Dynamic Performances of the Automatic Flight Control System

Gabriela STROE*,[1], Irina-Carmen ANDREI[2], Tiberiu Adrian SALAORU[2]

*Corresponding author
*,[1]POLITEHNICA University of Bucharest, Faculty of Aerospace Engineering,
Gh. Polizu Street 1-7, Sector 1, Bucharest, 011061, Romania,
ing.stroe@yahoo.com
[2]INCAS – National Institute for Aerospace Research "Elie Carafoli",
B-dul Iuliu Maniu 220, Bucharest 061126, Romania,
andrei.irina@incas.ro, icandrei28178@gmail.com, salaoru.tiberiu@incas.ro

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Abstract: *This paper explains why the combination of programming codes represents a true engineering tool in aircraft systems investigating. Flight safety and flying quality are extremely important to modern aviation industry. The aircraft responses, which are measured during real flight, are compared to the responses that are obtained from the simulations. Typically, aircraft problems consist in finding the solutions for basic work in all kind of areas, using knowledge from fields of science such as physics, mathematics and computer science. The purpose is to present such problems solved by computer simulations. Some of the advantages of performing numerical simulations are the low risk and low cost involved as compared to performing aircraft experiments. Another major advantage is the physical insight which one can gain in the behavior of the system subjected to different conditions and different values of the characteristic parameters of the aircraft's dynamic performances.*

Key Words: *Automatic Flight Control System, computer simulations, dynamic performances*

1. INTRODUCTION

Digital Flight Control Systems are made possible by replacing the classical mechanical or hydraulic linkages between the pilot's controls and aircraft active control surfaces with electrical signal connections, a new technology named Fly-By-Wire Flight Control. B-777 jetliner featuring its Digital Flight Control Systems, and the B-787, Boeing's next commercial aircraft, will use a similar system. With both the major commercial aircraft manufacturers involved in the Fly-By-Wire Flight Control for the future, a careful examination of the advantage and drawbacks of this technology is warranted, [16-17].

Fly-By-Wire Systems offer significant advantages over Mechanical and Hydraulic Flight Control Systems. From the design perspective, the fact that Fly-By-Wire Systems use copper wiring to convey pilot commands to control surfaces means that engineers are free to route

the wires through the aircraft wherever they choose without increasing cost or degrading the performance of the controls. For airlines, the reduced weight of a Fly-By-Wire Flight Control Systems translates into lower operational costs and higher profit margins, [18-21].
Digital Flight Control Systems also facilitate the introduction of computer-based technology to monitor the pilot input to ensure that the aircraft does not stall or otherwise depart from its flight envelope, [18-21].
Digital Flight Control Systems introduce new concerns, including the use of new software in a Flight Control System, the susceptibility of electrical wiring to Electromagnetic Interference - EMI, and the difficulty in modeling the possible flight conditions a Flight Control System might encounter [18-21].

2. B-777 DIGITAL FLY-BY-WIRE FLIGHT CONTROL SYSTEMS - DFBW-FCS

Airliners typically operate between 0.85 and 1.15 G - forces in the interest of all passengers comfort. If atmospheric turbulence occurs during the flight the pilot usually cannot react quickly enough to counteract the rapidly shifting aerodynamic forces, resulting in spilled passenger beverages and stained clothing. The Fly-By-Wire system is often able to detect atmospheric turbulence via the air and inertial data sensors and can subsequently smooth the ride by making many of adjustments per second to the Flight Active Control Surfaces - FACS. This smoothing is an example of Stability Augmentation System - SAS. In addition to all passengers comfort, the capability of Digital Flight Control Systems to rapidly detect and correct for Dynamic Flight Conditions - FDC- enables it to address a host of issues including fuel loading, aero elasticity, and other changing flight conditions without further taxing the pilot, [16-17].

