stick assembly (Figure 3-1). Although pilot is holding the stick’s grip his applied force does not really move the stick body as it is held in position by the motor. Grip is equipped with force and position sensors; information about stick position is passed directly to FCS to drive respective surface deflection; force sensors output information about pilot's applied force into motor control unit where it is compared to force which is required for given stick deflection and aircraft state. In case of difference between desired and actual force feedback the controller moves the stick to achieve desired force by applying EC motor torque on the grip.

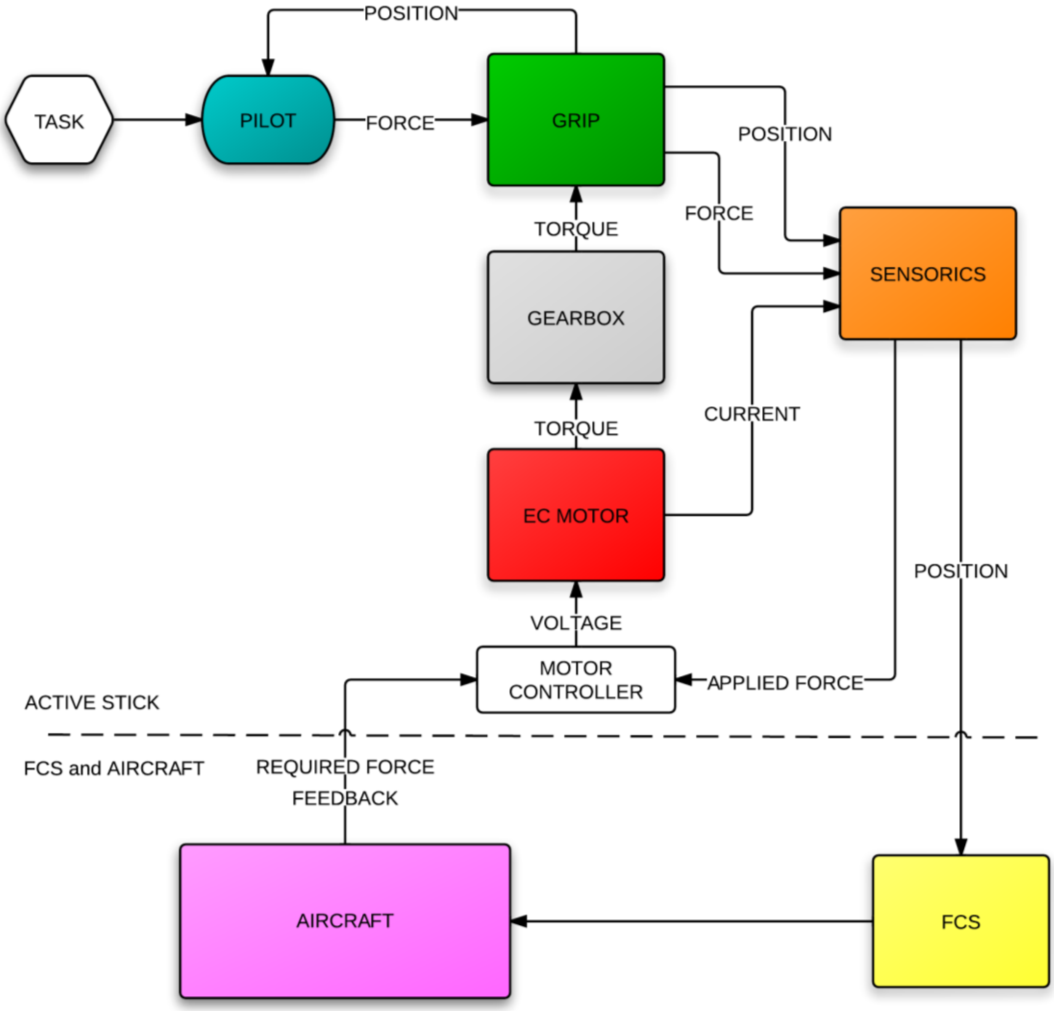

Figure 3-1: Active Side Stick Functionality - Pitch Axis

The **mechanical subsystem** is a model of stick's grip rotating about one axis. Model is representation of Lagrange equations of the second kind for a mass suspended on a spring with friction moment (Equation 3-1 through Equation 3-7).

$$\frac{d}{dt}\left(\frac{\partial E_K}{\partial \dot{\varphi}}\right) - \frac{\partial E_K}{\partial \varphi} + \frac{\partial E_D}{\partial \dot{\varphi}} + \frac{\partial E_P}{\partial \varphi} = \frac{\partial P}{\partial \varphi} \qquad \text{Equation 3-1}$$

where:

$$E_K = \frac{1}{2} I \dot{\varphi}^2 \qquad \text{Equation 3-2}$$

$$E_P = \frac{1}{2} k l_k^2 \varphi^2 \qquad \text{Equation 3-3}$$

$$E_D = 0 \qquad \text{Equation 3-4}$$

$$P = M_f + M_M \qquad \text{Equation 3-5}$$

$$M_f = C * sign(\dot{\varphi}) \qquad \text{Equation 3-6}$$

$$I = \frac{1}{3} m l^2 \qquad \text{Equation 3-7}$$

where:

φ	stick deflection
E_K	kinetic energy
E_P	potential energy
E_D	energy of damping (covered by friction moment)
I	grip's moment of inertia
k	spring stiffness
l_k	spring position
P	work of outer forces
M_f	friction moment
M_M	motor moment
C	friction constant

Such way of grip modeling provides the passive centering feature with force magnitudes in corner deflection described in section 2.4.

The stick deflection is directly driven by the motor through **gearbox subsystem**. Gearbox ratio is 1:180 with efficiency of 72%. It was already justified above (chapter 3) that this is a sufficient way of modeling a torque transition.

Motor is a simplified application of equations taken from [9]. Motor is torque regulated and thus for simulation purposes we can manage with basic current regulator as generated torque is directly proportional to armature current. Current regulator is designed using modulus-optimum tuning method per [13]. The current control loop is system with one time constant and transfer function per Equation 3-8. Standard proportional-integral regulator form gives desired regulator transfer function per Equation 3-9.

$$F(p) = \frac{1}{1 + \tau_\sigma p} \qquad \text{Equation 3-8}$$

$$R_i(p) = \frac{1}{2 * \tau_\sigma p} \qquad \text{Equation 3-9}$$

where:

$$\tau_\sigma = \frac{L}{R} \qquad \text{Equation 3-10}$$

where: $F(p)$ open loop system transfer function

τ_σ	time constant
$R_i(p)$	current regulator transfer function
p	Laplace operator
L	terminal inductance
R	terminal resistance

Generated torque is then equal to armature current multiplied by motor torque constant as per Equation 3-11.

$$M_M = K_M * i \qquad \text{Equation 3-11}$$

where:

K_M	motor torque constant
i	armature current

The applied force, stick deflection and motor current are consumed by **simulated sensors** to produce required variables. Armature current is measured to reproduce motor generated torque. Force and position sensors are implemented by adding a sensor noise to simulated variables to illustrate real sensor behavior.

Input force for the mechanical subsystem is generated by a **pilot model**. The basic idea of pilot input modeling is taken from [14], [15] and [7]. Pilot's behavior is modeled as a simple proportional gain with a time delay and stick position feedback (pilot is aware of the deflection) thus creating a stick position controller. For purposes of force feedback efficiency evaluation a method of "soft limits" for pilot force was implemented as the simulation sometimes needs to be able to put stick in different position than he is requesting. This method is inspired by anti-windup compensators; force pilot is applying on stick is in no way limited but when a certain defined threshold is reached the amount of force over the threshold (filtered through a system with a small time constant) is subtracted from the basic pilot model input.

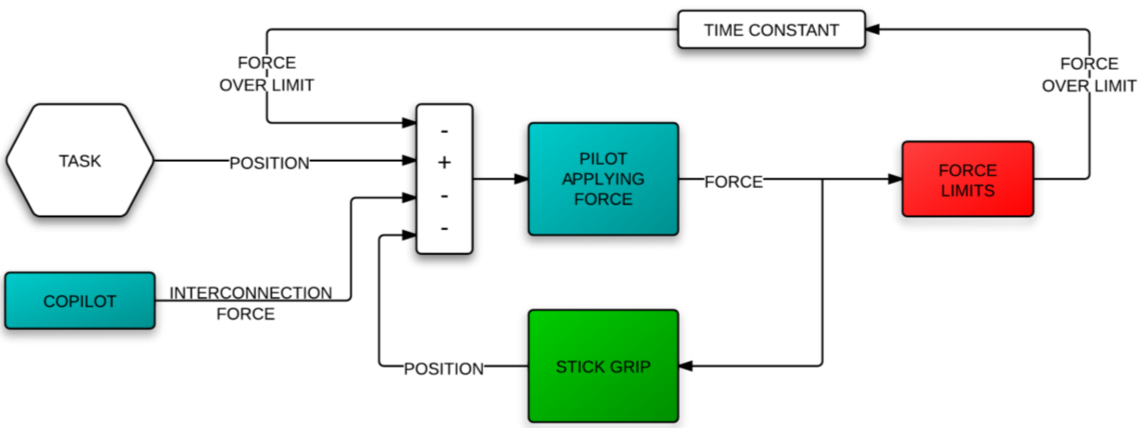

Figure 3-2: Pilot's Force "Soft Limits" Algorithm

This applied force regulation has proven very effective and is similar to expected pilot's behavior (Figure 3-3). In shown simulation pilot first gain desired stick position with appropriate force feedback. If the force feedback control algorithm starts generating a greater force pilot reacts with enlarging applied force to keep stick position. When certain limit force is present pilot eventually relaxes his grip and lowers the deflection.

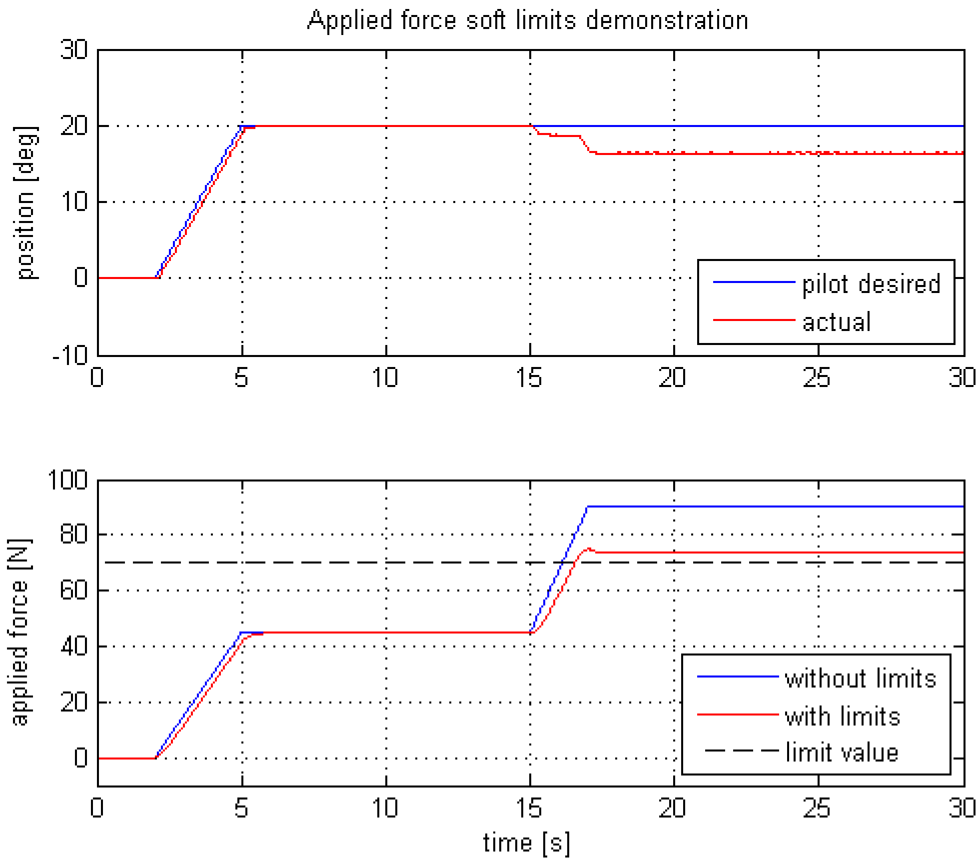

Figure 3-3: Demonstration of Pilot's Force "Soft Limits"

Pilot model also implements second pilot's force coming through stick interconnection simulation awareness. When pilot feels rapid copilot's action with different magnitude than his, he relaxes his grip. This is necessary in simulation in order to avoid keeping the desired position by pilots applying exactly same forces of opposite directions.

This model is obviously very sensitive to thresholds of soft limit and settings of speed and amount of deflection being relaxed under steady pressure. Many different parameter combinations were tested during aircraft response simulations and when necessary different settings were used to simulate certain behavior pattern (for example slower growth of applied force in combination with low soft limits is better model for artificial stick rate limiting tests, section 6.1.1). Another soft limit with greater time constant can be added to pilot model to simulate long term behavior as well. If this limit is set to zero pilot will over a time period slowly return to null position (preferably within minutes). This is however not important for dynamic behavior we are investigating in this thesis and such behavior is not implemented.

3.2. Two Axes Combined

In previous chapter we described the design of one axis and stated an assumption that the two axes are in design very similar. Combining the two axes is then reduced to placing them next to each other as there is no coupling.

The difference of the roll axis from previously described pitch axis is that the force feedback magnitude is considerably lower (Table 2-1). The passive force feedback spring was therefore tuned to produce the desired centering moment. Together with mechanical parameters the whole power drive can be redesigned as the smaller demanded torques don't require motor of same size and power as for the pitch force feedback. This factor should be considered during design of actual hardware. For our simulation no further changes were made as the roll axis was not used in any of the developed algorithms.

3.3. Two Active Side Stick Models Coupling and Force Feedback

The goal of side stick model development was a simulation of two side sticks coupling to demonstrate active stick advantage in this field. Two same stick models were connected through a subsystem called "stick control unit" providing desired coupling between pilot's and copilot's stick. Let's review the produced model.

Both side stick models are exactly the same per description in sections 3.1 and 3.2. Only the noise added to simulated sensors has a different pattern as it never can be the same in real sensors. The stick control unit elaborates pilot commands, determines aircraft force feedback magnitude and hosts a force feedback augmentation algorithm. That is a function providing the necessary pilot – copilot – aircraft coupling and is able to produce pilot's forces to copilot's side stick and vice versa. Augmentation forces are then all forces which are to given stick presented by other system than its pilot (i.e. the second pilot, forces to achieve desired feedback defined by aircraft state and forces by PIO mitigation algorithm described in section 6.3). An aircraft model to compute real forces which should be presented into the side stick is yet to be developed so the desired force feedback is computed only from stick deflection; this means the aircraft force feedback is passive in this simulation, only the stick coupling uses an active force feedback.

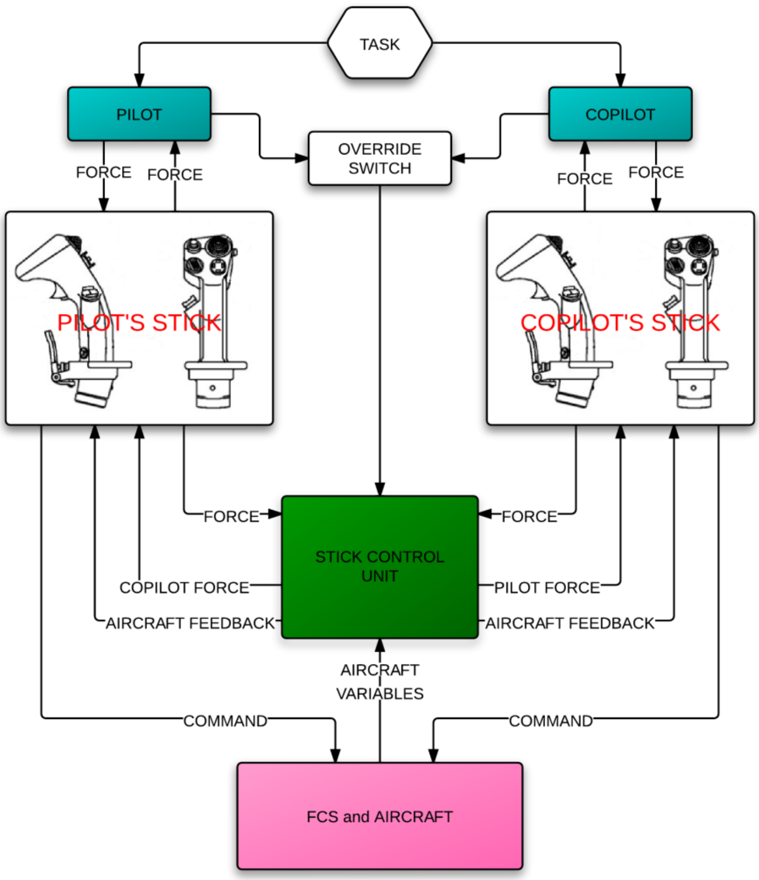

Figure 3-4: Two Active Side Sticks Coupling

Now we will look closer on the stick control unit. The main function is to present pilot's forces into copilots stick and vice versa. There is no additional logic on this path except override switch gain described below. Stick control unit also determines the amount of force feedback which both pilots should feel. The total desired feedback is split between pilots based on forces they're applying. This means that pilot who is applying a greater force will receive greater part of aircraft force feedback.

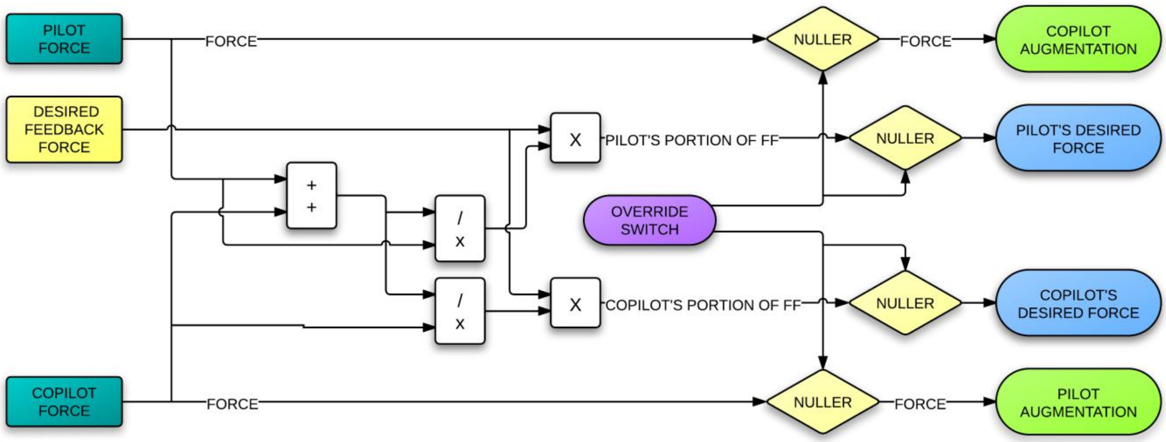

Figure 3-5: Force Feedback Augmentation Controller

We will consider a situation where pilots are to follow a given task represented by input stick deflection in pitch axis (Figure 3-6) and describe the model behavior on several examples.

