In Flight Simulation for Flight Control Law Evaluation of Fly-by-Wire Aircraft (I)

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Abstract: The paper presented here covers the work associated with the flight control law design, ground based and in flight simulation and handling qualities assessment of the Fly-by-Wire type Aircraft (FBWA). The control law was designed for the most unstable aircraft configuration flight regime for the target aircraft (FBWA). The ground based simulation including math-model, real-time pilot-in-the-loop and iron bird simulation were used for validation of the control law before the experimental in-flight simulation on the IFS (In–Flight-Simulator) aircraft. The flight tests results showed that Level 1 handling qualities for the most unstable flight regime were achieved.

Keywords: In-Flight Simulation, FBW Flight Control System, Control Law, Handling Quality, VSS, Model Following

1. INTRODUCTION

Recently the Korean aviation industry has been developing intensively. This development was aimed to creating the Korean new generation aircraft including the prospective and rather sophisticated maneuverable aircraft.

The present paper is dedicated to in-flight simulation in the IFS and research of flight control laws of the Fly-by-Wire Aircraft (FBWA). A few important aspects should be emphasized hereof. The first one is that, in one hand, the highly augmented digital FBW flight control system (like one installed at FBWA) gives a chance to optimize the aircraft handling qualities in the most high degree. On the other hand, some inherent FBW system features like its discrete nature, cascaded element chains and relevant time delays, actuator rate saturation and other nonlinearities could provoke the new phenomena and embarrass the handling qualities optimization. Some of these phenomena (like PIO, for instance) could be hardly revealed in ground simulation and demand the direct pilot assessment of aircraft in flight. In this case, when the new aircraft does not exist yet, only the specially equipped IFS could be applied for relevant research, evaluation and further flight control law corrections.

The other important aspect is that the familiarization with the specific features of the future aircraft at the earlier stage of FBWA development could be useful to be well prepared for the flight test of the aircraft prototype handling qualities.

The present paper covers the pre-flight related ground based open loop and pilot-in-the-loop math simulation of the FBWA dynamics and IFS expected dynamics in regime of simulation of the most unstable FBWA configuration corresponding to FBWA flight at Mach number M=0.8 and altitude H=300ft, in-flight simulation of the flight control law in the IFS. Finally, test pilot evaluation and engineering analysis of the FBWA expected handling qualities against the given criteria.

2. FBWA DESCRIPTIONS

2.1 FBWA Characteristics

The FBWA (object to be simulated) is a Class IV type aircraft. The airframe dynamics is nominally unstable in the longitudinal channel.(Table 1)

2.2 FBWA Control Law

The target aircraft is equipped with a digital Fly-by-Wire flight control system (FCS) in pitch (longitudinal), roll and yaw (Lateral/Directional) axes.

Table 1 FBWA Characteristics

Contents		Values
Aircraft geometry	Wing surface area	255 ft^2 (23.69 m^2)
	Mean aerodynamic chord	9.603 ft (2.93 m)
	Wing span	29.875 ft (9.1 m)
	Aircraft weight	17,659 lbs
Moments of inertia	Ix	6502.4 slug-ft^2
	Iy	43,114.3 slug-ft^2
	Iz	38,084.7 slug-ft^2
	Ixz	1,371.8 slug-ft^2

2.2.1 Longitudinal axis flight control law

The objectives of the FBWA longitudinal axis control laws are stabilization of the unstable aircraft and attainment of adequate handling qualities. Fig. 1 shows the detail control law functional block diagram of this structure. The feedback parameters are a blend of pitch rate (q), normal acceleration (Nz) and angle of attack (α).

A normal acceleration command system gives good flight path control in the mid to high dynamic pressure flight regime because Nz is proportional to flight path (γ). Angle of attack and pitch rate feedback provide good stability augmentation in terms of short period frequency and damping respectively[1].