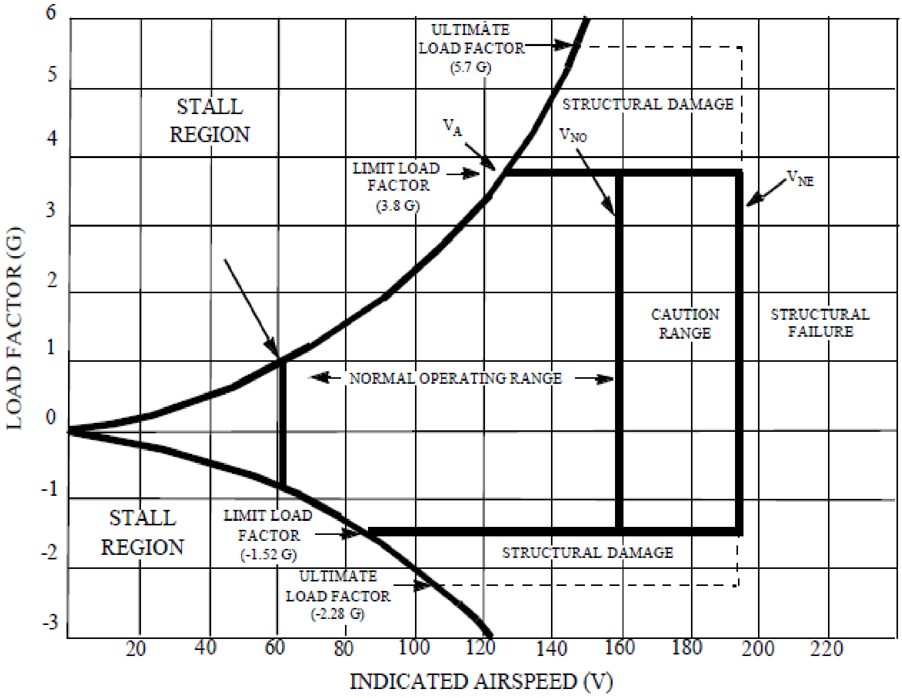

Fig. 1 - Typical Flight Envelope [16]

The B-777, being a fully Fly-By-Wire aircraft, has no physical connections between the pilot and the control surfaces. Consequently, the pilot is unable to experience any of the tactile cues to the flight condition of the plane. Boeing engineers have attempted to solve this problem through the implementation of a feedback system designed to faithfully replicate these sensations via servo motors controlled by the Actuator Control Electronics- ACEs.

To provide a sense of speed, the B-777 increases resistance to yoke inputs in 3 lb. increments per 10 knots [17]. Using this system, the aircraft is able to communicate to the pilot the increased loading on the airframe just as would a mechanical system. As the loading increases, so does the yoke resistance, culminating in a form of soft envelope protection. If the pilot attempts to configure the aircraft in a manner that might induce a stall, the Actuator Control Electronics react by sending a signal to shake the controls in a similar fashion to what might be experienced in a classical aircraft in the moments prior to stalling, [18-21].

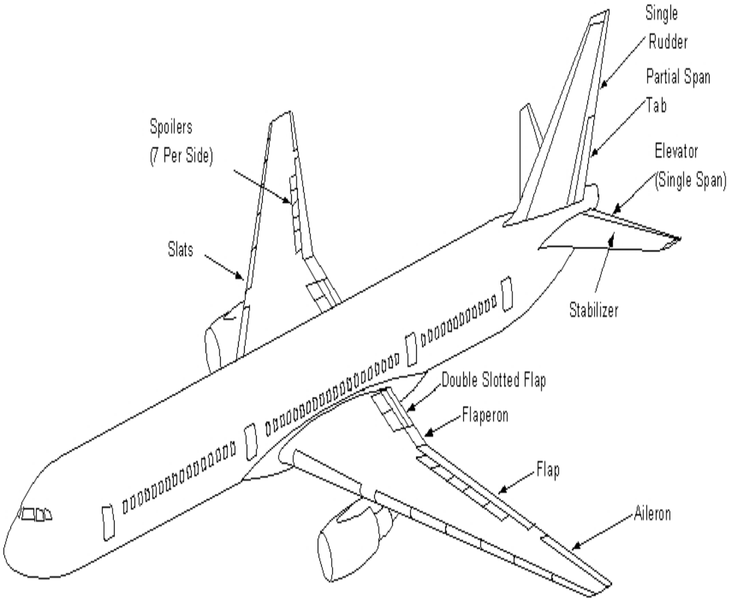

Fig. 2 - B-777 - Flight Control Surfaces [20]