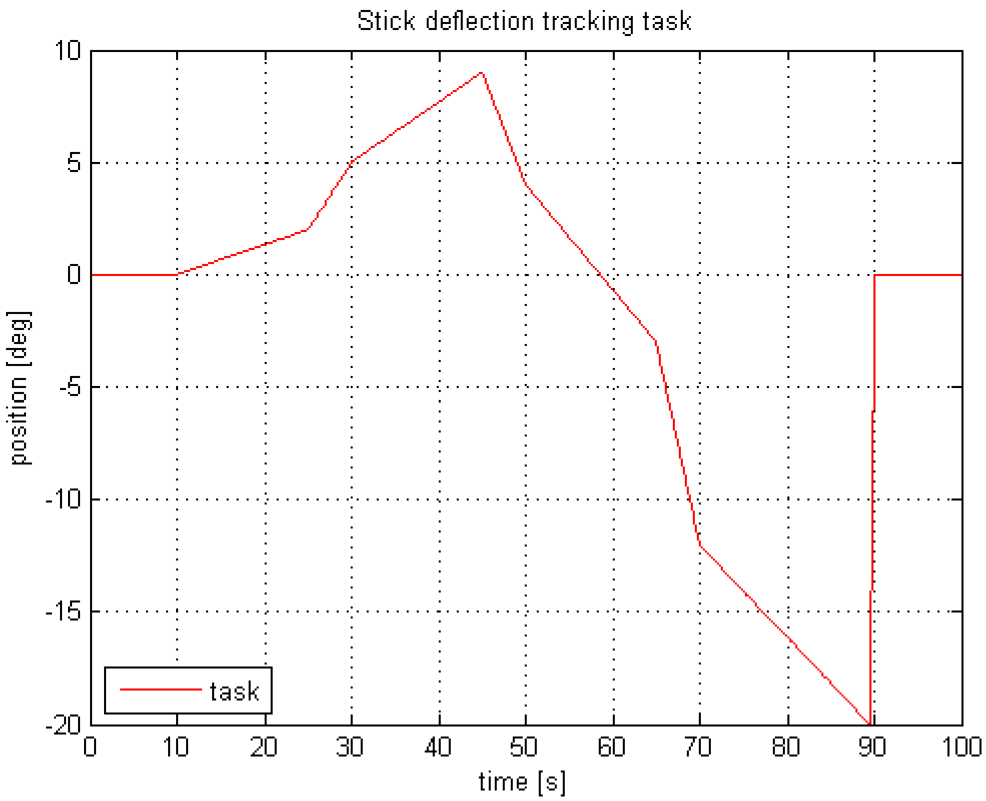

Figure 3-6: Stick Deflection Tracking Task for Stick Coupling Demonstration

There is obviously infinite number of pilot behavior variants but we can group the possible behaviors by certain patters:

- Both pilots follow the desired task
- One pilot is over- or under-commanding his stick
- One pilot is not holding his stick
- One pilot requests takeover

The ideal situation is when **both pilots** commands are exactly as desired. In this case both pilots generate the same command and feel the same force feedback computed from aircraft model (or in this case the passive feedback). Thanks to pilot – copilot coupling the magnitude of felt forces is split between both pilots and the simulation acts as if the two pilots are holding one collective stick. Both stick position and felt force graphs are almost identical for pilot and copilot (Figure 3-7) (the difference is caused by different sensor noise patterns).

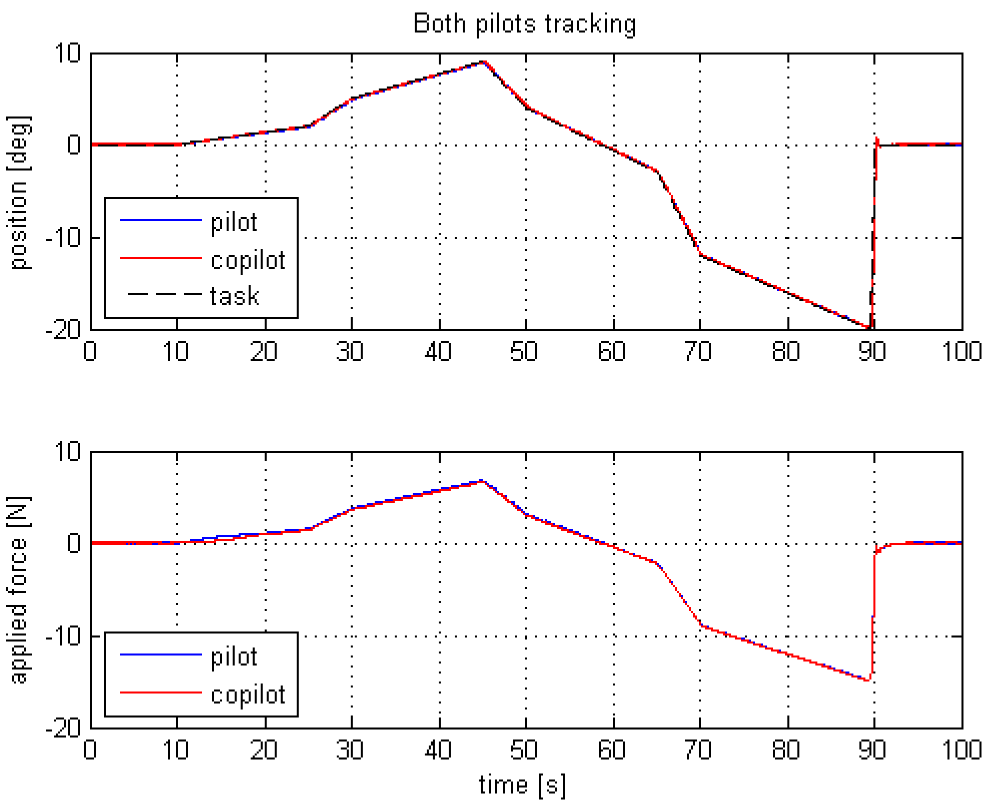

Figure 3-7: Both Pilots Commanding per Given Task Scenario

Next we will consider the case of **copilot under-commanding** stick. There are two scenarios possible. First is that copilot wants to track the same stick position as pilot but uses insufficient forces. In second scenario copilot tries to track entirely different task.

First we will demonstrate situation when copilot is not using the correct force magnitudes. In Figure 3-8 (zoomed for easier reading) we see that the resulting stick position is a bit lower than in case when correct forces are applied by both pilots. Lower magnitude of copilot commands forces pilot to compensate the position difference by applying a greater force and the resulting sum of both pilots' forces is equivalent to achieved stick position.

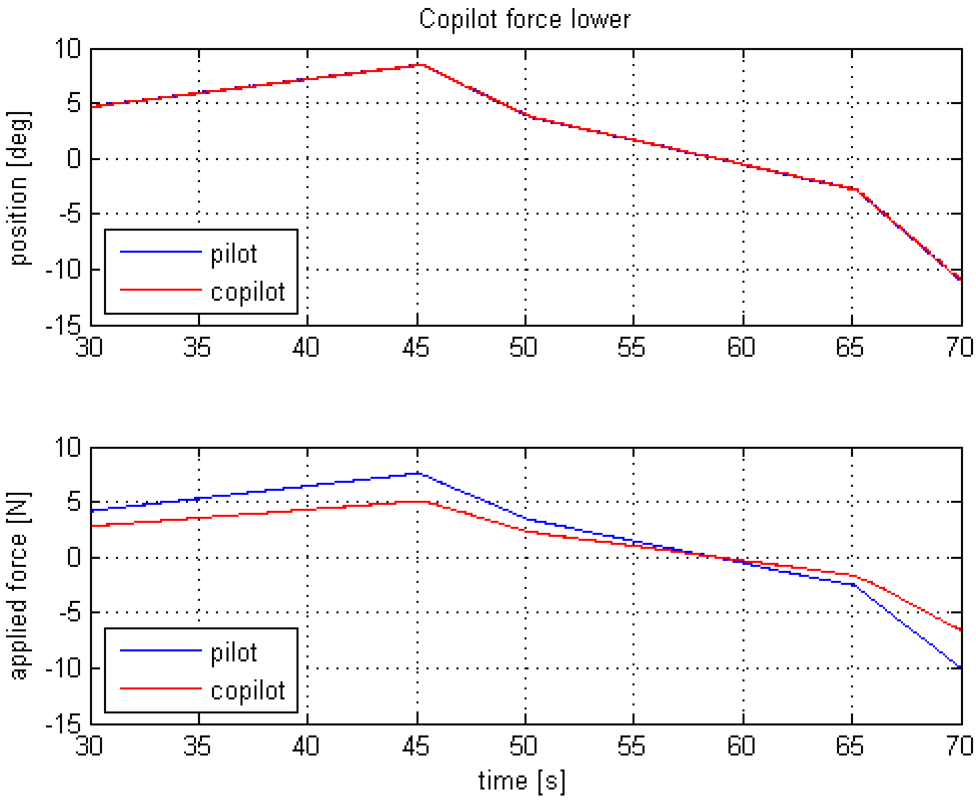

Figure 3-8: Copilot Using Lower Force Magnitudes Scenario

Slightly different situation occurs when copilot is not tracking the same task as pilot is. Let's consider the copilot is tracking a similar scenario but with lower stick deflections. The copilot's stick deflection gain is set to 75 percent of pilot's in this simulation.

When both side sticks are moved only by their respective motors by torques defined from sum of all applied forces, there is no possibility of position difference between the two sticks. We can see that the achieved stick position is average of both pilots desired positions (Figure 3-9; zoomed for easier reading). This is caused by the insufficient copilot's inputs coming from different desired stick position. If pilot tries to increase his applied force to move stick more to position he's requesting the copilot changes his force by the same magnitude but in opposite direction to compensate grow of error between him desired and actual stick position thus keeping the forces in balance.

The force magnitudes are different from case when both pilots would command the averaged deflection from Figure 3-9 (pilot's force is higher, copilot's is lower) because they're changed in attempt to achieve respective desired position. Pilot (who is creating a greater deflection) thus feels the stick force feedback increasing over the expected force magnitude for given position, his stick is getting rigid when he tries increasing deflection while copilot feels his stick more “willing” for increasing the deflection. This difference in expected and actual forces and further rapid grow of force when trying to change stick deflection are for pilots typical signs of second pilot’s action.

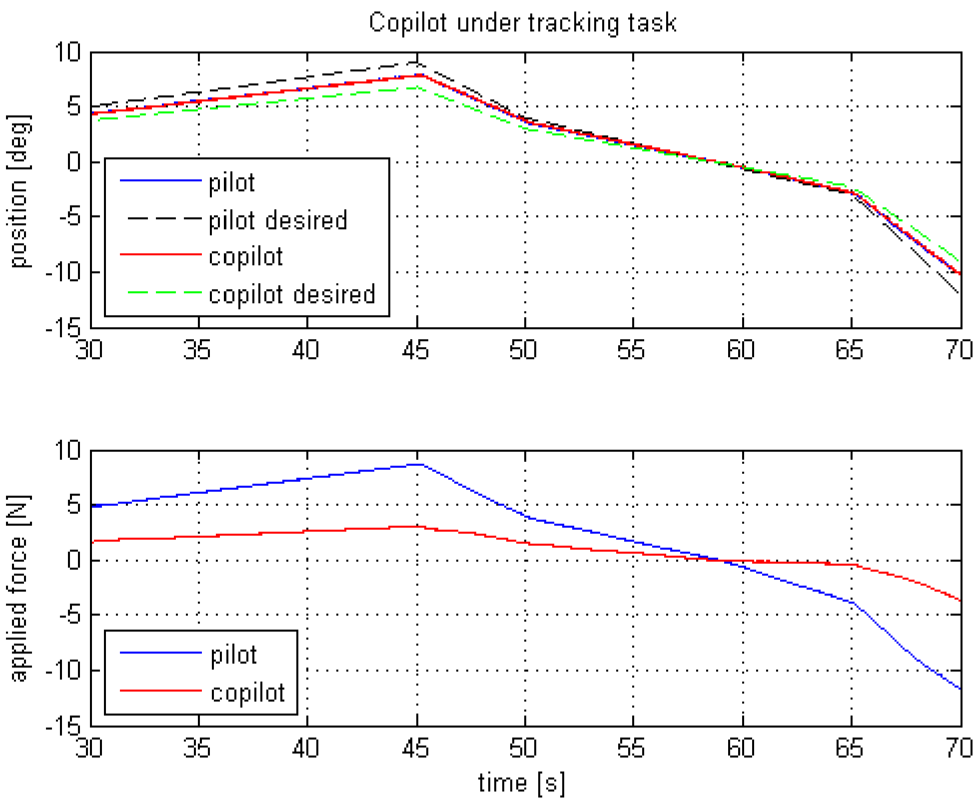

Figure 3-9: Copilot under Tracking Task Scenario

When one of pilots is not able to achieve the desired stick position due to additional forces presented into his stick by second pilot actions he can use an override switch to request a takeover. As shown below in takeover scenario description, when pilot is requesting takeover the force augmentation from second pilot is cut off and only one pilot is then in control. This may be vital in situations when there is a need of rapid commands but both pilots are commanding their sticks in different manner. In contrast to passive sticks, when this issue occurs pilots are already aware of the command difference by the force feedback and use of the override switch comes more natural.

The override switch is also implemented in model. There are in fact more switch positions needed in model than on real airplane. The real switch would have only three positions – both pilots in control, pilot and copilot’s override. For model we need also positions for “pilot not present” for situation when one of the stick is released. The override subsystems in Figure 3-4 use the override switch position to null the input and desired forces when such situation is to be simulated. Override subsystems are also present in the stick control unit (Figure 3-5) where they null the augmentation command and desired forces for pilots when one of them demanded takeover.

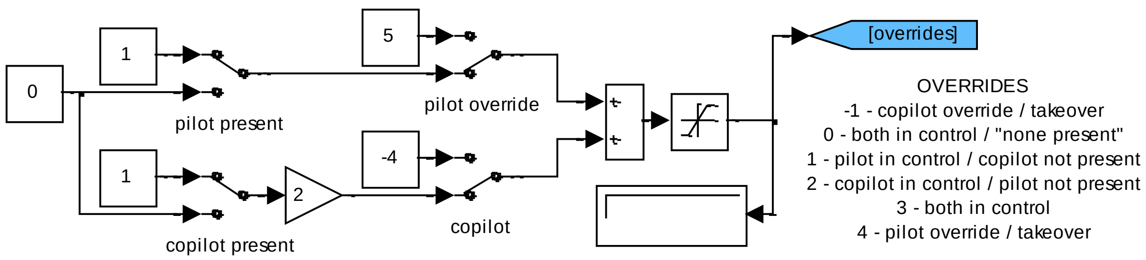

Figure 3-10: Override Switch Design

The switch position “**copilot not present**” will be used for demonstration of the active force feedback for the third pilots’ behavior pattern. This situation occurs for majority of the length of flight as pilots usually take turns in piloting without using override switches. In this scenario the free stick should only track position of the stick being commanded.

As shown in Figure 3-11 copilot’s force applied is zero and only pilot is commanding the aircraft. We can see that the force feedback augmentation works perfectly for this situation and is keeping both sticks in the same position. When there is no load force from copilot his side stick moves along with pilot’s stick due to presenting of the pilot’s force commands. Aircraft feedback distribution scheme ensures that pilot is receiving full and copilot none feedback as all the present forces come from the pilot. If we compare Figure 3-7 to Figure 3-11 we see that the force pilot is applying is twice as big when there is no copilot action. We can again imagine the pilot – copilot coupling as both pilots commanding one collective stick. When there is no help from the copilot, pilot has to produce greater forces to track desired stick position. The augmentation force command to copilot’s stick is then equal to pilot’s applied force and augmentation to pilot is zero as copilot is not applying any force.