The longitudinal axis design employs proportional plus integral (PI) control. The Nz-error or q-error is sent to the integrator. Separate gains are applied for the command paths and the proportional feedback paths. The aircraft response (feedback) is compared to the maneuver command, then the resulting difference drives the actuator to reduce the maneuver error to zero through the forward loop integrator. Consequently, the aircraft is automatically kept in wings level trim with hands off since any uncommanded aircraft pitch rate or normal acceleration is reduced to zero by the action of the integrator.

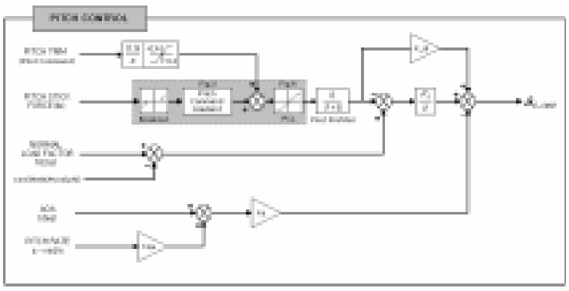

Fig. 1 Longitudinal Flight Control Law Structure

2.2.2 Lateral/Directional axis flight control law

The lateral/directional flight control law for FBWA is composed with the roll rate (p) feedback configuration for lateral axis and the lateral acceleration (Ny) feedback configuration for directional axis control law. Fig. 2 shows the detailed functional control law block diagram of this structure. This feedback system features a proportional roll rate command and rudder position command system. In this structure, the following three feedback signals are required:

- roll rate feedback is used to adjust the roll mode time constant and improve the Dutch roll damping characteristics. The lateral axis control structure is fundamentally a roll rate control, therefore, no wash-out (high pass) filter is needed;
- yaw rate (r) feedback is used to augment the Dutch Roll frequency and damping. To prevent the stability augmentation from interfering with the pilot in steady turns, a wash-out filter is applied to the yaw rate signal.
- lateral acceleration feedback is also used for the directional stability augmentation and establish maximum command sideslip capability;

Also, this control structure includes the Aileron-to-Rudder Interconnection (ARI) to counter the yawing moment produced by the roll control surfaces. Therefore, the pilot is not required to coordinate rolling maneuvers, even at high angle of attack.

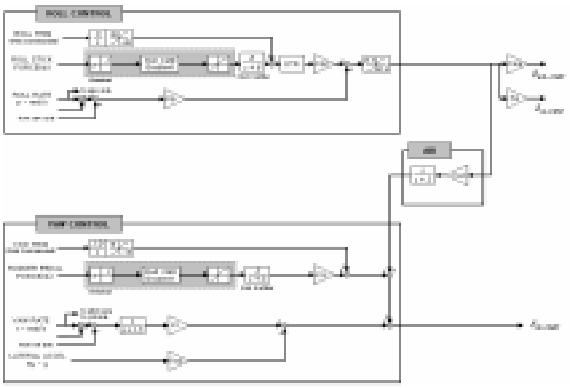

Fig. 2 Lateral/Directional Flight Control Law Structure

2.3 Math Model Simulation

The equations of aircraft motion were integrated using Euler numerical integration method with sample rate of 0.01sec. To simulate the Digital Flight Control System and integrate the relevant discrete control law (presented in the form of analog equations) the Tustin`s algorithm (also called a bilinear transformation) of the same sample rate was applied. The FBWA motion has been simulated for the given flight regime. The simulation results are presented in Fig. 3.

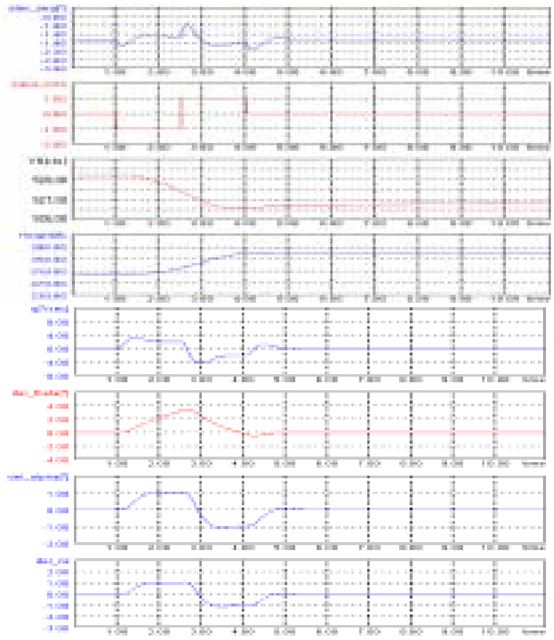

Fig. 3 Examplary time histories of FBWA. Pitch channel, H=300 ft, M=0.8.