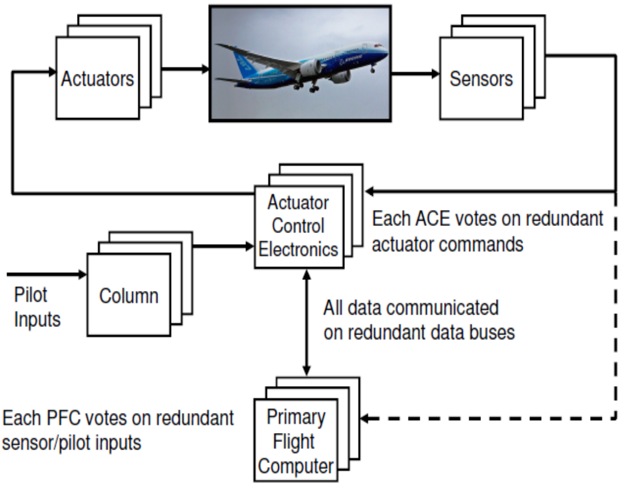

Fig. 3 - B-777 - Triplex Control System Architecture [17]

Boeing’s design methodology in the development of the B-777 Flight Control Systems has centered on keeping the responsibility for aircraft safety resolutely in the hands of the pilot.

Fig. 4 - B-777 - Fly-By-Wire System [18-19]

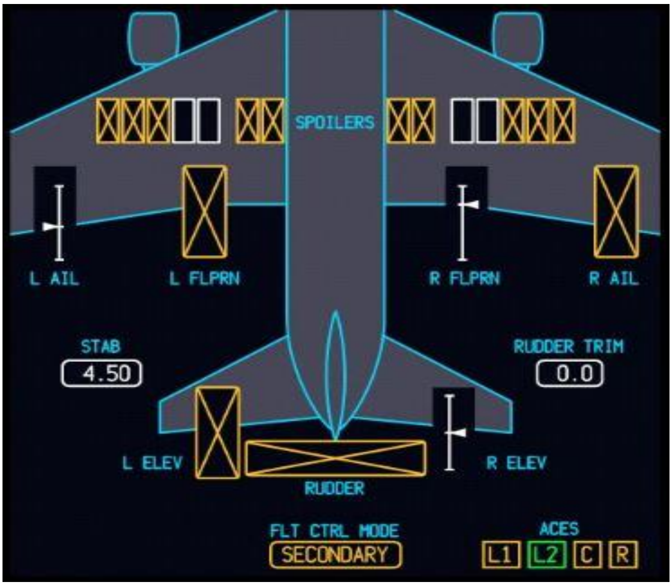

Fig. 5 -B-777 Operating Modes [18-19]

In the cockpit, the pilot can overview the status of the system through the Flight Control synoptic, accesible via Multi-Function Display, [20-21].

3. QUANTIFICATION STABILITY OF AEROSPACE SYSTEMS

Nonlinear flight dynamics equations are linearized by small perturbations approximation and the longitudinal and lateral equations are expressed by the dimensioned derivatives [15]:

$$\boldsymbol{x_{LONG}} = [u \quad w \quad q \quad \theta]^T \tag{1}$$

$$\boldsymbol{u_{LONG}} = [\delta_{t1} \quad \delta_{t2} \quad \delta_e]^T \tag{2}$$

$$\boldsymbol{\dot{x}_{LONG}} = \boldsymbol{A_{LONG}x_{LONG}} + \boldsymbol{B_{LONG}u_{LONG}} \tag{3}$$

where control variables are the engine throttle settings δ_{t1} and δ_{t2} and the elevator deflection δ_e, [4-5]. For the lateral dynamics, the state and control vector is:

$$\boldsymbol{x_{LAT}} = [v \quad p \quad r \quad \phi \quad \psi \quad y]^T \tag{4}$$

$$\boldsymbol{u_{LAT}} = [\delta_{t1} \quad \delta_{t2} \quad \delta_e \ \delta_r]^T \tag{5}$$

$$\boldsymbol{\dot{x}_{LAT}} = \boldsymbol{A_{LAT}x_{LAT}} + \boldsymbol{B_{LAT}u_{LAT}} \tag{6}$$

$$\boldsymbol{u_{LONG}} = \begin{bmatrix} \delta_{t2} \\ \delta_e \end{bmatrix} = -\boldsymbol{K_{LONG}x_{LONG}} \tag{7}$$

$$\boldsymbol{u_{LAT}} = \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix} = -\boldsymbol{K_{LAT}x_{LAT}} \tag{8}$$