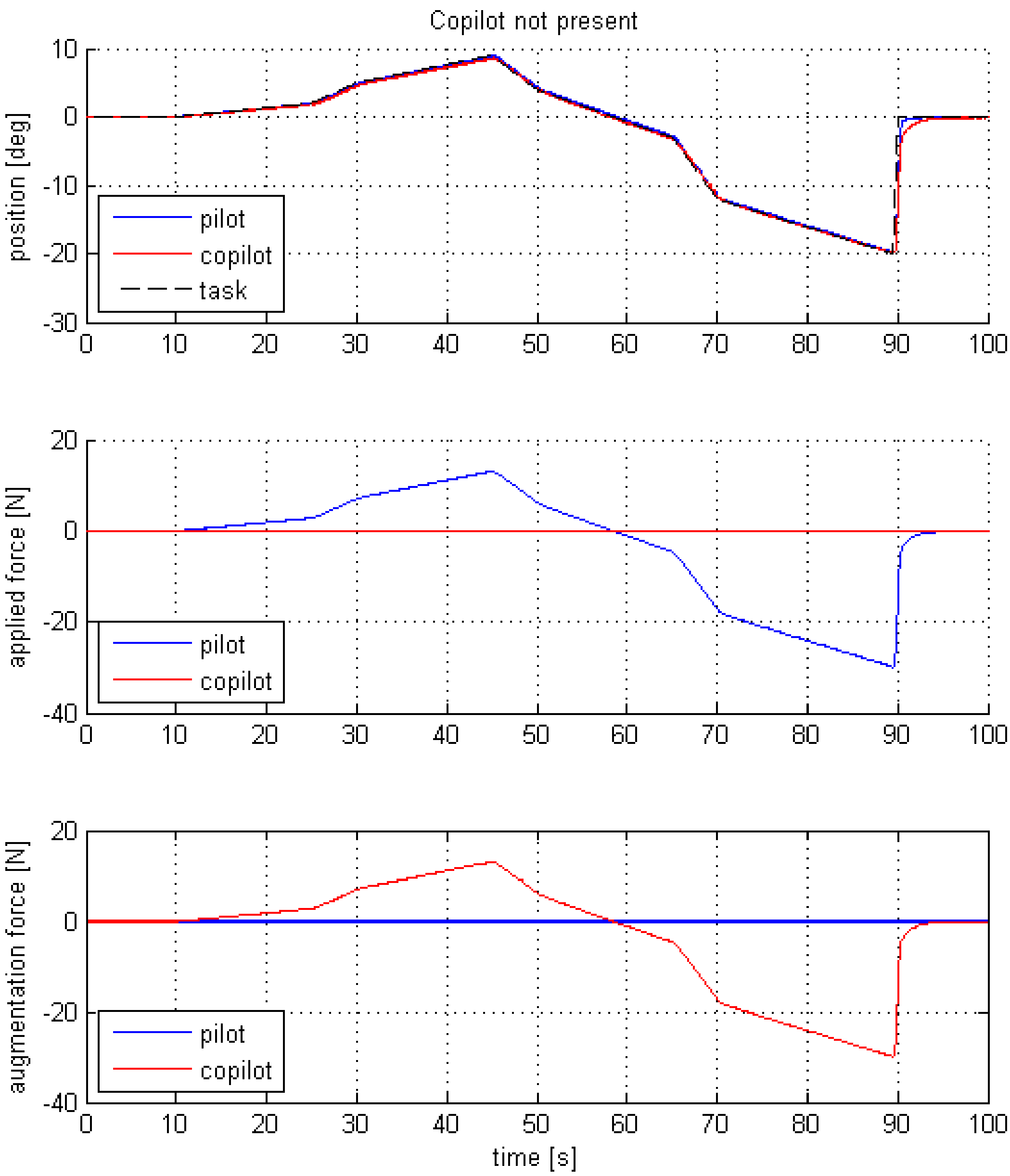

Figure 3-11: Copilot Not Holding the Stick Scenario

To complete the list of possible pilots' behavior patterns situation when one of the pilots **requests takeover** is shown. In such situation the augmentation to pilot requesting takeover is nulled (with a certain time constants to avoid force peaks). Augmentation to second pilot still exists so the second stick is also under first pilots control and when second pilot is trying to move his stick into different position additional force is presented. This is the only scenario when only one pilot command is driving the FCS (command is not averaged from both sticks).

A case when copilot desires to keep null stick deflection and pilot requested takeover to control the aircraft is shown in Figure 3-12. Copilot's actions are not either presented to pilot's stick nor in fact into copilot's stick. Both sticks track pilot's actions no matter how copilot tries to achieve the null position.

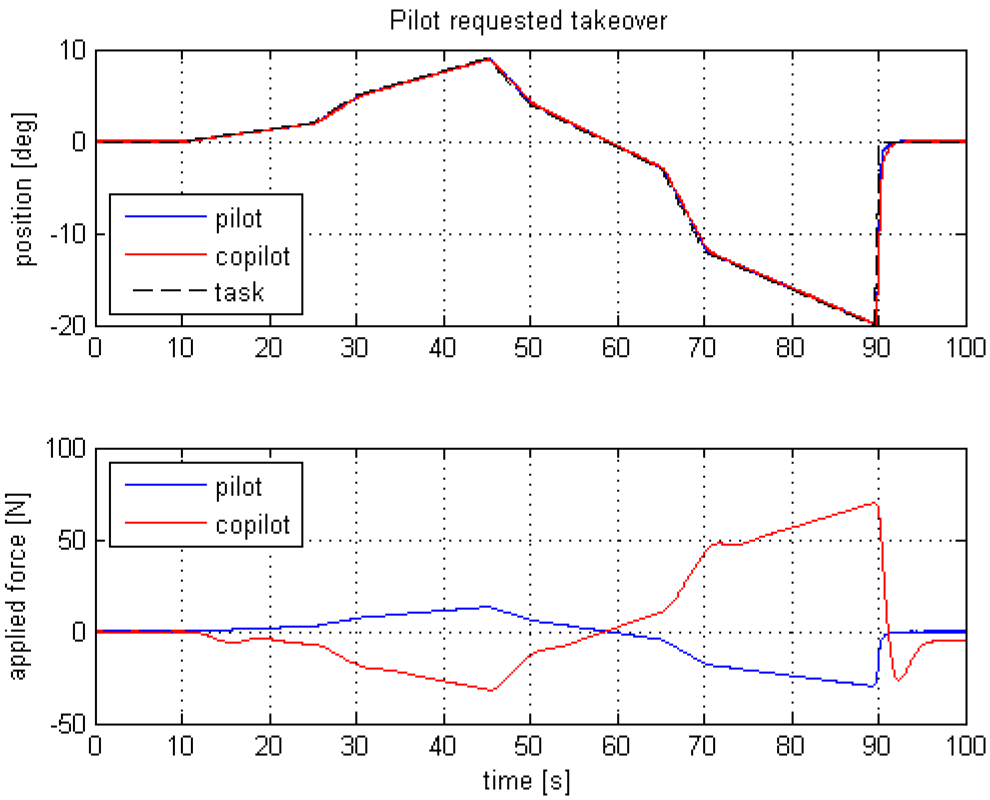

Figure 3-12: Pilot Requesting Takeover Scenario

Pilots usually use the override switch when they consider other pilot's actions to be faulty and want to null his effect on their stick and more importantly on the surface deflection commands. This situation is demonstrated on Figure 3-13 where copilot is tracking a different task and pilot requests takeover when copilot's actions are jeopardizing pilot's ability to perform given task (around 35. second of the simulation). We can see a change in copilot's stick position and rise of his applied force when copilot's actions are neglected because of the pilot's takeover request.

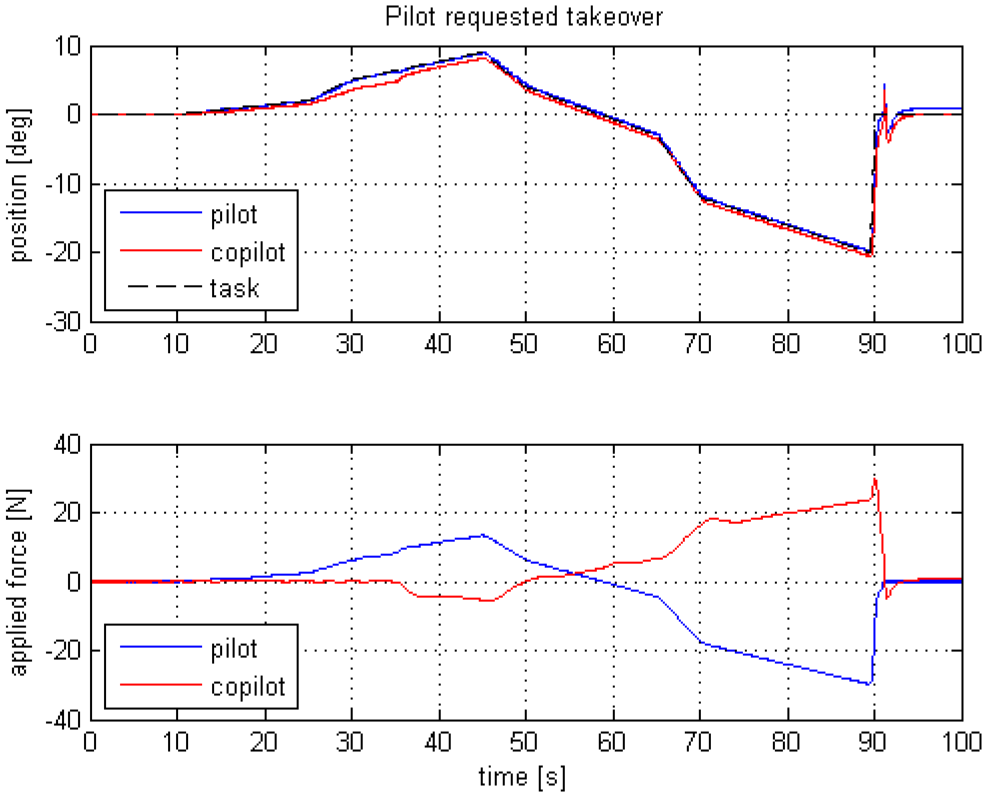

Figure 3-13: Pilot Requested Takeover When Copilot's isn't Cooperating

One of the advantages of active side stick mentioned in chapter 2.2 is the possibility to alter overall haptic feedback characteristics to suite pilot needs. When a pilot is used to greater forces present in cockpit controls he can adjust the feedback magnitudes to gain desired feedback. On Figure 3-14 is shown a situation when only pilot is in control tracking the given task and has set his force feedback to be twice as large as default settings. The force gain is implemented on force sensor output path; the measured force is divided by selected gain (2 in described situation). This way both the motor controller and the stick control unit receive information of pilot force with default magnitude, even though he is creating force of greater magnitude, and the whole system behavior is in no way different than in case of default feedback gains.

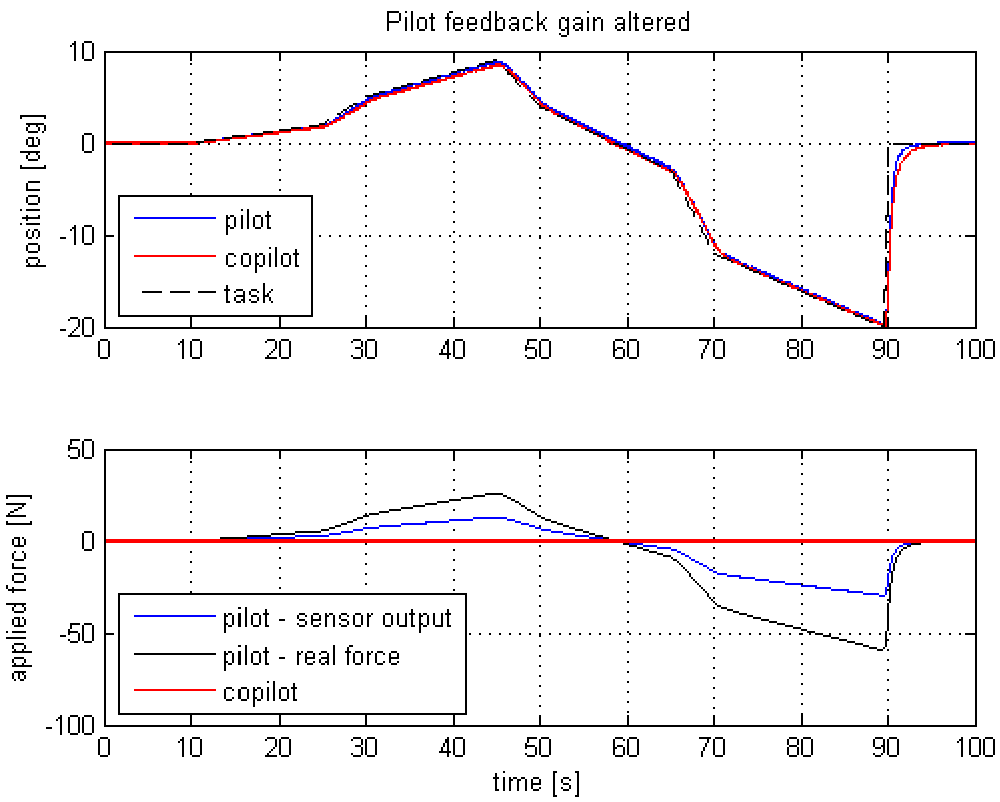

Figure 3-14: Pilot Force Feedback Gain Tuning

3.3.1. Real Hardware Simulation

The developed model of active side stick was used for a hardware-in-the-loop simulation. As it is not part of this thesis to build side stick prototype two gaming force feedback joysticks were chosen as substitutes. Gaming joysticks definitely don't have chances to imitate real flight sticks but are sufficient for demonstration and validation of used force distribution concept.

Figure 3-15: Active Side Stick Hardware Simulation

On demonstration video ([16] or archive) we can see the “one pilot not holding the stick” scenario. The free stick follows commanded stick’s position through force feedback augmentation. Note that used joysticks are not equipped with reliable position sensors nor the force feedback is powerful enough to move them sufficiently.

Also scenarios when both pilots are commanding sticks were tested. The force feedback obviously can’t be seen in these cases on video but is present in sticks. Simulations confirmed that the concept of force feedback and force feedback augmentation described in section 3.3 is valid and that the behavior described and simulated on models corresponds to real behavior.

4. Pilot-Induced Oscillations

“Pilot interactions with the aircraft are referred to as aircraft-pilot-coupling. This coupling will vary according to the particular task the pilot is trying to achieve, whether it is a demanding task, such as airborne refueling, or a straightforward task such as cruising in clear weather conditions. In general, the result is a closed-loop system between the pilot, the aircraft controller and the aircraft, with the pilot generating the commands that are tracked by the aircraft.” [15, p. 37] “A pilot-induced oscillation (PIO) results from the interaction of the pilot and the dynamics of the vehicle being controlled. It may be caused or affected by several elements of the aircraft design or mission task. PIO affects the pilot’s ability to perform a given task, ranging from an annoying aircraft motion to inability to complete the task to, in the most extreme cases, jeopardizing the safety of the aircraft and crew. Because it occurs sporadically, PIO can be one of the most insidious flying qualities problems.” [6, p. iii]

The introduction of fly-by-wire systems appears to have increased the probability of PIO occurrence, as the direct physical link between pilot and controlled surface has been removed and the “feel” of surface response is not present in the control stick. The aircraft response is often transmitted to pilot by inserting forces in control stick artificially, using springs or motors as described in section 2.2. This method may not be sufficient for high demanding tasks where great precision of flight is required and therefore many modern aircrafts host PIO detection and/or suppression algorithms. Most of the algorithms are implemented in FCS computer and modify in various way the pilot commands in order to avert forthcoming PIO. Goal of this thesis is to develop algorithm for PIO compensation using force feedback into control stick. At the beginning multiple PIO detection and compensation schemes will be described and compared. Several schemes will be tested using aircraft model developed in MATLAB Simulink.

4.1. PIO Categories

Pilot-induced oscillations are commonly defined as being one of three categories [15], [14], [6], [7]:

Category I: essentially linear oscillation generally occurs in situations where pilot is unfamiliar with aircraft dynamics or there is unexpected effect in aircraft dynamics (e.g. excessive phase lag in control system). PIO may occur during learning process and are not considered to be threatening. Oscillatory behavior is often not divergent.

Category II: most frequently caused by actuator rate or position limits. Oscillatory behavior is quasi-linear, divergent and therefore threatening. Majority of reported and documented aircraft crashes caused by PIO are due to category II PIO. Pilot is generally not aware of PIO in progress even though they are easy to identify once occurred.

Category III: essentially nonlinear oscillations, complicated to detect and avoid. PIO are complicated to describe and often involve transitions either from the pilot or from the aircraft (for example (oscillatory) transitions of FCS mode, nonlinearities in actuators etc.).

The force feedback would certainly have positive effect to category I PIO occurrence as the dynamics of aircraft would be more apparent to pilot. However pilot always needs to know the airplane dynamics to avoid category I PIO. As this can be overcome with practice this thesis will not focus on category I PIO. To justify this we can point out there are numerous documented cases of such PIO on airplanes with mechanical FCS where force feedback is always present [17].

As for the category III PIO the force feedback would not probably mean any advantage as it has no effect on present nonlinearities. The rest of the thesis will focus on category II oscillations where the force feedback benefits are most notable as analyzed bellow.

4.2. Category II PIO

Section 4.1 states that category II PIO are behind the majority of PIO caused accidents. Table 4-1 sums up the famous category II PIO cases over the modern history of aeronautics where most of them led to an accident. If we leave out the cases of system failures (which although causing category II PIO may be considered a system nonlinearity – category III PIO cause) we can see that all the well-known PIO happened during high demanding tasks as take-off, landing, formation flying or aerial refueling. Those are situations where pilot needs a precise control over the aircraft and immediate command responses. When there is an unexpected command limitation (either from surface rate or position limiting or caused by malfunction of FCS) pilot may suppose that his commands are not sufficient to control given situation and tries to enhance his response. Due to the limitation this only worsens the error as pilot command is greater than before and aircraft is still lagging behind the controls.

All PIO categories can be observed on both pitch and roll axes (yaw axis isn't usually PIO prone due to slower pilot's dynamics compared to surface one) or even combined on both axes [18]. Most of the roll axis PIO cases are observed in task such as aerial refueling [19] or formation flying. We will focus mainly on PIO occurring during landing phases (approach and flare) and hence on pitch axis PIO which are more likely to occur in such situation.

Aircraft	Flight Phase
XS-1	PIO during glide approach
XF-89A	dive recovery
X-15	gliding flight approach and landing
XF2Y-1	take-off; destructive PIO
F-86D	formation flying
Space Shuttle	landing approach glide; lateral PIO prior to longitudinal
DFBW F-8	touch and go
CH-53E	multiple occasions in precision hover, heavy loads, refueling
B-52	roll PIO; aerial refueling
F-15E	cruise; invalid airspeed data
JAS 39	power approach
F-14A	hydraulic failure; aerial refueling
JAS 39	low altitude demonstration
B777	landing with automatic systems

Table 4-1: Famous PIO in History [7], [6]

Figure 4-1 shows a demonstration on how the category II PIO may occur due to surface rate limit combined with a small system delay. Pilot desires to momentarily set the pitch attitude angle (climb angle) to certain value in order to adjust aircraft position during some critical flight phase (e.g. gaining additional height after rethinking faulty landing maneuver). Due to increased workload during high demanding situation pilot perception of aircraft behavior is altered and his gain in control loop increased. His input thus doesn't correspond to given task and an impression of excessive lag in aircraft response occurs. He subconsciously applies greater command than necessary to make aircraft respond faster. When he realizes the aircraft is closing to the demanded height the controls and more importantly the surface are already deflected in undesired position causing the aircraft to continue its upward movement. Surface cannot be moved to null position quick enough to stop the aircraft movement and even continue to deflect when pilots command is still greater than current surface deflection due to previous over-commanding. Pilot compensates the created error by opposite command entering induced oscillations.