2.4 VSS (Variable Stability System) Control Law

For the FBWA simulation the Model Following System (MFS) technique have been applied because of it is more universal and provides a high accuracy of simulation even in case of nonlinearities of the simulated aircraft parameters. A single dynamic parameter (for instance, either acceleration or attitude rate) in the each channel (pitch, roll and yaw) may be simulated in the Flight Simulation Facility (FSF) in a time. The FSF was supposed to reproduce the FBWA flight dynamics in the most unstable (without highly augmented flight control system) configuration at flight regime of Mach number M=0.8 and altitude H=300ft. In general case, the aircraft accelerations should have a preference for in-flight simulation at high airspeed. On the other hand, the attitude rate is of more importance from viewpoint of any task-oriented evaluation, usually associated with the aircraft attitude control. For instance, since the given altitude is very low a task of aircraft angular position control seems to be of more criticality and preference then acceleration. Furthermore, some criteria from the MiLS (Man-in-the-Loop Simulator) Aircraft Flying Qualities Design Guide Document[2], like Bandwidth Criterion and Gibson Criteria, are formulated in terms of aircraft attitude rate response to stick command.

Therefore, the all arguments and further probable task-oriented evaluations, the attitude rates were selected for FBWA in-flight simulation. This option was taken into account while developing the VSS control law below.

FSF equations of motion can be written in the form:

$$\dot{x} = A*x + B*u$$

where, x - state vector; u - control vector; A - state matrix; B - control matrix.

Let's write FBWA equations of motion in the same form with subscript "m" (i.e. model):

$$\dot{x}_m = A_m*x_m + B_m*u_m$$

The task of FBWA dynamics simulation on FSF is as follows: Find out such control for FSF which provides $x(t)=x_m(t)$, when $t > t_0$, under the condition $x(t_0) = x_m(t_0)$.

The MFS solution is written as:

$$u = B^{-1} [\dot{x}_m - A^*x + C^*(x - x_m)]$$

The block diagram for relevant flight control law is presented in Fig.4. The basis of this method is that by means of feedback the FSF is converted into the simulated object which is invariant to the environmental disturbances impact and which follows the FBWA state vector.

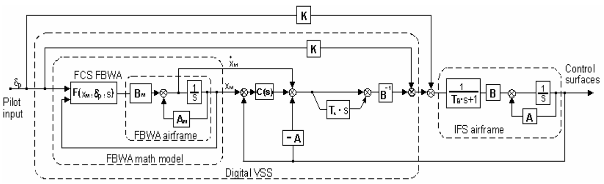

Fig. 4 VSS Control General Block Diagram (Model Following System Technique)

It is very important to analyze in advance and eventually confirmed during the ground based math simulation both in non-real time and in real time pilot-in-the-loop simulation. Although, the experimental FBW is of triplex redundancy and expected to be rather reliable, the IFS high airspeed may entail the unsafe IFS behavior in case of the experimental flight control system complete failure. The demanded FBWA dynamics may be simulated very truthfully and the needed pilot's perception and subjective assessment of handling qualities may be obtained at lower airspeed.

The math simulation was provided to determine the lower airspeed and safe flight regime at which the FBWA unstable configuration is simulated accurately.

At first step, the VSS control law was adjusted for IFS flight regime being similar to FBWA, i.e. H=300ft, M=0.8. Math simulation results for IFS with VSS control law and real actuators math models reproducing FBWA dynamics are presented in Fig. 5.