Optimal Kalman gains $\boldsymbol{K_{LONG}}$ and $\boldsymbol{K_{LAT}}$ are calculated via solving the Algebraic Riccati Equation -ARE ([10-15]):

$$\boldsymbol{A^T P} + \boldsymbol{PA} + \boldsymbol{Q} - \boldsymbol{PBR^{-1}B^T P} = 0 \tag{9}$$

$$\boldsymbol{K} = \boldsymbol{R^{-1}B^T P} \tag{10}$$

$$\boldsymbol{u_c} = \begin{bmatrix} \delta_{t1} \\ \delta_{t2} \\ \delta_e \\ \delta_a \end{bmatrix} = -\boldsymbol{K_c x_c} \tag{11}$$

$$\boldsymbol{x_c} = [u \quad w \quad q \quad \theta \ \ x_e \ \ v \ \ p \ \ r \ \ \phi \quad \psi \quad y_e\ ]^T \tag{12}$$

Stability is of concern for any control system but it is especially important in the attitude control of the aircraft which may be inherently unstable in the absence of the active control.

Gain margin and phase margin represent the tolerance of a control loop to perturbation in loop gain and phase delay, [1-3].

Stability requirements specified as gain and phase margins are convenient because they can be measured in a closed loop control system by artificially introducing variations in the loop gain or the phase delay until instability is observed, [1-3].

These stability margins can be found analitically by examinating the open-loop tranfer function, Bode diagram, the Nichols Chart gain and the phase cross plot, or the Nyquist plot of real vs. imaginary parts, [6-9].