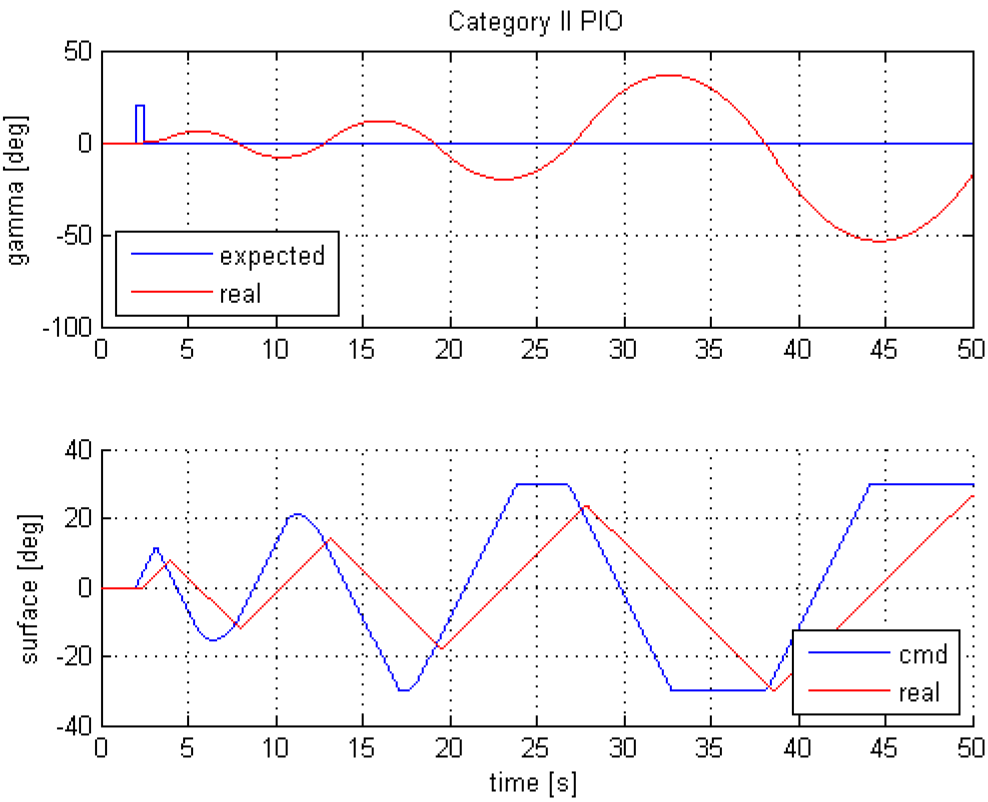

Figure 4-1: Category II PIO Evolution

Even from the simplest simulation used to generate Figure 4-1 we can define which variables makes an aircraft (and an aircraft-pilot closed loop) a PIO prone system. As already stated multiple times the **surface rate or position limiting** has a dominant effect on PIO occurrence.

Rate limits are present in all FBW controlled aircrafts due to speed limits of used actuators and actuator control electronics. There also can be a cockpit controls rate limiter although this is not common on fixed wing aircrafts (but can be found on some helicopters) and also rate limit on the command path implemented in FCS to ensure operation within aircraft structural limits.

Position limits are given by aircraft construction for both surface and controls position and shouldn't be cause of PIO on properly designed aircrafts during normal operation. Position limits in FCS are also believed to be set to guarantee maximum maneuverability. PIO may however occur in case of FCS malfunction.

Tightly connected to rate limits is the overall **control loop delay** as it results in increasing pilot commands in the same way as rate limits. When aircraft response is lagging due to system transport delay pilot may consider aircraft not responding. Modern FCSs are designed to have a minimal delay to meet handling qualities requirements so the transport delay shouldn't cause category II PIO (although it may cause category I PIO for inexperienced pilots). This PIO cause was relevant mainly during early phases of FBW FCS development (DFBW F-8 in Table 4-1 was first aircraft for testing digital FBW, [20]).

Another factor contributing to PIO is the overall **aircraft dynamics**. This is more of category I issue but some cases of such nature are classified as category II PIO [7], especially when aircraft configuration cannot be considered as suitable for normal operation (e.g. specific placement of center of gravity). Plus when aircraft dynamics is particularly “lazy” the aircraft behaves similar to cases when rate or position limits are present.

Possibly the greatest influence to PIO occurrence has **the pilot** himself. Coming from the phenomena term the oscillations are generally caused by improper pilot’s behavior. There are virtually no cases of involuntary category II PIO reported while aircraft is in low demanding flight phase (cruising, climbing). From this we shall deduce that the main cause of PIO category II lays in pilot behavior when proximity of other objects changes his normal flight habits.

4.2.1. Category II PIO and Force Feedback

All cases of category II PIO documented in Table 4-1 appeared on aircraft with FBW or hydraulically augmented FCS. The reason is apparent, in case of mechanical FCS pilot can in no way generate a significantly greater stick deflection than is allowed by the surface movement. Physical rate limits in the mechanical interconnection (caused by stiffness, elasticity or friction in mechanical components) may be present but pilot is notified by force generated in control stick and is not able to move the stick faster than the control surface. The dominant rate limit is thus included in pilot’s behavior which will not contribute to PIO.

When using a side stick with active force feedback we certainly want to use the haptic feedback to simulate mechanical linkage impression so pilot will be aware that his rate of deflection is greater than maximal surface rate. This feedback was added to side stick model to analyze its effect. Because the system has force-based regulators and also the motor is driven based on applied force information the implementation of stick rate limiter is reduced to implementation of motor rate limiter. Rate limiting is performed in motor controller by calculating maximal required motor moment which will not exceed given stick rate. Note there is an assumption that stick deflection ranges are similar to surface deflection ranges and so are the respective rates of deflection. In case when for example stick deflection range is significantly smaller so should be the maximal rate of stick deflection, i.e. if it takes one second for the surface to reach its maximal deflection it should also take the stick on second to reach its maximal deflection no matter of difference of those two values.

The process of stick rate limiting is illustrated on Figure 4-2. Pilot is applying force on stick grip in the usual manner and force is measured and converted to information about desired stick deflection in degrees. The newton to degrees gain is computed from feedback force which would be generated for hypothetic reference stick (and surface) deflection in current aircraft situation. In other words it is assumed there is a linear dependence of stick deflection and feedback force for given aircraft state and reference deflection is used to avoid obtaining a zero gain. Next there is a simulation of stick mechanical part implemented in motor controller with applied stick rate limit (note again the surface to stick position gain; computation of surface rate limit is not implemented but can be easily performed by comparing rapid stick commands with surface response). The simulated stick's position limited by the stick rate limit is measured, converted back to newton units which now represent force that should have been applied to achieve stick position while respecting stick rate limit. The armature current regulator then commands motor to achieve desired position.

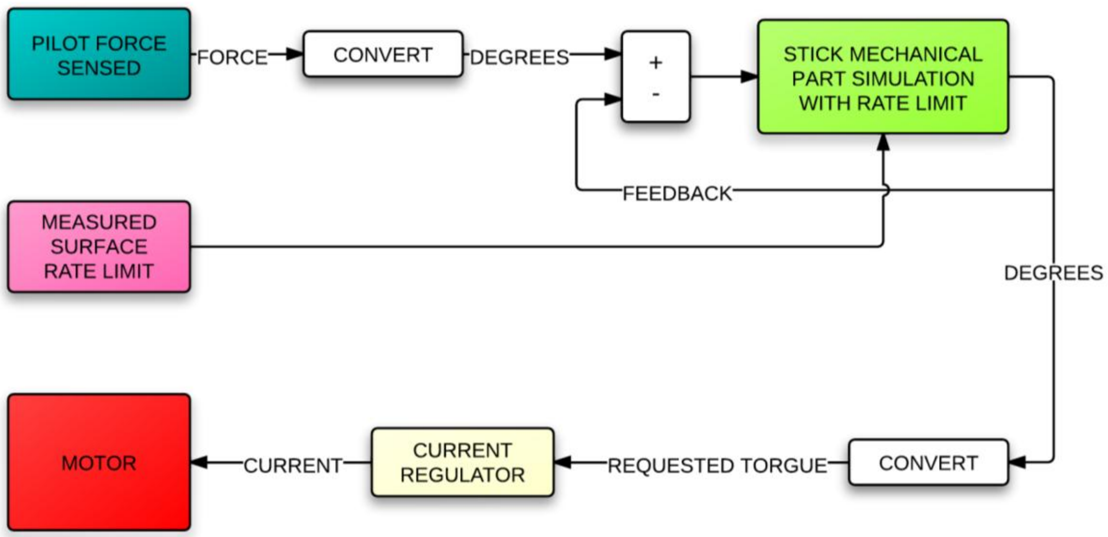

Figure 4-2: Stick Rate Limiting Algorithm

Pilot model was updated to simulate pilot's force rate limit awareness by creating a feedback loop similar to the maximal applied force "soft limit" loop (Figure 4-3). Maximal force rate is computed similar to degrees to force conversion gain with surface rate limit included.

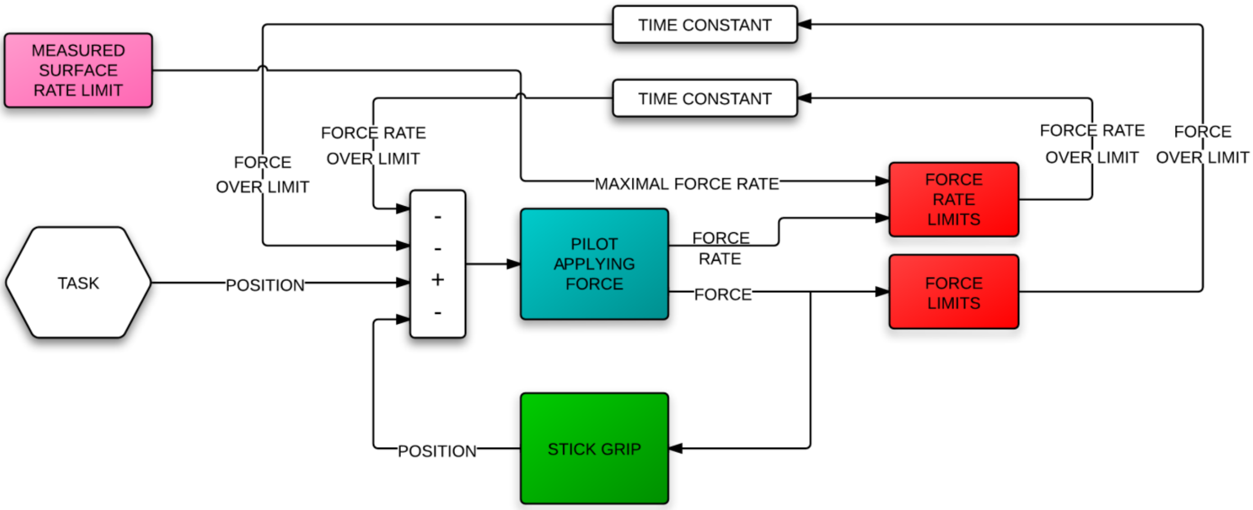

Figure 4-3: Pilot Model with Rate Limit Loop

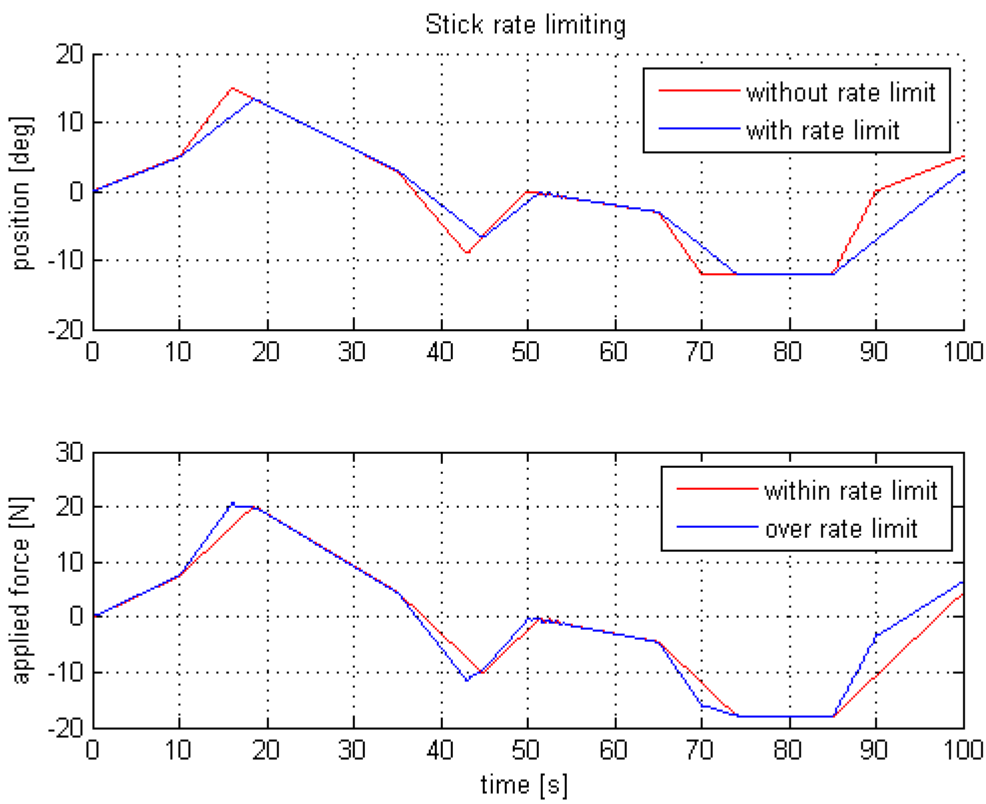

Figure 4-4: Force Augmentation Algorithm with Rate Limiter Part

The outcome of stick rate limiting algorithm is that only stick deflection rate which cause surface movement within surface rate limits is allowed. Figure 4-4 shows a simple tracking task which was changed for demonstration of rate limiting to include higher rates of movement. Results clearly show additional force being felt by pilot when rate limit exceeds the given surface maximum (note that surface rate limit is intentionally set to 1 degree per second which, although it is absurdly low value, it is necessary for PIO simulation; reason is described in section 5; for reference, normal surface rate is about 40 degrees per second [21]). Pilot is commanding the stick at rate exceeding the maximum. Motor moves the stick by the maximal allowed rate thus generating force feedback opposite to pilot's actions.

Note that from now on a single side stick is used in all models. This can be justified by comparing results shown in section 3.3, situation when one pilot is applying force on his stick or when takeover is requested is considered in all further simulations. Sensor noise is suppressed in some of following situation as its influence was shown on previous results.

5. Aircraft Model

A model of aircraft was needed to be assembled for computation of force feedback magnitudes and simulation of PIO response. Aircraft dynamics equations from [2] and [22] were used as base for model development. There are already several models available for aircraft simulation some of which were used for model verification. We won't also go very deep in aircraft model description for this reason.

Developed model includes only pitch axis which, as implied above, is sufficient for our case. No roll or yaw movement is allowed in model. The general equations of motion in pitch axis are as follows [2]:

Aerodynamic forces and moments:

$$F_{A_x} = -C_D \bar{q} S \qquad \text{Equation 5-1}$$

$$F_{A_z} = -C_L \bar{q} S \qquad \text{Equation 5-2}$$

$$M_A = C_m \bar{q} S \bar{c} \qquad \text{Equation 5-3}$$

Thrust forces and moments:

$$F_{T_x} = T \cos \alpha \qquad \text{Equation 5-4}$$

$$F_{T_z} = T \sin \alpha \qquad \text{Equation 5-5}$$

$$M_T = -T d_T \qquad \text{Equation 5-6}$$

Kinematics:

$$\dot{\theta} = q \qquad \text{Equation 5-7}$$

where:

$$C_D = C_{D_0} + C_{D_\alpha}\alpha + C_{D_{i_h}} i_h + C_{D_\delta}\delta \qquad \text{Equation 5-8}$$

$$C_L = C_{L_0} + C_{L_\alpha}\alpha + C_{L_{i_h}} i_h + C_{L_\delta}\delta + C_{L_q}\frac{\bar{c}q}{2V_p} \qquad \text{Equation 5-9}$$

$$C_M = C_{M_0} + C_{M_\alpha}\alpha + C_{M_{i_h}} i_h + C_{M_\delta}\delta + C_{M_q}\frac{\bar{c}q}{2V_p} \qquad \text{Equation 5-10}$$

F_{A_x}, F_{A_z}, M_A	aerodynamic forces and moments in respective axes
F_{T_x}, F_{T_z}, M_T	thrust generated forces and moments in respective axes
θ	pitch attitude angle
α	aircraft angle of attack (AOA)
i_h	horizontal stabilizer (HS) position
δ	control surface deflection
d_T	distance of thrust line to center of gravity
$\bar{q}$	airplane dynamic pressure
S	airplane area

$\bar{c}$	mean geometric chord
V_p	airplane airspeed
q	airplane angular velocity
T	engines thrust
C_D, C_L, C_M	drag, lift and moment coefficients
$C_{D_0}, C_{L_0}, C_{M_0}$	drag, lift and moment coefficients for zero conditions
$C_{D_\alpha}, C_{L_\alpha}, C_{M_\alpha}$	AOA contribution coefficient to drag, lift or moment
$C_{D_{i_h}}, C_{L_{i_h}}, C_{M_{i_h}}$	HS position contribution coefficient to drag, lift or moment
$C_{D_\delta}, C_{L_\delta}, C_{M_\delta}$	surface deflection contribution coefficient to drag, lift or moment
C_{L_q}, C_{M_q}	airplane angular velocity contribution coefficient to lift or moment

Constants and coefficient values are listed in Appendix A: Learjet 24 Aircraft Stability and Control Derivatives.

The aircraft chosen for simulation was Gates Learjet 24, a medium large twin-engine business jet, as all of required constants were easy to obtain. This aircraft is not equipped with FBW FCS, which is however not necessary as the simulation model can alter the airplane characteristics. This aircraft was also never reported as PIO prone which was proven during simulation as well. An artificial rate limiter will be added for PIO demonstration.