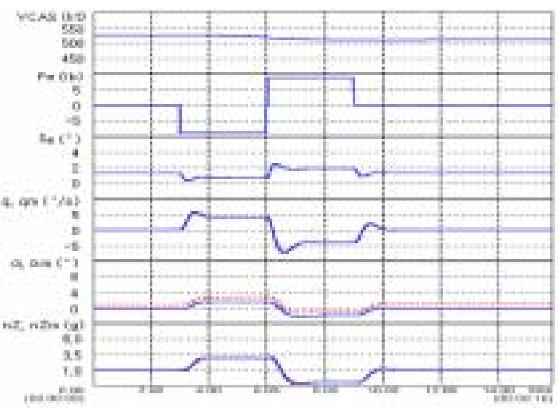

Fig. 5 Pitch channel. Response to stick doublet command. Math simulation, H=300 ft, M=0.8

Next, the math simulation was provided to determine whether the FBWA unstable configuration may be simulated in IFS with an identical accuracy at the lower airspeed and safe flight regime. The math simulation within the wide range of airspeed was provided. Eventually, as the most acceptable and safe one the flight regime of airspeed Vcas =230-250 knots at altitude H=16,000-19,000ft was determined. The math simulation results below demonstrate that this regime is quite acceptable for in-flight simulation from viewpoint of accurate simulation of FBWA unstable configuration attitude rates, see Fig. 6.

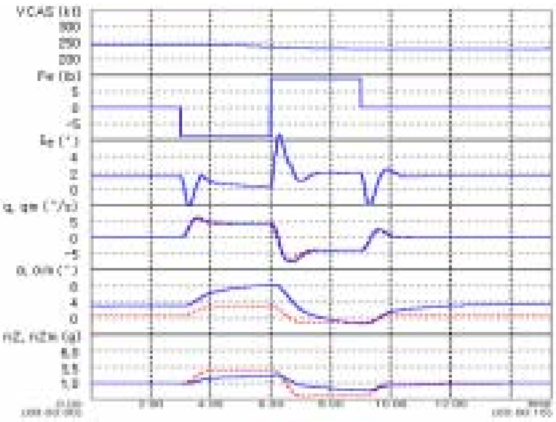

Fig. 6 Pitch channel. Response to stick doublet command. Math simulation, H=18,000 ft, Vcas = 243 kts

3. GROUND BASED SIMULATION

3.1 Pilot Work Station

To provide the FBWA and IFS real time simulation with the pilot-in-the-loop, the Pilot Work Station (PWS) was arranged and utilized. The general view of the PWS is shown in Fig. 7. This station consists of the pilot's simplified cockpit environment (including the central stick, pedals, thrust lever and primary flight display), simulation computer comprising the IFS airframe dynamics and airplane dynamics and simulating the actual analog signals from onboard sensors, and real onboard computers.

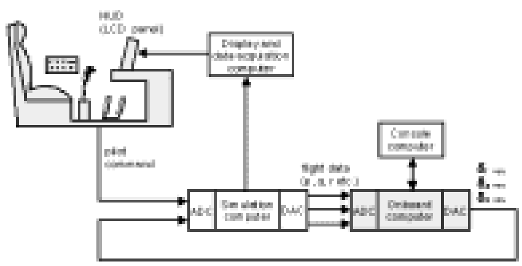

Fig. 7 Block Diagram of Pilot Work Station Arrangement

The particular feature of the pilot work station is that it comprises a set of actual onboard experimental computers, thus both the actual software, hardware and related interface regarding the IFS`s experimental digital fly-by-wire flight control system may be tested, verified and validated before further Iron Bird simulation and the each test flight.

The FBWA dynamics and all kind of the VSS control laws have been passed through and thoroughly evaluated in this pilot-in-the-loop simulation procedure.

Maneuvers similar to math simulation inputs and those to be performed in real flight were applied during pilot work station simulation (Fig. 8).