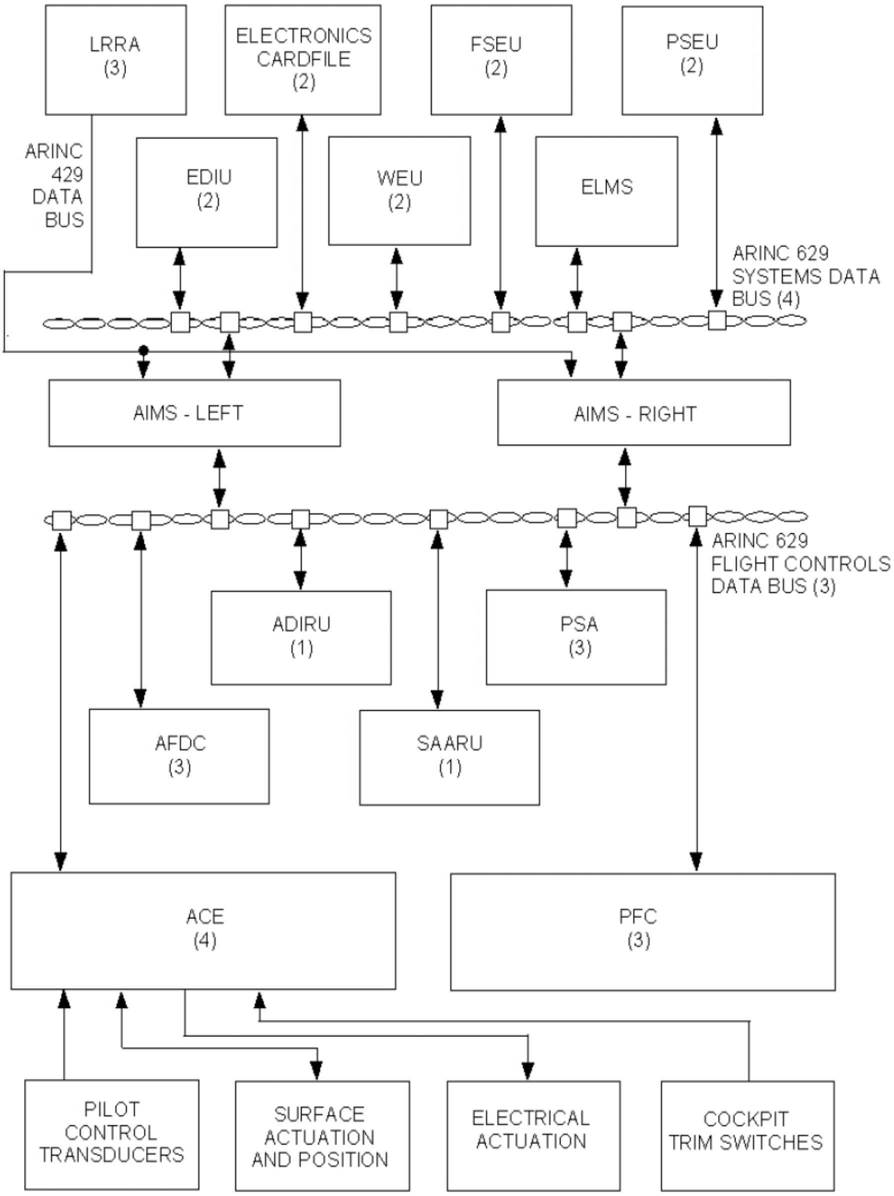

Fig. 6 - Block diagram of the electronic components of the B-777- PFCS-Primary Flight Control System [20]

The Boeing 777 Fly-By-Wire Primary Flight Control System - PFCS utilizes a new technology to provide significant benefits over that of an aircraft conventional system. These benefits include a reduction in the overall weight of the aircraft, superior handling characteristics, and improved maintainability of the system. At the same time, the control of the aircraft is accomplished using classical flight deck controls, thereby allowing the pilot to fly the airplane without any specialized training when transferring from a more conventional commercial jet aircraft. The technology utilized by the B-777 Primary Flight Control System has earned its way onto the airplane, and is not just technology for the sake of advanced technology, [20-21]. The Flight Envelope Protection System - FEPS is designed such that the operational and structural limits, e.g. maximum angle-of-attack, maximum bank angle, maximum speed or Mach number, maximum load factor, will not be exceeded.

In case the pilot is about to exceed one of the limits, compromising the safe operation of the aircraft, the control surface deflections commanded by the Stability and Control Augmentation System - SCAS are modified to prevent this from happening. This system increases the safety and allows the pilot to react rapidly and strongly if necessary, without having to worry about exceeding the operational or structural limits of the aircraft. When the Enhanced Ground Proximity Warning System -EGPWS issues a warning, the pilot should climb as fast as possible. With the Flight Envelope Protection System - FEPS the pilot can pull back the column to the maximum position without exceeding the maximum attitude and apply full throttle, [13-15].

The Digital Fly-By-Wire Flight Control System has many advantages over the Mechanical Flight Control System, both in terms of implementation as well as functionality.

The Digital Fly-By-Wire Flight Control System is completely dependent on electric and hydraulic power, which makes these systems critical for the safe operation of the aircraft. This is already the case for large commercial aircraft with hydraulically-boosted controls without manual reversion, [15-18].

The Flight Control Laws are now purely embedded in software and the only hard boundary is the structural limit of the airframe itself. It is now possible to add features to the Flight Control Laws such as pilot command shaping, Flight Envelope Protection. In order to ensure the availability of the system, redundant sensors, actuators, Flight Control Computers are implemented and their performance is crosschecked continuously. The software of each Flight Control Computer may have to be written by a different team and compiled with different compilers. Dissimilarity in software and hardware reduces the risk of generic failures, i.e. failures that occur in all similar redundant components at the same time. Fault detection and identification schemes need to be added to the system in order to manage all the redundant hardware. This adds to the cost of the Digital Fly-By-Wire Flight Control System as compared to that of the Mechanical Flight Control System, [15-18].

4. NUMERICAL SIMULATION AND CONCLUSIONS

Stability requirements are often specified in terms of gain margin and phase margin. These are independent margins describing how much either the gain or phase alone can be varied before the system becomes unstable. These two margins are represented as separate independent points on the Nichols plot, [10].

However the true stability objective is to specify how 'close' a system is to becoming unstable for any combination of gain and phase, [1-5].

This is compactly and precisely measured by Stability Margin which describes the closest approach of the open-loop transfer function to the (-1, 0*j*) point on the complex plane in a Nyquist plot. Stability margin contours can be draw on the Nichols plot to show the Nyquist boundary of different combination of gain and phase deviations that can be tolerated with a certain level of robustness to instability. The gain and phase margins, as well as the Nyquist Stability Margin contour connecting them, are defined in the frequency domain. The margins and the contour can be verified in time domain simulations by injecting different combinations of gain and phase perturbations from nominal.

The general function of the Flight Control Laws in the Fly-By-Wire Flight Control System is to improve the handling qualities of the bare aircraft, in particular with respect to Stability, Control and Flight Envelope Protection.