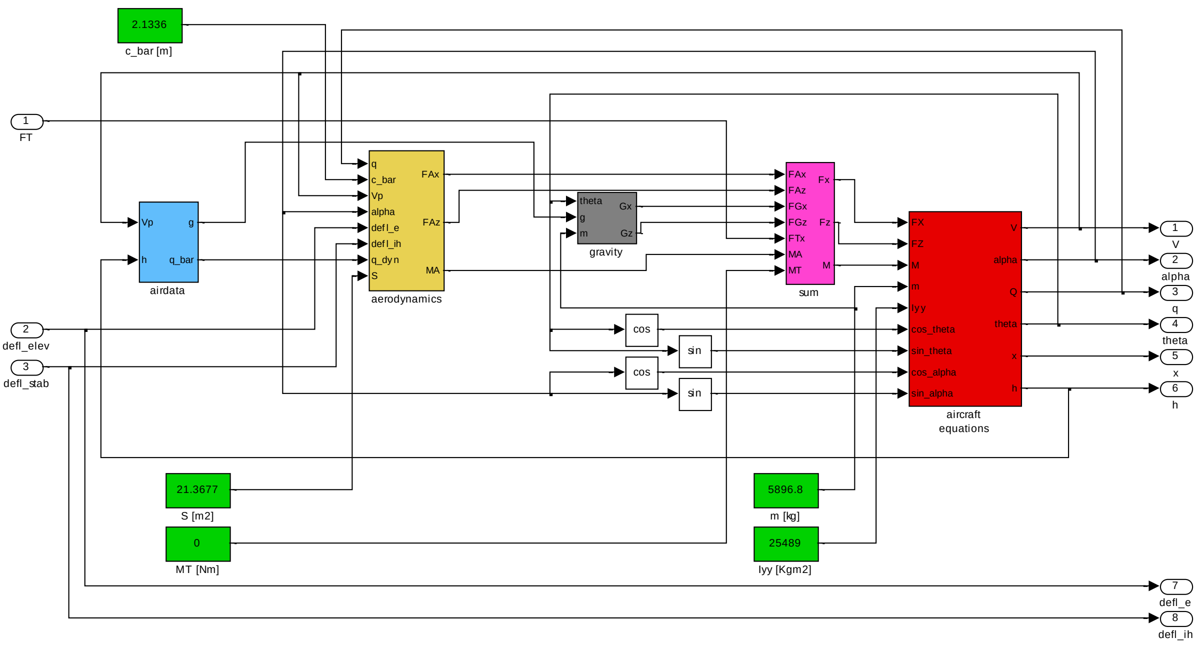

Figure 5-1: Aircraft Simulation Model

5.1. Force Feedback Magnitude Computation

The aircraft model was also used to gain some variables required for computing the force to be presented into cockpit controls. Equations for the force magnitude were again taken from [2] and verified in [22]. As can be seen in Equation 5-11 the hinge moment M_H generated by aerodynamic forces on deflected surfaces depends on airspeed (or better say dynamic pressure), angle of attack of the plane, horizontal stabilizer position and obviously deflection of the control surface itself.

$$M_H = \bar{q}_h S_e \bar{c}_e \left[C_{h_\alpha} \left\{ \alpha \left(1 - \frac{d\varepsilon}{d\alpha} \right) + i_h - \varepsilon_0 \right\} + C_{h_\delta} \delta \right] \quad \text{Equation 5-11}$$

where:

$\bar{q}_h$	dynamic pressure on tail surfaces
S_e	elevator surface area
$\bar{c}_e$	elevator surface mean geometric chord
C_{h_α}, C_{h_δ}	surface hinge moment contributions from AOA or surface deflection
ε	downwash angle

The hinge moment is in aircrafts with mechanical FCS presented through the mechanical interconnection back to cockpit controls. The maximal force effect has to be computed during aircraft design and levers in the interconnection are set in such manner that the maximal moment will cause defined maximal forces in control stick. For a FBW equipped aircraft the whole process of interconnection mechanism calculation and design is covered by defining a simple proportional gain per Equation 5-12. The force gain can be left as tunable parameter for the pilot to determine how powerful responses from the aircraft he requests to feel. Together with parameter for tuning pilot – copilot coupling force feedback magnitude is gearing gain available for pilots to determine overall force feedback characteristics of their sticks based on their personal needs.

$$F_S = G * M_H \quad \text{Equation 5-12}$$

where:

F_S	stick force
G	gearing gain

Let’s just note that force feedback magnitude computed in described manner is sufficient for quasi-static maneuvers as PIO but for dynamic maneuvers there should be also contribution of normal acceleration included (bob-weight function).

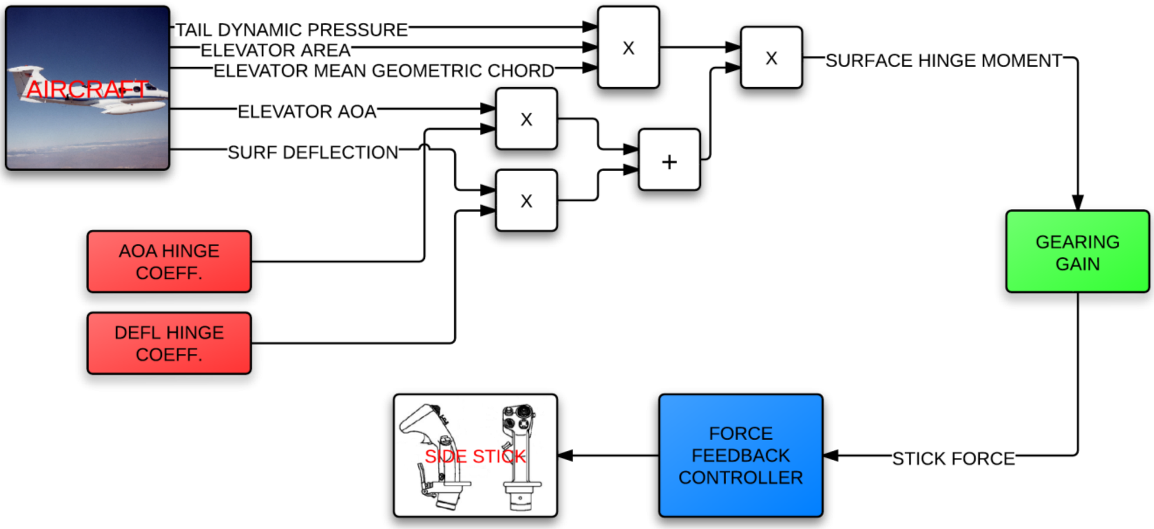

Figure 5-2: Elevator Hinge Moment and Stick Force Computation

6. PIO Detection and Suppression

Several PIO detection and suppression schemes are currently being used on different aircrafts to ensure handling qualities [15]. Part of this thesis is to compare results from the most reliable ones from the combination with force feedback point of view. In this section we will sum up the most important PIO mitigation algorithms and compare their behavior using developed aircraft model.

For PIO invocation in simulation a pitch attitude tracking task with a short impulse (50 degrees for 0.5 seconds; taken from [14]) of demanded attitude was used. Pilot reacts to this task by applying a rapid command to surface, the lagging aircraft reaction and pilot actions then cause a case of category II PIO as described in section 4.2.1.

The aircraft model was altered for PIO simulation as used aircraft is normally very stable with fast responses to commands. A transport delay of 200 milliseconds was added on the pilot command signal path representing possible delay from FBW control system. A FCS malfunction is simulated to make aircraft – pilot control loop a PIO prone system. As the surface rate limit has the most significant effect on category II PIO occurrence (section 4.2) the FCS malfunction is simulated by significantly lowered elevator surface movement rate. Surface deflection rate limit was set to 1 degree per second.

Different configurations of parameters with potential to make aircraft a PIO prone system were tested to determine the respective relevance of parameters to category II PIO occurrence. The causes described in section 4.2 and their effects on PIO severity were confirmed. Simulating change of maximal surface rate to achieve PIO liability is the most logical variant as this can occur in flight much more likely than for example a change in aircraft dynamics or inertia moments significant enough for PIO occurrence. Rate limit change slightly altered airplane dynamics as well. As seen in various simulation results oscillation occur on significantly lower frequencies than most cases described in literature.

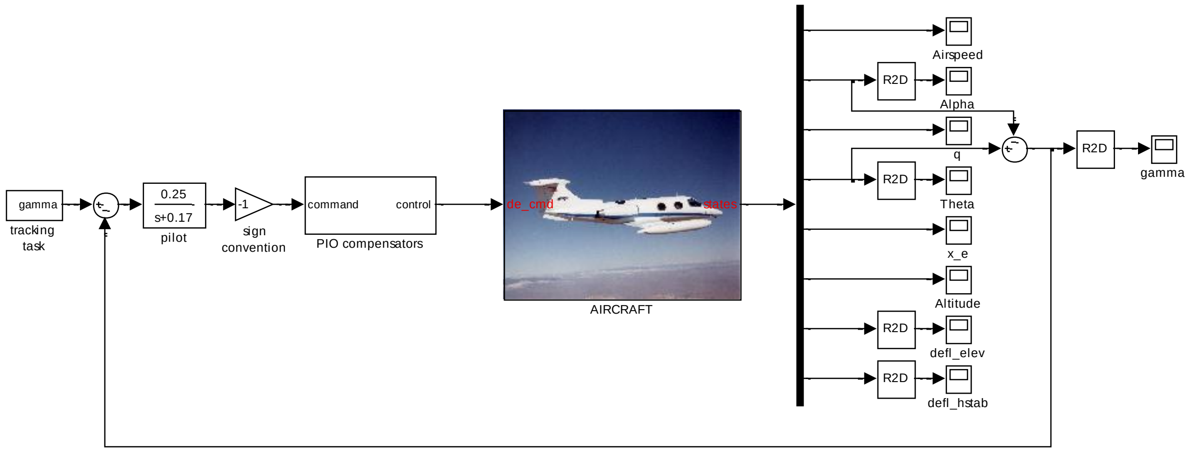

Figure 6-1: PIO Demonstration Model

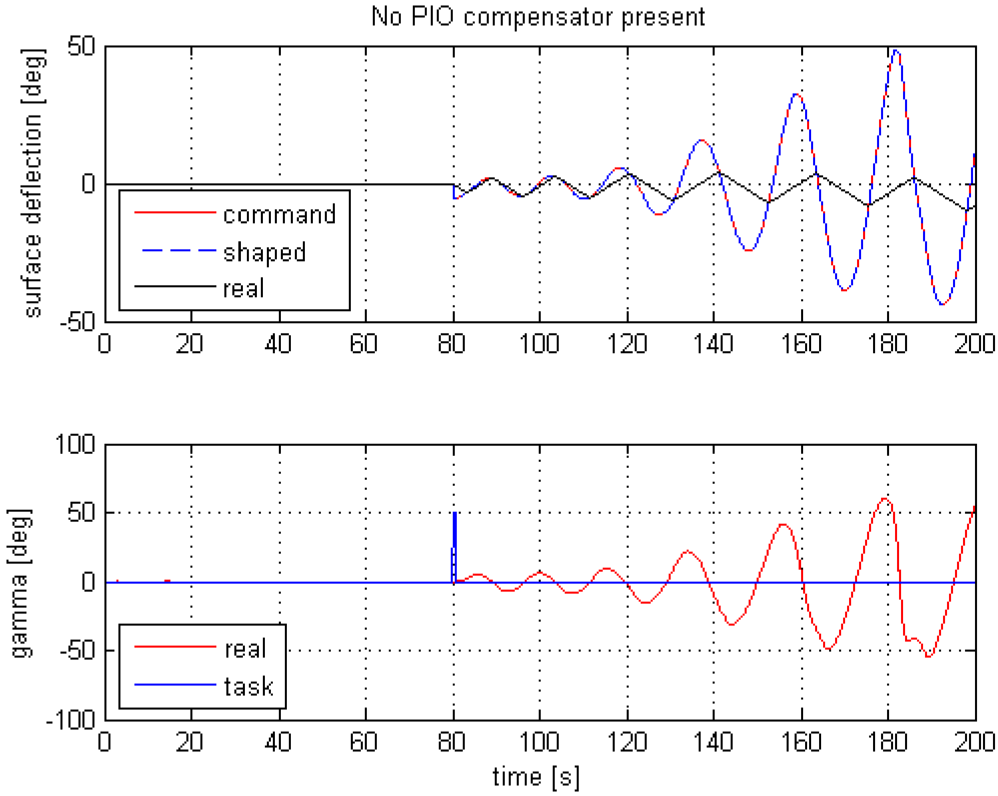

Figure 6-2: PIO Case without Compensation

6.1. PIO Mitigation Schemes

Most of PIO mitigation schemes currently in use deal with the main cause of PIO – the surface rate limit. The easiest but most inconvenient way of PIO preventing is use of **filters** on pilot command [14], [21] smoothening rapid commands in such manner that the rate of command entering actuator control unit does not exceed surface rate limit. In case of rapid stick position changes commonly accompanying PIO occurrence the peaks in pilot command are filtered and surface responds quite swiftly to command direction changes. The obvious disadvantage of this compensation is that the pilot authority is nearly always reduced preventing him from dynamic control actions, degrading handling qualities especially for high bandwidth tasks [14]. In Figure 6-3 we can see shaped command coming from filter has always smaller magnitude than pilot's original command. The surface movement tracks the shaped command without errors. PIO case is suppressed very quickly due to limited pilot authority.

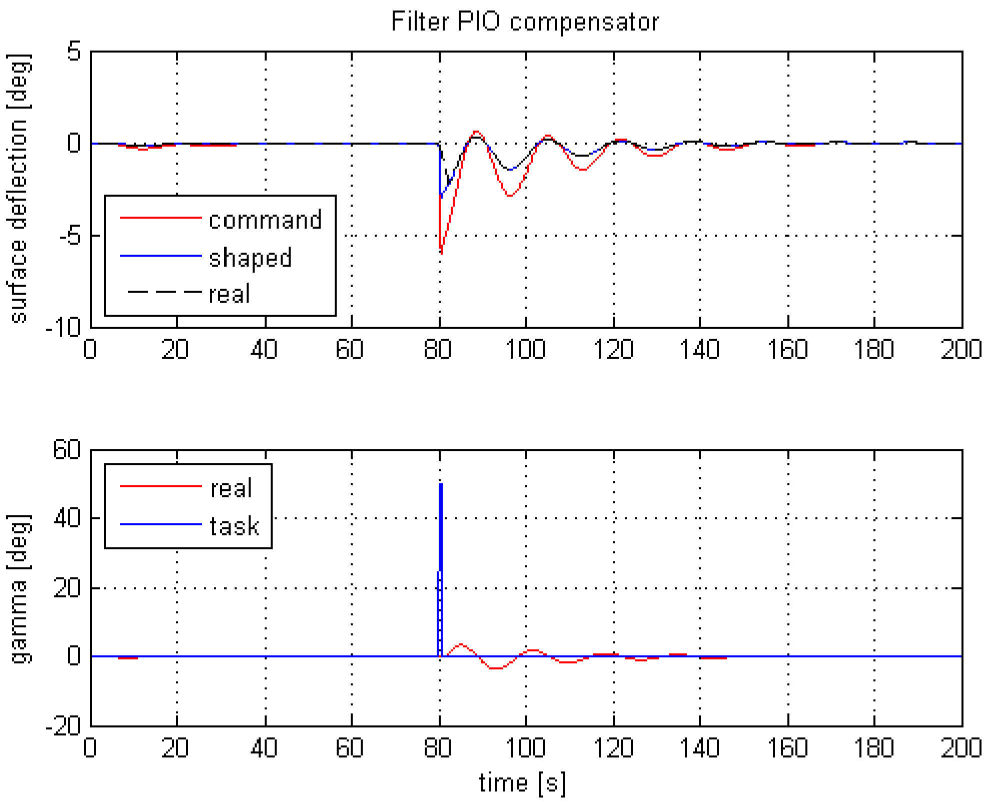

Figure 6-3: PIO Case Suppressed by Command Filtering

More elaborated is use of **anti-windup algorithms** which are also preventing excessive commands to enter actuator control unit [15]. The essence of anti-windup controllers is to avoid saturation of controller integrator due to feedback loop and saturation of controlled element. In FBW applications the anti-windup controller can be implemented on pilot command signal processing path. The main advantage of anti-windup algorithm is that the non-saturated integrator will drive surface in opposite direction shortly after command direction change where in case of integrator saturation an additional lag would occur. This scheme shapes pilot command exactly to given actuator rate limit which brilliantly solves the saturation problem but still may not be sufficient for highly dynamic control required on fighter aircrafts.

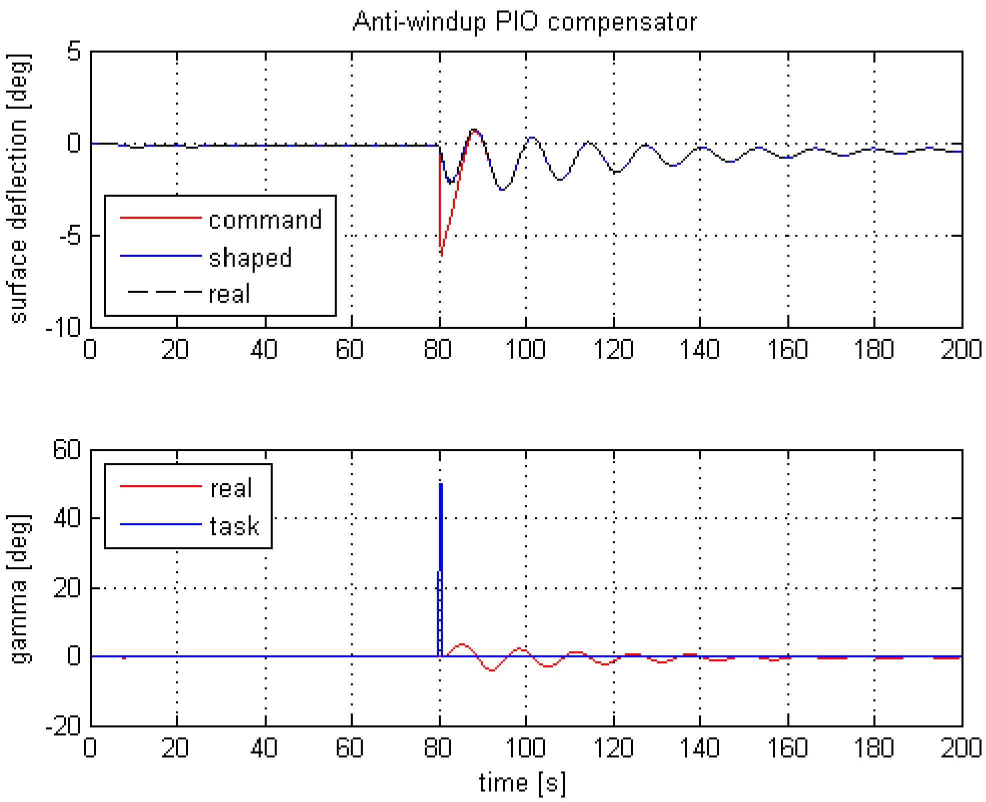

Figure 6-4: PIO Case with Anti-windup Algorithm

SAAB AB company developed a PIO mitigation algorithm which combines advantages of anti-windup controller with possibility of rapid commands. The algorithm consists of anti-windup loop handling the actuator saturation and a feedforward bypass circuit allowing overriding the anti-windup limitations for aggressive commands [15]. Reason for such algorithm development was mainly the accidents of JAS-39 Gripen (Table 4-1) caused by PIO occurrence. SAAB developed a reliable PIO mitigation algorithm suitable even for theirs highly maneuverable fighter planes. From simulation results we can see that SAAB algorithm as well as anti-windup controller algorithm limits the first rapid pilot's demand to command which surface can handle. When pilot's actions are within the surface limits no authority reduction is performed and both shaped command and surface position follows stick deflection.

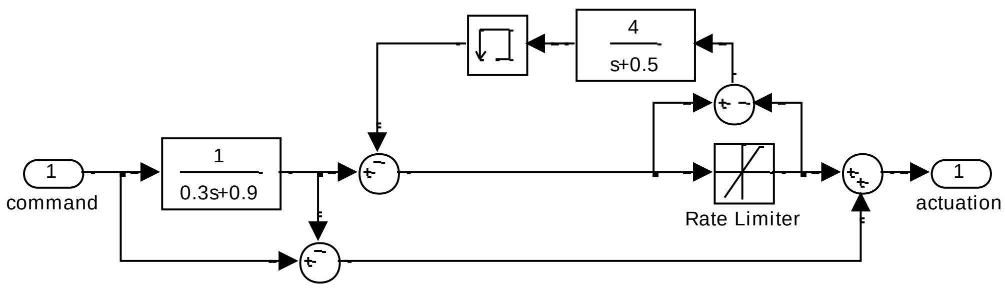

Figure 6-5: SAAB PIO Mitigation Algorithm

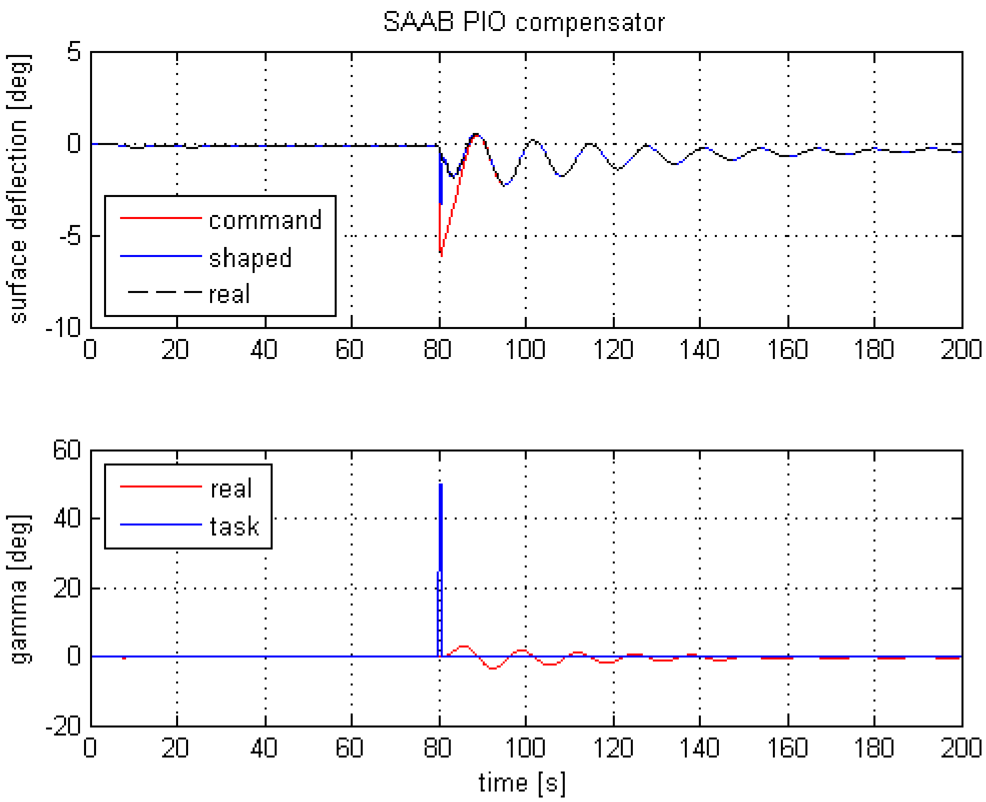

Figure 6-6: PIO Case with SAAB PIO Mitigation Algorithm

Behavior of SAAB mitigation algorithm and anti-windup controllers is very similar in case of PIO occurrence as both of them are mainly limiting pilot command per surface limitations. The difference is best seen on the first wave of a dynamic task (Figure 6-7). While the anti-windup controller limits the command rate the whole time, the SAAB scheme reaches the maximal commanded deflection in the first occurrence and limits the command when stick position starts oscillating. This allows pilot to use aggressive command if needed but the further oscillation is suppressed, thus preventing PIO invocation.

If we compare both schemes to case without PIO mitigation algorithm the phase lag of surface position is significantly reduced when using anti-windup controller and even more reduced in case of SAAB algorithm.

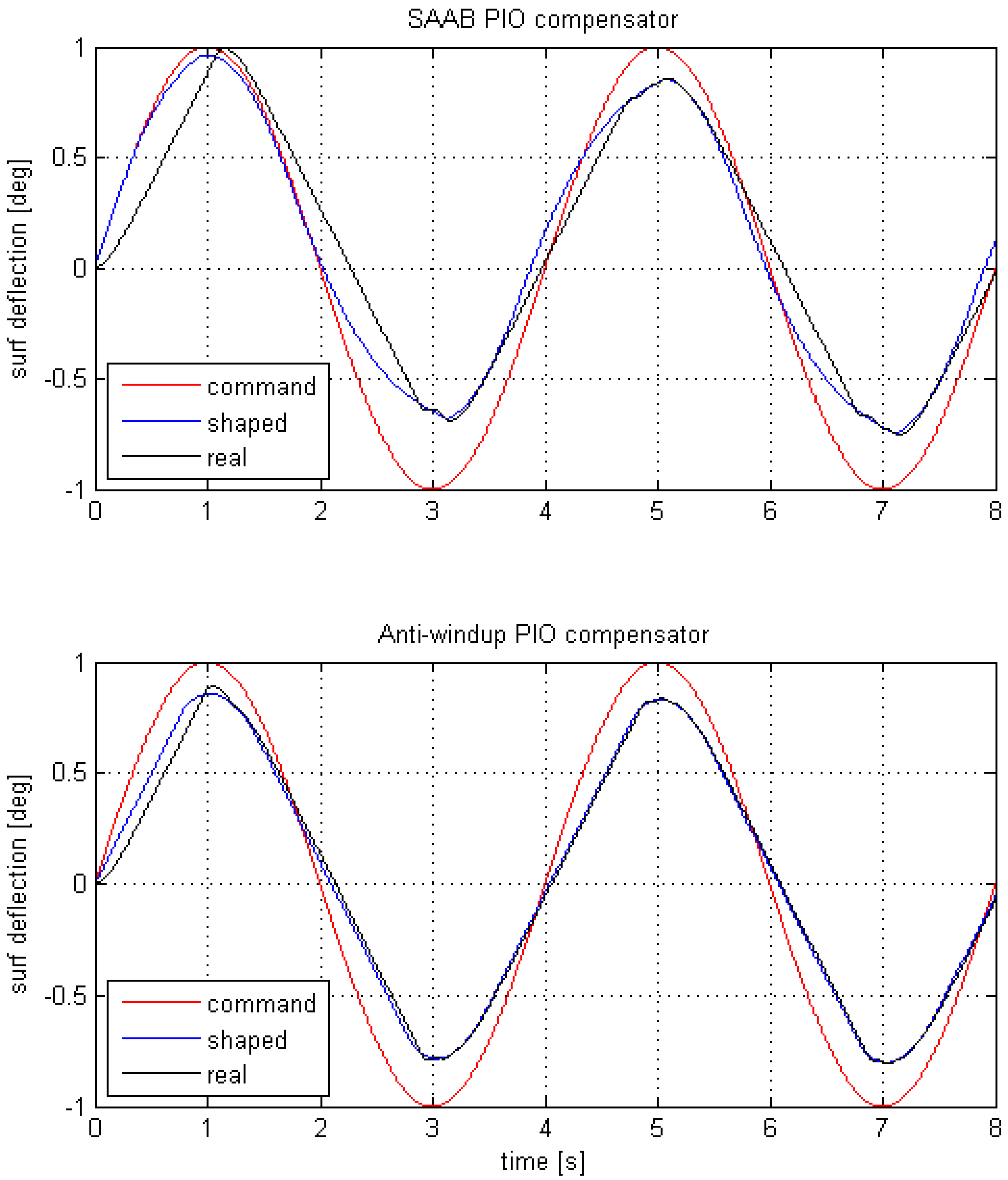

Figure 6-7: Comparison of SAAB and Anti-windup PIO Compensation Schemes Behavior

6.1.1. Using Force Feedback for PIO Prevention

In section 4.2.1 we shown that active control stick can use force feedback to present surface rate limits into cockpit controls. This can be also considered as PIO mitigation or rather PIO prevention scheme if the haptic feedback is performed with high fidelity. However this algorithm requires an elaborated pilot model for successful demonstration. If the increased force feedback doesn't make the pilot to rethink his control strategy he will try to generate the same stick positions as without the rate limiting feedback, only with a slower rate. Simulation was performed to confirm this hypothesis and at least show the increased feedback. In Figure 6-8 we can see that although pilot is receiving greater haptic feedback he can still manage to produce excessive stick deflection and aircraft starts to oscillate. When compared to case without rate limit based feedback the oscillations graduates slower as pilot is slightly reducing his commands when the stick movement rate is lowered. The use of force feedback for rate limiting application is therefore generally not faulty but needs an advanced pilot model to prove contribution to PIO prevention.

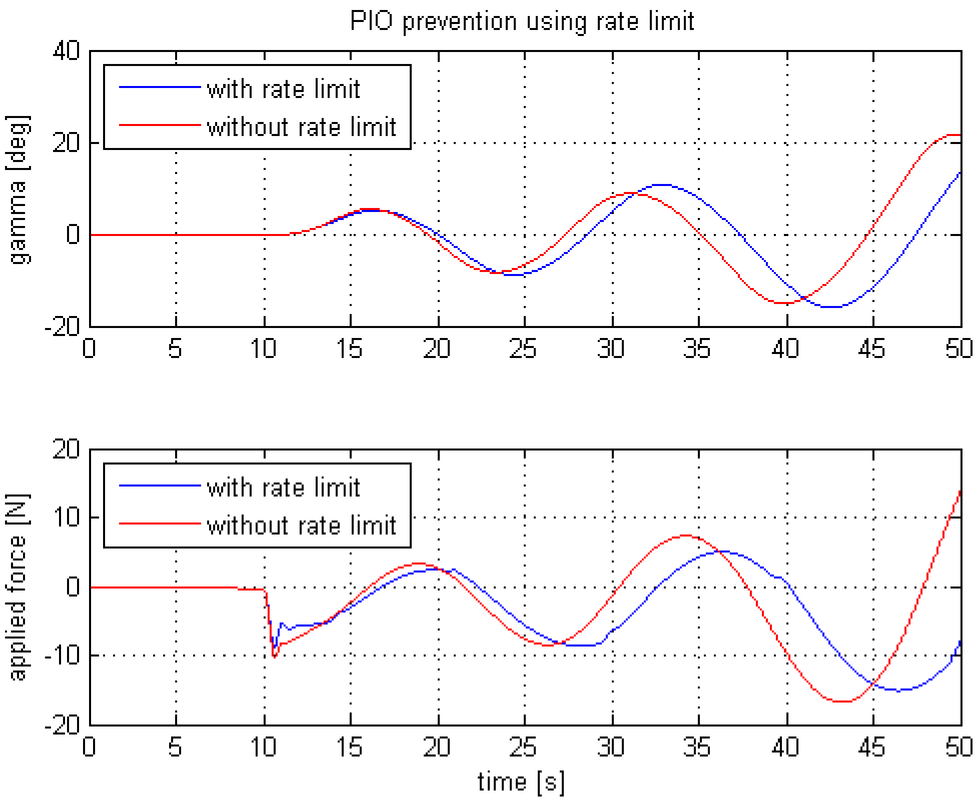

Figure 6-8: PIO Prevention Using Force Feedback Rate Limiting

6.2. PIO Detection Schemes

When we look at most of PIO suppression schemes we see that their biggest disadvantage is that they're always filtering the pilot commands which can lead to pilot's lack of situation awareness. If we don't want to implement sophisticated filters to avoid reduction of pilot authority when it's not appreciated but still be able to suppress PIO we may apply the pilot authority reduction only when PIO occur. This requires a PIO detection algorithm which will reliably reveal occurring PIO. PIO detection algorithm can be used only for pilot warning (using visual or acoustic stimulus or in case of force feedback equipped sticks a haptic stimulus like stick shaking) or better in combination with PIO suppression scheme. On the other hand PIO suppression scheme should be never used to drastically reduce pilot authority without pilot knowing otherwise his inputs may become even more rapid to compensate the reduced aircraft's response.

Majority of PIO detection schemes works with pilot's inputs and known surface rates and delays, comparing filtered and non-filtered commands and assumed surface behavior. If we use the aircraft model developed earlier we can use information of aircraft behavior to detect impending PIO. Aside of the pilot commands and surface response aircraft's angular velocity is proving to be the most important variable to PIO detection. In [14] (which is a master thesis aimed to develop a PIO detection algorithm and implement it on real aircraft) we can find a proposed structure of PIO detection scheme using mentioned variables. The scheme called **ROVER** (Real-time Oscillation VERifier) implements four conditions which need to be satisfied to confirm occurring PIO:

- significant change of aircraft pitch rate magnitude
- significantly large pilot commands
- sizeable phase angle differences between pilot command and pitch rate
- oscillations only in given frequency range

All of mentioned conditions are pretty straight forward and are quite easy to determine which makes the scheme reliable and easy to develop and implement. However it is important to determine the right ranges where respective conditions will be satisfied.

- The PIO detector should not trip when oscillations are present but are small or well damped. [14] makes an example using formation flying where small oscillations always occur to keep aircraft position.
- Similar as in first condition a small range of pilot command is not supposed to cause PIO. From the phenomena term the oscillations are to be mainly caused by pilot actions and small magnitude of stick deflections should not affect aircraft stability.
- The phase difference condition represents the time lag in aircraft response to pilot action. When aircraft response stays in phase with pilot command situation awareness is not altered a PIO are not likely to occur.
- The frequency range condition is based on historical data of severe PIO occurrences and comes from frequencies of PIO in documented cases [6]. High frequency oscillations are less likely to cause significant amplitude response, low frequency oscillations, on the other hand, are often result of different aircraft behavior (normal operation or phungoid mode)

ROVER detection scheme is set to switch to filtered pilot command when all conditions are satisfied and provide a visual and acoustic feedback [14]. To enhance scheme contribution to PIO mitigation a warning of impending PIO when only three of four conditions are satisfied is provided. Pilot is then alerted and may perform actions to avoid PIO occurrence. (Note that when stick rate limiting algorithm is used the probability of creating a phase delay between commands and surface responses is virtually zero. The phase angle condition is left out for simulations which implement stick rate limiter.)

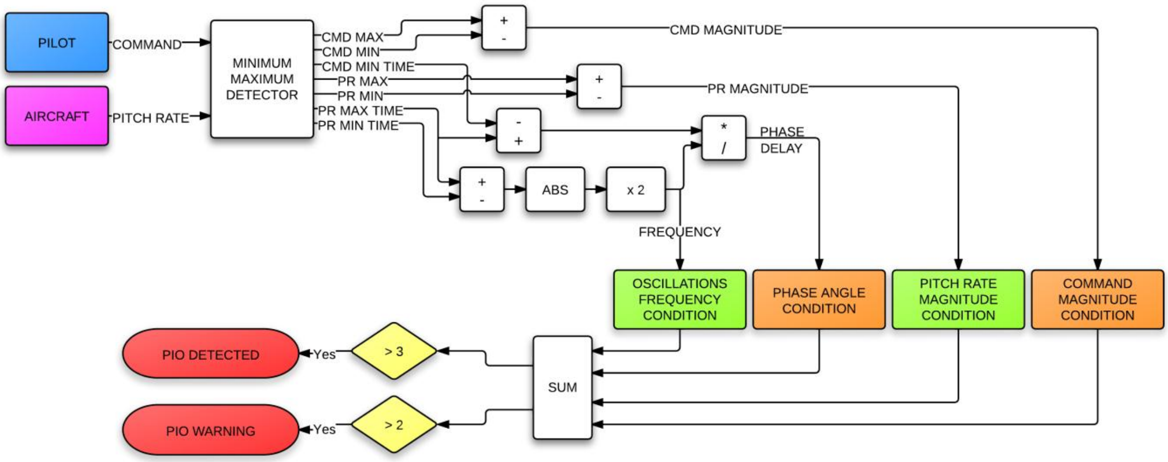

Figure 6-9: ROVER PIO Detection Algorithm

A MATLAB Simulink model of ROVER scheme was developed. The implementation is slightly different than the one described in [14] but uses the same principles. Minimal and maximal values of pilot command and aircraft pitch rate are detected and values and time of their occurrence are held until next period (Figure 6-10). The current differences of minimal and maximal values determine amplitudes of pilot commands and pitch rate, the difference between time of minimal pitch rate and maximal pitch rate gives half of oscillations period and difference between minimal pilot command and maximal pitch rate (maximal due to sign conventions) divided by oscillation frequency determines phase delay between command and aircraft response.