The design of the Flight Control Laws is a nonlinear control problem due to the nonlinear aircraft dynamics, which also vary with the Flight Condition and aircraft configuration.
The linearized model for longitudinal motion is described as follows ([5]):

$$\begin{bmatrix}\dot{u}\\ \dot{w}\\ \dot{q}\\ \dot{\theta}\end{bmatrix}=\begin{bmatrix}X_u & X_w & X_q & X_\theta\\ Z_u & Z_w & Z_q & Z_\theta\\ M_u & M_w & M_q & M_\theta\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}u\\ w\\ q\\ \theta\end{bmatrix}+\begin{bmatrix}X_{\delta_e}\\ Z_{\delta_e}\\ M_{\delta_e}\\ 0\end{bmatrix}\delta_e \tag{13}$$

For the short-period approximation, only the downward velocity w and the pitch rate q are considered, while the forward speed is assumed to be constant $-\ \dot{u}=0$ ([5]):

$$\begin{bmatrix}\dot{w}\\ \dot{q}\end{bmatrix}=\begin{bmatrix}Z_w & Z_q\\ \widetilde{M}_w & \widetilde{M}_q\end{bmatrix}\begin{bmatrix}w\\ q\end{bmatrix}+\begin{bmatrix}Z_{\delta_e}\\ \widetilde{M}_{\delta_e}\end{bmatrix}\delta_e \tag{14}$$

The Flight Control Computer Model includes the cross-channel data link, the voter or monitor for sensor or actuator fault detection and identification, the Flight Control Laws to improve Stability and Control, the Autopilot and the Flight Envelope Protection Modes.

The longitudinal aircraft motion is divided into two oscillatory Eigen-motions, namely the short-period motion and phugoid motion.

The phugoid motion has a low Eigen-frequency and is typically poorly damped. During the phugoid motion the aircraft exchanges kinetic energy for potential energy and vice versa, which results in variations in airspeed and altitude.

The short-period motion describes the aircraft dynamics along the Y -axis in terms of the pitch rate and the angle-of-attack or downward speed.

Fly-By-Wire Flight Control System provides:

- Protection against over speed, stall and structural overstress;
- Stability Augmentation System;
- Pilot controls adaptation;
- Aerodynamic configuration optimization.

Primary Flight Control Surface position orders are:

- Electrically commanded;
- Performed by actuators -either hydraulically or electrically powered.

Fly-By-Wire Flight Control System Trends:

- New aerospace vehicle designs employ FBW;
- Advancing high-speed digital processing and sensor technology is making digital FBW even more capable;
- Complementary advances in flight simulation allow precise modeling, design, and tuning of FWB systems prior to flight;
- Adaptive control system are getting more sophisticated:
  - change vehicle response based on mission and flight regimes;
  - compensate for missing human pilot adaptation;
  - Build-in compensation for sub-optimal, non-linear aerodynamics;
  - Stealth airframe design;
  - Space planes.
- Fiber optics employed for high-speed networks: Fly-By-Light.