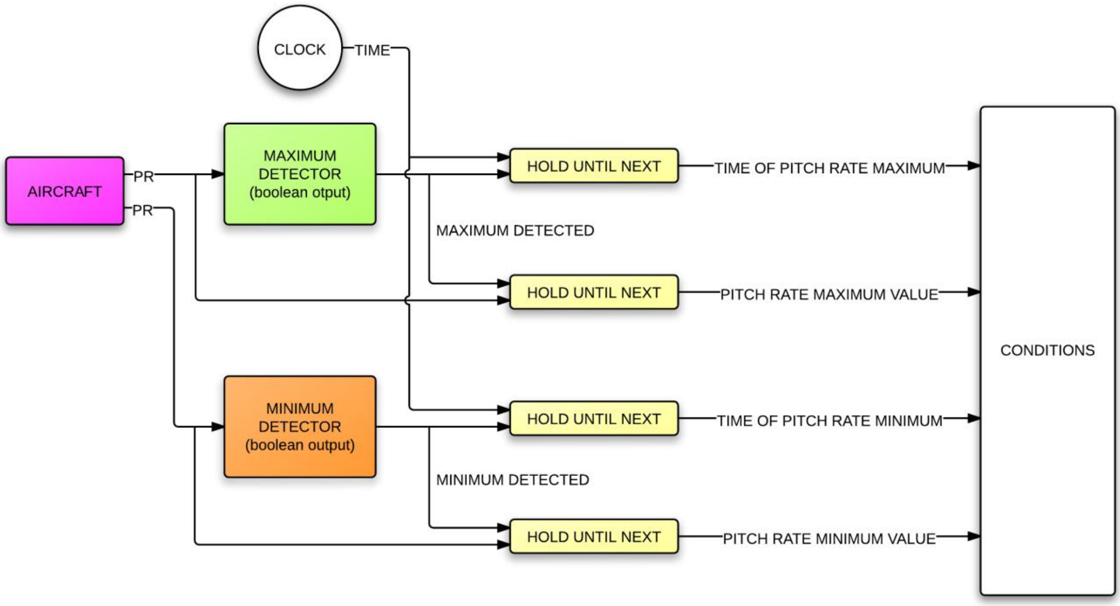

Figure 6-10: ROVER Algorithm Pitch Rate Elaboration Subsystem

When the command filtering is performed only in situations where PIO occur a much simpler methods of PIO mitigation can be used. To demonstrate this ROVER scheme was implemented into aircraft control loop together with a PIO suppression scheme represented by a simple proportional gain. When ROVER detects PIO pilot authority is reduced for duration of PIO debounced for certain time period. When PIO are suppressed pilot authority reduction fades out gently to prevent causing another case of PIO due to step in filtered pilot command.

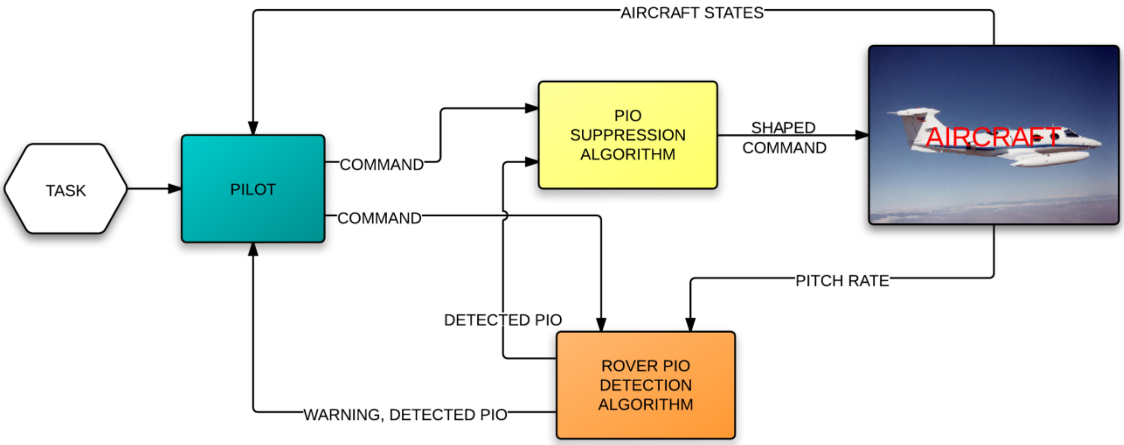

Figure 6-11: ROVER Scheme in Aircraft Control Loop

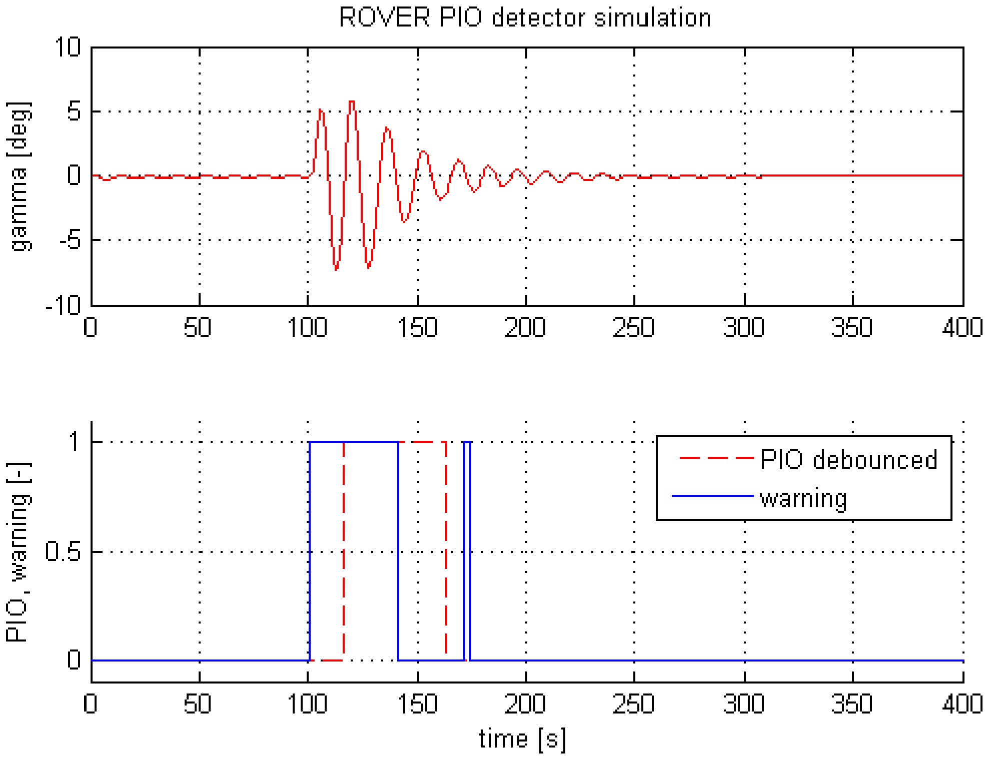

Figure 6-12: Suppression of PIO Using ROVER

As can be seen in Figure 6-12 warning of impending PIO is displayed immediately after first rapid command when surface position lags behind commanded due to surface rate limit and FBW system delay. When pilot doesn't react to this warning and PIO occur (detection approximately at the start of second period) his authority is swiftly reduced and oscillations amplitude starts to descent due to natural damping of control loop PIO. After PIO are suppressed detector holds the information for a chosen debounce time to ensure safe recovery and then starts to return full authority to the pilot (Figure 6-13).

PIO detection schemes can be combined with different suppression schemes to achieve balanced results from dynamics and stability points of view. We will further on show PIO detection scheme in combination with active force feedback.

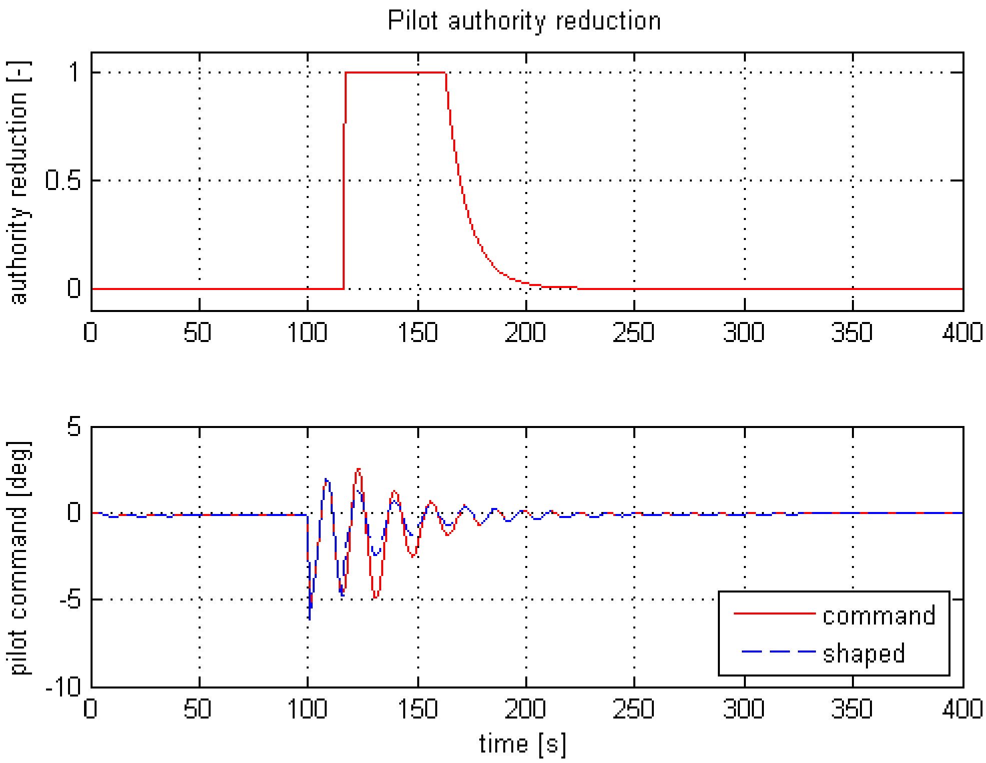

Figure 6-13: Reduction of Pilot Authority when Using ROVER

6.3. PIO Suppression Using Active Side Stick

In this chapter we will use developed active side stick simulation model to control aircraft model equipped with ROVER PIO detector and show the advantage of active feedback in the field of PIO suppression. Active side stick model will be connected to control loop model described in section 6.2 instead of PIO suppression subsystem (containing logic for pilot authority reduction).

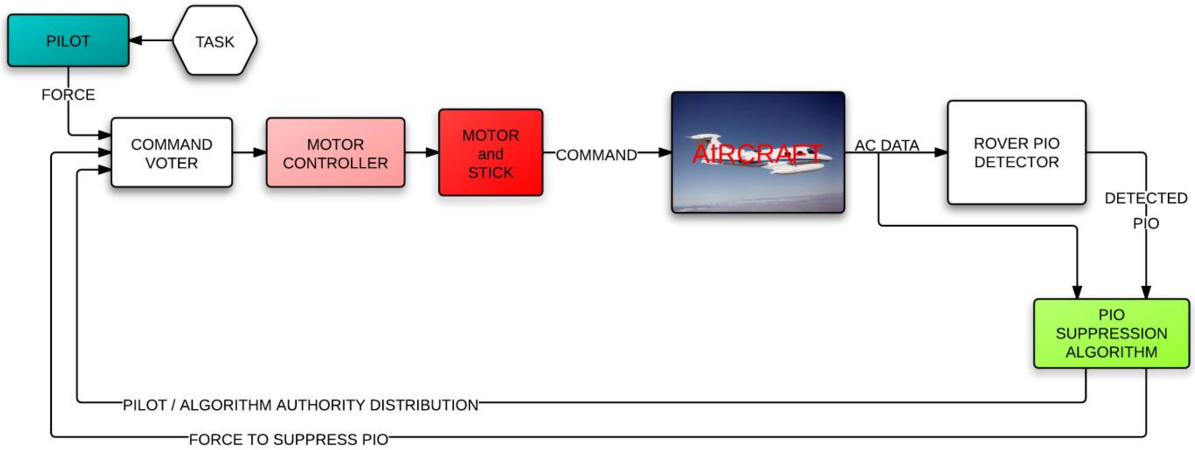

Figure 6-14: Scheme of Active Stick PIO Suppression Model

The algorithm used to determine force feedback needed to mitigate PIO is quite simple (Figure 6-15) thanks to reliable information about PIO occurrence coming from ROVER detector and use of motor driven side stick. When PIO is detected in ROVER algorithm a warning is announced, pilot authority is reduced and a PIO suppression regulator is put in control of the stick. Once PIO are suppressed pilot's authority is slowly restored to avoid rapid control stick movement due to pilot's generated forces.

Such authority reduction algorithm certainly requires an override button in the cockpit so the pilot can regain his authority any time when needed. Also warning signals (visual, haptic, acoustic or combined) are vital for a safe function of suppression algorithm. Pilot needs to be aware of the authority reduction and decide whether or not to use override button to restore his authority. Let's just note that the override button position should be within immediate reach of the pilot, preferably on the side stick assembly itself, because of the safety critical nature of situations in which PIO usually occur. The PIO warning signal and "push" from the stick may be sufficient for most of pilots to adjust their control strategy and suppress PIO by themselves. This behavior is again very hard to simulate and therefore a full-length pilot suppression is implemented in presented model.

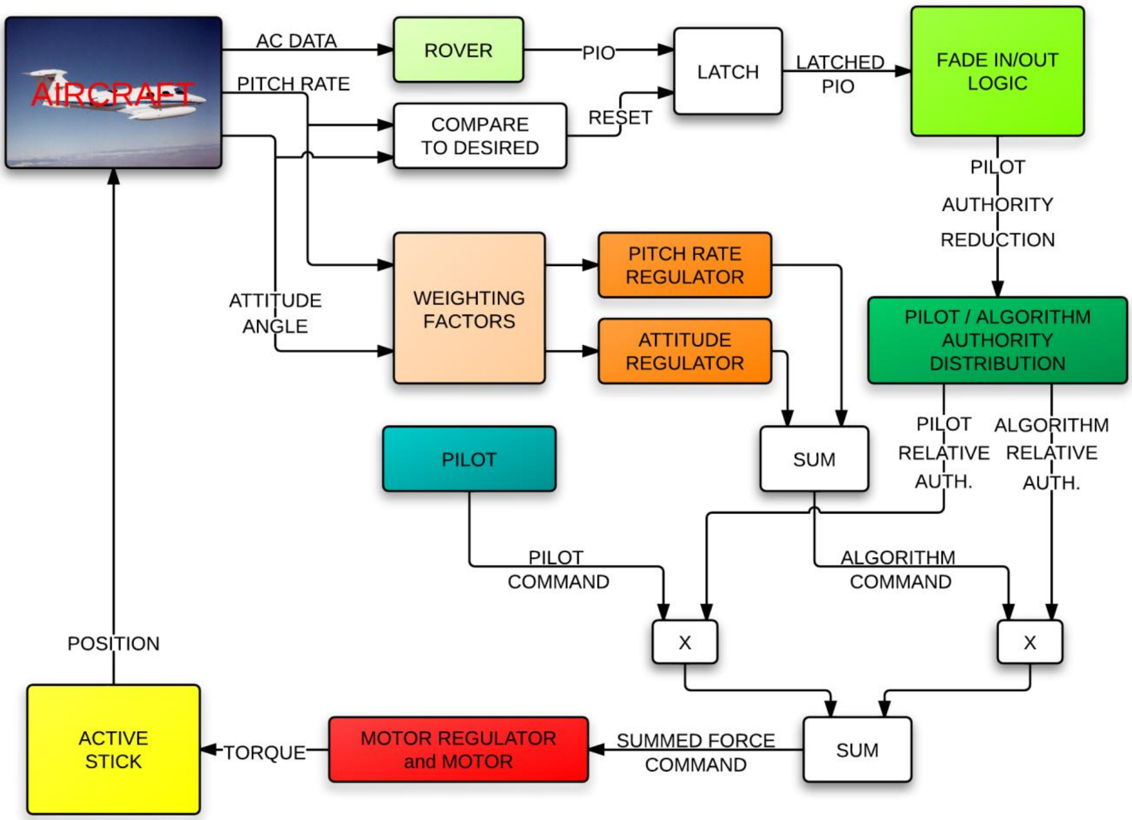

Figure 6-15: Active Stick PIO Suppression Algorithm

Let's review the PIO suppression regulator algorithm itself. The best solution for flight safety would be having aircraft states regulators which would track the given task when pilot won't be able to. Sadly, the task is never truly known in details especially in high demanding situations. A creative way to stabilize the aircraft was used. The airplane pitch rate (or pitch angular velocity) and pitch attitude angle variables were selected as regulator inputs. As the requested aircraft's trajectory is not known the regulator primarily tries to stabilize (null) the pitch rate. Note that pitch angular rate is derivation of pitch attitude and therefore the flight phase into which the algorithm is trying to stabilize the aircraft is not horizontal level flight (null pitch angle) but rather a direct flight with arbitrary pitch attitude. To avoid stabilizing aircraft for example into a steep descent a pitch attitude regulator is also used. Set of weighting factors is used to adjust regulators' priorities giving the pitch rate regulator priority over the attitude angle regulator.

PIO suppression regulator is naturally acting the whole time of flight, prepared to step into action when requested. An authority distribution scheme is used as mentioned before to switch between pilot and regulator in control. During normal operation only pilot is in control. When PIO is detected the motor controller inputs switch (with fade-in time constant) to PIO suppression regulator and pilot's authority is latched to zero. Authority can be restored by pilot's override button as described above. When the pilot doesn't use override his authority is zeroed until PIO suppression regulator achieves stable aircraft state and then is slowly restored (compare Figure 6-13 to Figure 6-16) to smoothen effects of PIO mitigation algorithm by gently retrieving pilot situation awareness provided by haptic feedback in normal situation after PIO is successfully suppressed.

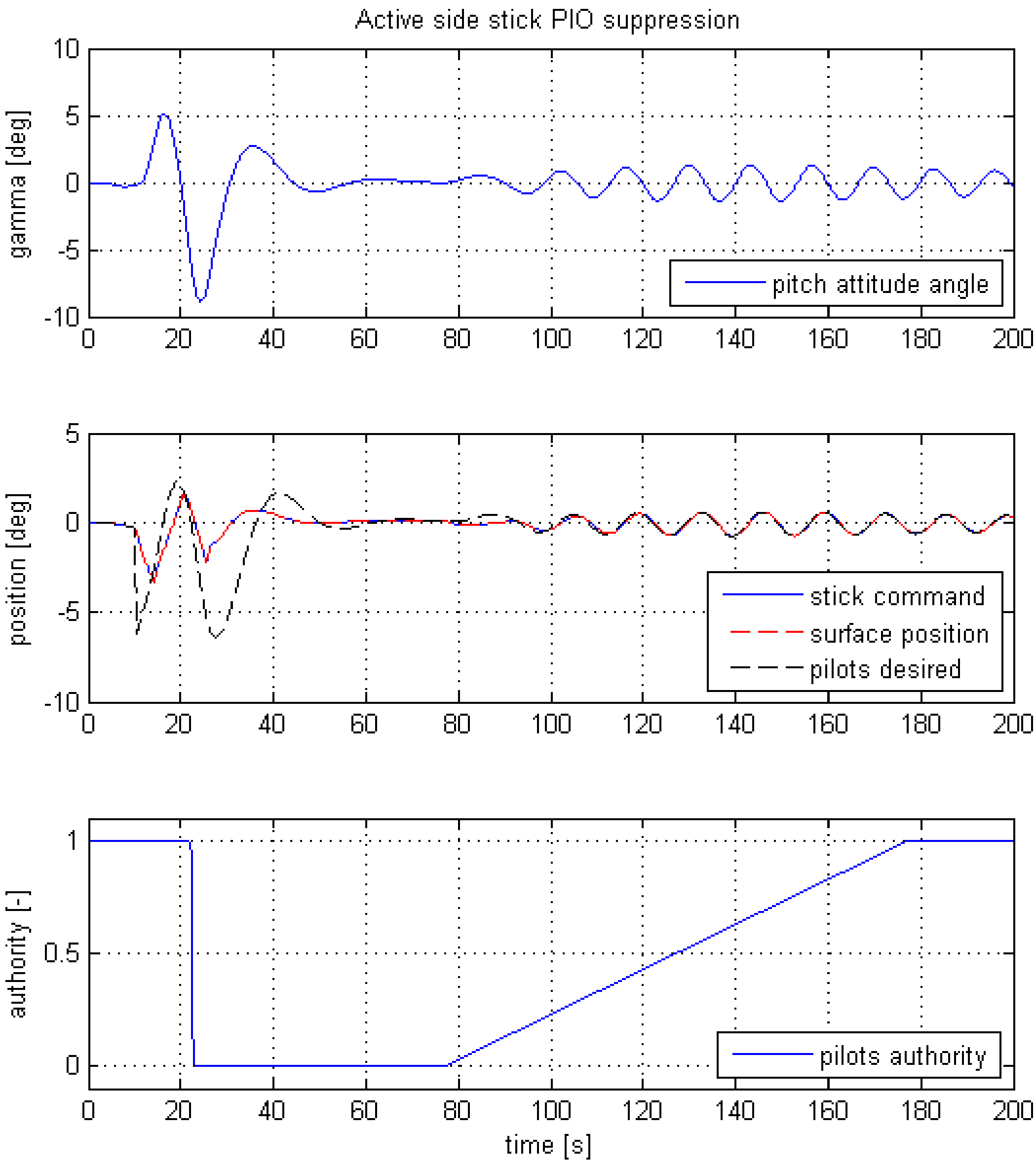

Figure 6-16: PIO Suppression using ROVER Detector and Active Side Stick

From the simulation results we clearly see the effect of active side stick use on PIO suppression. Pilot commands surfaces over rate limit (Figure 6-16) and increases his force commands further to overcome imaginary idleness of the aircraft although the stick moves only within rate ranges allowed by surface rate limits and increased feedback force is present. ROVER scheme detects impending PIO during first oscillation period and requests to reduce pilot’s authority. PIO suppression regulator stabilizes aircraft into a level flight and confirms that pilot authority can be restored. At this time pilot is still generating some forces onto the stick's grip trying to pursue the original oscillatory stick position. These together with excessively enlarged pilot gain in high demanding situation cause damped oscillations after PIO are suppressed which however are within limits of ROVER PIO detector.

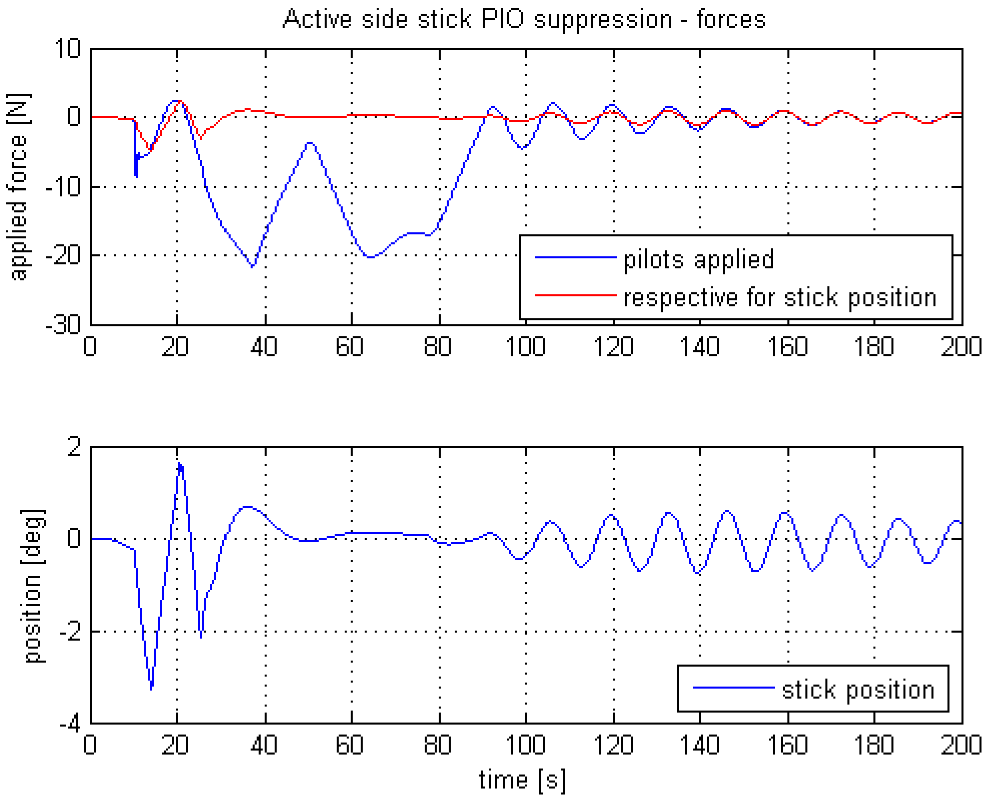

Figure 6-17: Forces during Active Side Stick PIO Suppression Case

Airspeed and angle of attack data prove the quasi-static nature of PIO (Figure 6-18). Pilot starts commanding only surface deflection to achieve quick attitude change, not the overall aircraft state and thus is acting as disturbance to all mentioned parameters.

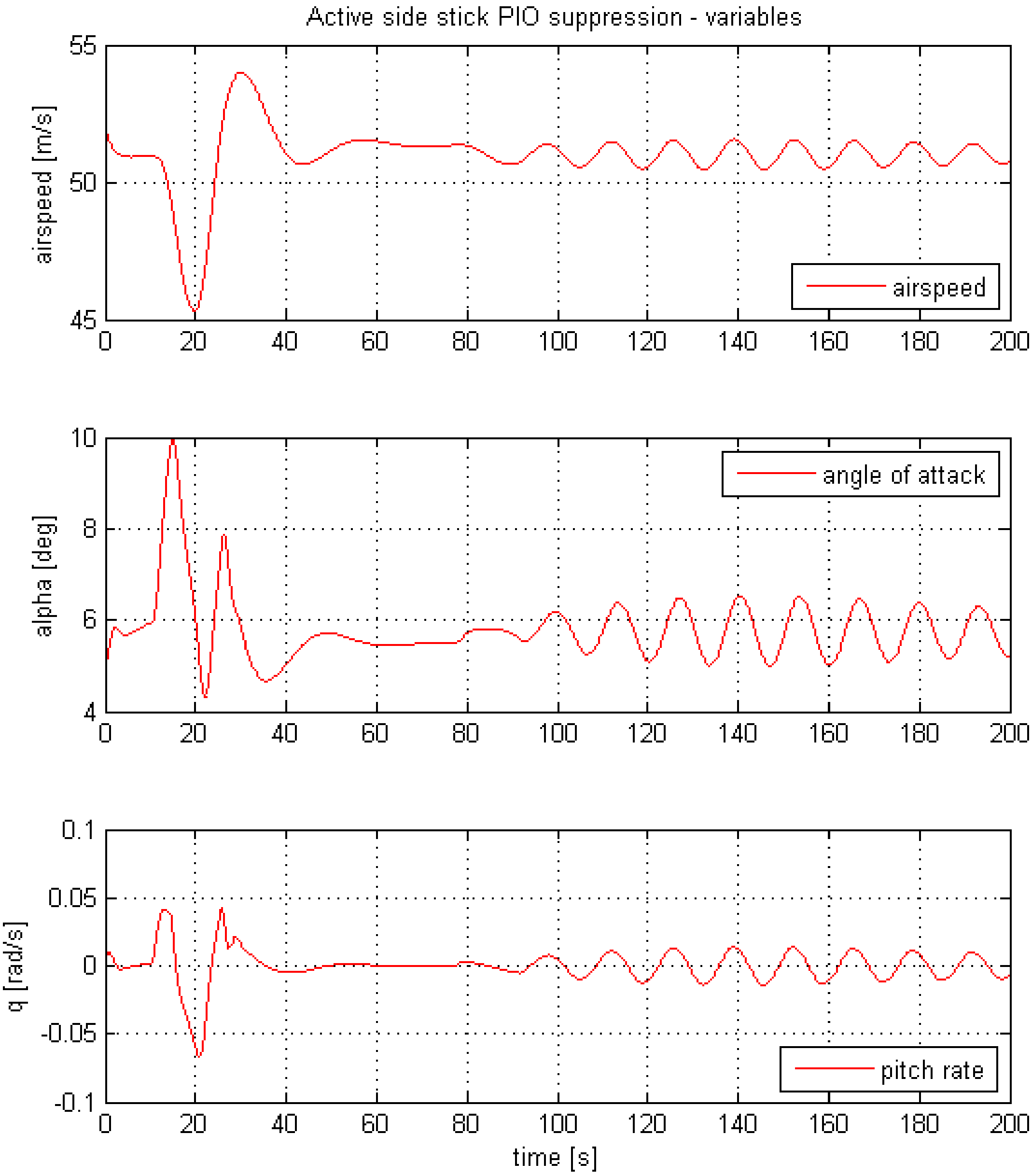

Figure 6-18: Variables during Active Side Stick PIO Suppression Case

7. Conclusions and Recommendations

This thesis was to create a MATLAB Simulink model of active side stick, use it to control an aircraft simulation and develop a PIO suppression algorithm based on active force feedback.

Demonstration of active side stick model functions was performed on two interconnected side sticks simulating pilot and copilot's sticks with override switch allowing different scenarios to be ran. Both side stick models were connected through stick control unit working as force feedback augmentation controller in order to simulate mechanical interconnection of the two side sticks. Force feedback augmentation is acting as a applied force controller and is distributing force feedback into respective sticks per magnitude of already applied commands and presenting forces applied on one stick into the second one and vice versa.

Side stick models were connected to aircraft simulation which provided necessary data to compute aerodynamic forces generated on control surfaces. These forces were normalized to given range of maximal applicable control forces and presented into the control sticks as the static part of force feedback (i.e. based on stick position/control surface deflection). Force feedback dynamic part (i.e. based on stick position/surface deflection rate) was performed by implementing a stick movement rate limiting algorithm to increase pilot's awareness of surface rate limits.

The second goal of thesis was to introduce PIO phenomena, determine several PIO categories and analyze factors contributing to PIO occurrence. Surface rate limiting and pilot behavior were determined as the most contributing factors and were focused on in PIO suppression algorithm development. PIO suppression schemes which are currently commonly implemented were reproduced to compare effectiveness and figure out disadvantages of respective schemes. It was established that the general disadvantage of all PIO suppression schemes is that their functionality is not limited to time when PIO occur and pilot authority may be reduced during other tasks as well. PIO detection scheme was reproduced to overcome this disadvantage. Simulations have shown reliability of detection scheme. PIO mitigation algorithm based on PIO detection scheme and active side stick was developed. Algorithm uses side stick's motor controller to move stick in desired manner to suppress pilot's commands that will result in PIO. The results show that this method can effectively suppress PIO after several oscillation amplitudes (Figure 7-1)

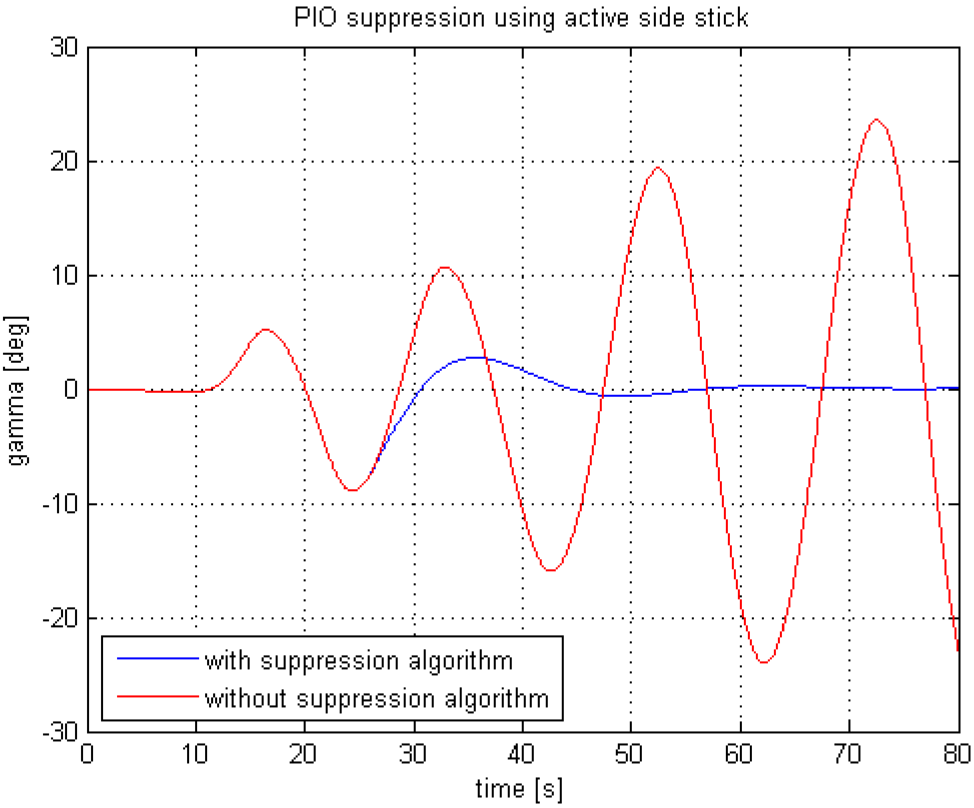

Figure 7-1: Demonstration of Force Feedback PIO Suppression Efficiency

Aircraft and pilot closed loop simulation is highly sensitive system with many dynamical characteristics mutually influencing each other. The weakest point of simulations presented in thesis is the pilot model which is essentially combination of contradictory requirements. For elaborative tests of PIO suppression schemes a more complex model should be developed or better a simulation with real pilot should be undergone. This would however require a real side stick with active force feedback as using gaming joystick shown in demonstration described in section 3.3.1 is not suitable for PIO suppression algorithm testing.

Appendix A: Learjet 24 Aircraft Stability and Control Derivatives

Geometry:

S	$21.3677\ [m^2]$
$\bar{q}$	$1642.3\ [N/m^2]$
$\bar{c}$	$2.1336\ [m]$
m	$5896.8\ [kg]$
d_T	$0\ [m]$
I_{yy}	$25489\ [kg\ m^2]$
T_{max}	$26200\ [N]$

Coefficients:

C_{D_0}	$0.0431\ [-]$
C_{D_α}	$1.06\ [rad^{-1}]$
$C_{D_{i_h}}$	$0\ [rad^{-1}]$
C_{D_δ}	$0\ [rad^{-1}]$
C_{L_0}	$1.2\ [-]$
C_{L_α}	$5.04\ [rad^{-1}]$
$C_{L_{i_h}}$	$0.85\ [rad^{-1}]$
C_{L_δ}	$0.4\ [rad^{-1}]$
C_{L_q}	$4.1\ [rad^{-1}]$
C_{M_0}	$0.047\ [-]$
C_{M_α}	$-0.066\ [rad^{-1}]$
$C_{M_{i_h}}$	$-2.1\ [rad^{-1}]$
C_{M_δ}	$-0.98\ [rad^{-1}]$
C_{M_q}	$-13.5\ [rad^{-1}]$

Appendix B: Archive Content

Part of thesis is CD with following data; online archive contains folders marked with **(a)**:

bibliography - sources referred in Bibliography section

figures - supplemental multimedia
- MATLAB figures - MATLAB generated figures used in thesis
- pictures - pictures from real hardware demonstration
- video - video from real hardware demonstration

models (a) - MATLAB Simulink simulation models
- **libraries (a)** - Libraries used in models; needs to be included in MATLAB directory
  - **servosystem_bs (a)** - servo system blockset; available at http://www.mathworks.com
  - mylib.mdl - author's library
- active_stick_model.mdl - two side stick models connected
- active_stick_model_coupling_test.mdl - model for hardware-in-the-loop demonstration
- active_stick_model_rate_limit.mdl - two side sticks with artificial rate limit implemented
- active_stick_model_tunable.mdl - side sticks with tunable feedback characteristics
- nonforce_compensations.mdl - non-force feedback PIO compensators
- rover.mdl - ROVER PIO detector
- SAAB.mdl - SAAB PIO compensator scheme
- suppression_force.mdl - force feedback PIO suppression simulation
- suppression_gain.mdl - ROVER demonstration
- suppression_rate_limit.mdl - PIO suppression using stick rate limit
- throttle.mat - data file with throttle settings
- lear_24.png - picture for masked aircraft subsystem
- sidestick_picture.png - picture for masked side stick subsystem

text (a) - text of thesis (this document)

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