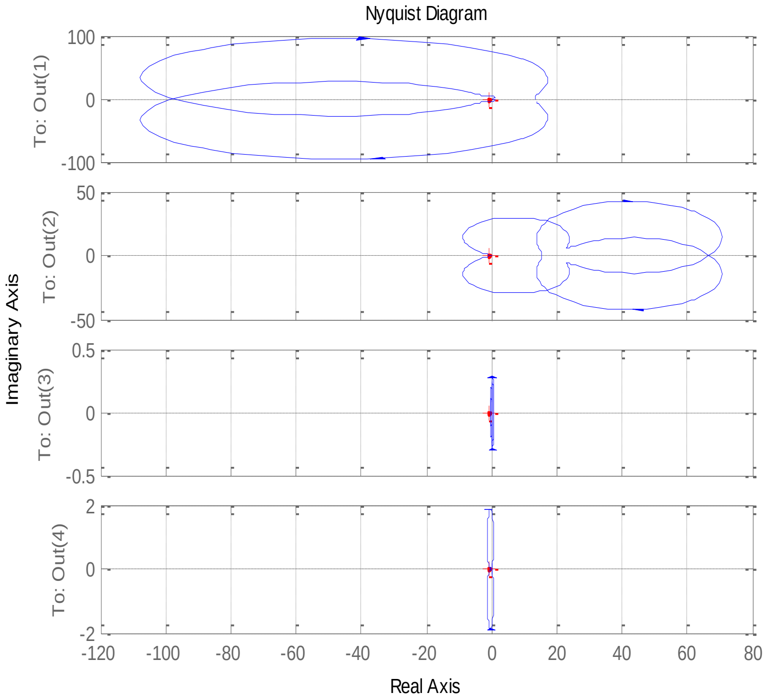

Fig. 7 - Nyquist Diagram

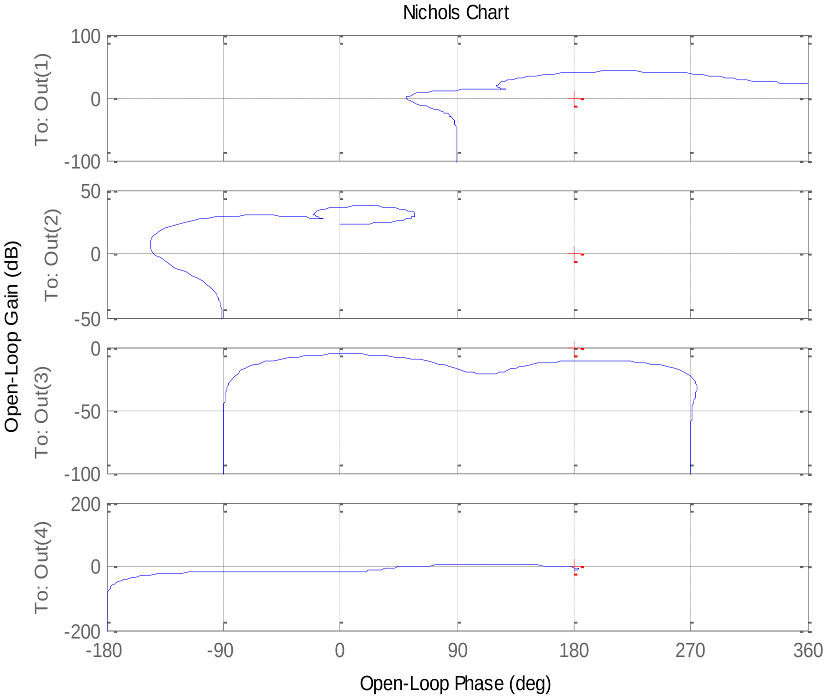

Fig. 8 - Nichols Chart

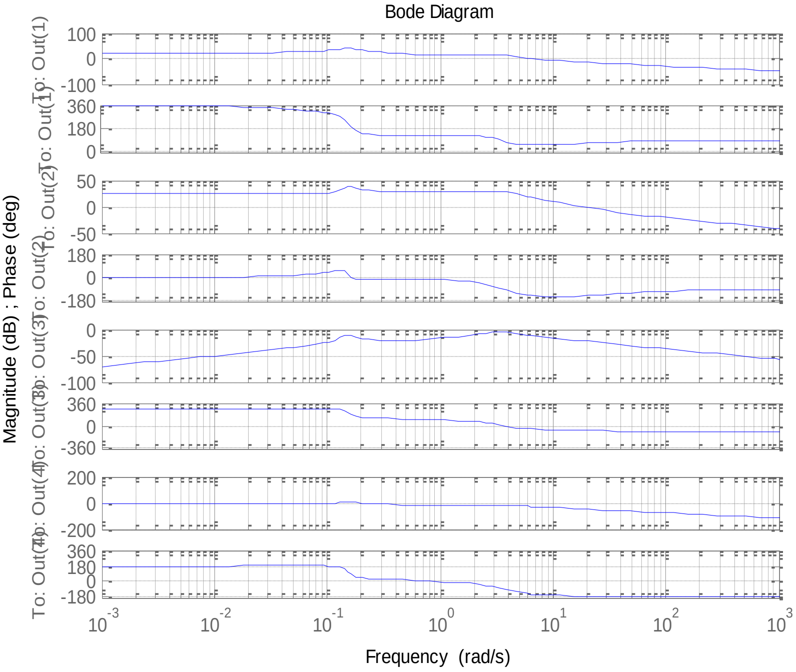

Fig. 9 - Bode Diagram

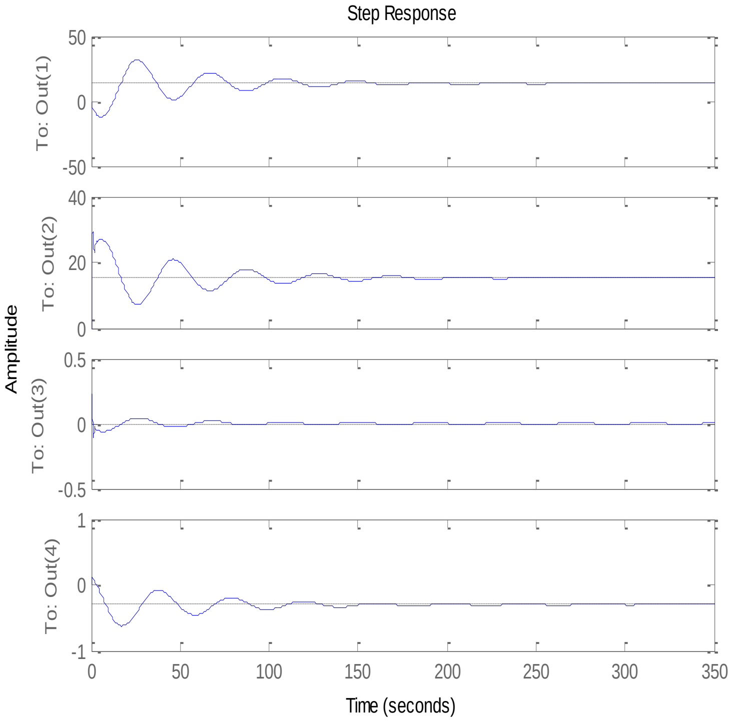

Fig. 10 - Aircraft - Step Response

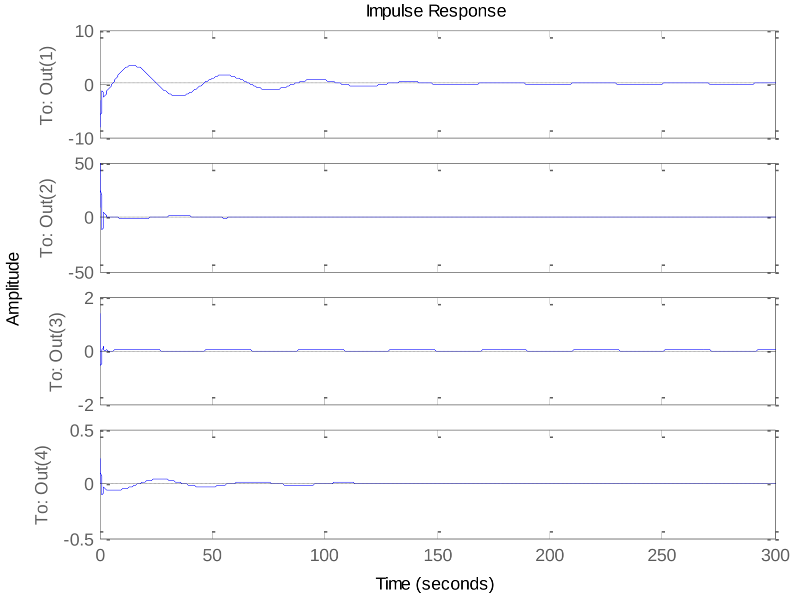

Fig. 11 - Aircraft - Dirac Impulse Response

Digital Flight Control and Fly-By-Wire Technology involve a variety of engineering considerations. Boeing anticipated that the B-777 would become the world's most technologically advanced and safest airliner.

The major components of the B-777 - Fly-By-Wire system consist of the Actuator Control Electronics - ACEs, the Primary Flight Computers -PFCs, and the Power Control Units - PCUs.

Each ACE onboard the B-777 is a quadruply-redundant system that serves as the backbone of the Fly-By-Wire system. The ACE bridges the gap between the analog and digital domains to interface between the air crew, flight surfaces, and flight computers.

In addition to controlling flight surface deflection via the Power Control Units, the ACEs also control the tactile feedback system.

The PFC is the heart of the B-777 Fly-By-Wire system, responsible for calculating control surface deflections based on pilot inputs, sensor data and relevant Flight Control Laws. The PFC also handles the Stability Augmentation and Automatic Trimming while working in close concert with many of the higher-level computer systems such as the Flight Management System - FMS and Autopilot to effect a high degree of automation in the cockpit.

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