3.2 "Iron Bird" Simulation

Iron Bird simulation was performed after preliminary testing of VSS control law using PWS. The Iron Bird (IB) arrangement block diagram is presented in Fig. 9. Main difference between PWS simulation and IB simulation is that now real IFS actuators are included in closed control loop. The

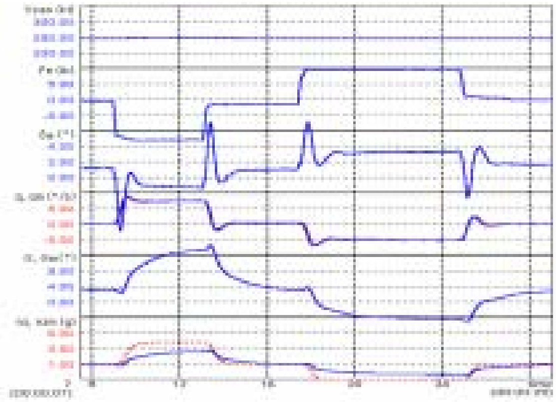

Fig. 8 Pitch channel. Response to stick input command. Pilot work station, H=18,000 ft, VCAS=243 kt

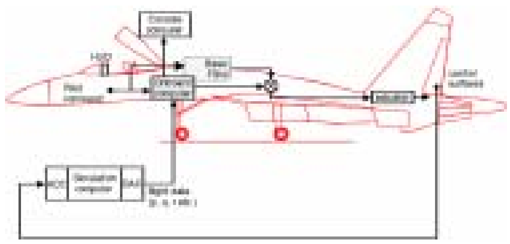

Fig. 9 "Iron bird" arrangement block-diagram

special machine was used to provide the hydraulic pressure necessary level for IFS onboard hydraulic system. The simulation is performed as following: pilot moves control stick, stick signal feeds an onboard computer and drives FBWA math model. It's also feeds a simulation computer (this is done to simulate a real direct link between pilot stick and control surface), where IFS airframe dynamics is implemented. The VSS control law, also implemented into onboard computer, calculates an output signal to control surface to simulate FBWA motion. This signal feeds an IFS real actuator and moves a real control surface. A control surface position is transferring to simulation computer, which calculates IFS response. This response (flight data) comes to onboard computer and VSS control law calculates the next command signal. So a control loop is closed through the real actuators. A main goal of IB simulation is to check whether there is any need for actuator dynamics compensation and reveal any possibility and danger of actuators rate saturation.

Example of IB simulation results is presented in Fig. 10 for longitudinal channel. IFS flight regime corresponds to FBWA pilot input signal is similar to real flight doublets. It is clearly seen that there is no need for any actuators dynamics compensation.

3.3 Pilot Pre-Flight Training in the Ground Based Simulator

For pre-flight test pilot familiarization and training the ground based simulator was used. The particular feature of this simulator that it is completely based on the mock-up of IFS cockpit (Fig. 11). The mock-up equipment and its characteristics is a complete replica of what is installed in IFS: central stick, side stick, pedals, thrust lever, instrumentation, multifunctional display, etc. Therefore it is suitably adjusted for the flight test procedures training. The simulator is connected with the PC-type computer real-time simulating the

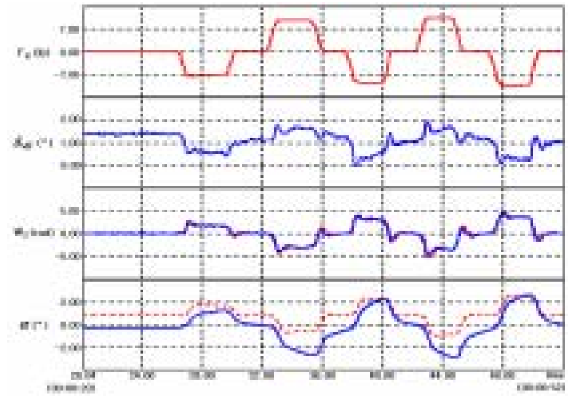

Fig. 10 Pitch channel. Response to stick input command. "Iron bird" simulation, H=300 ft, M=0.8

Fig. 11 Ground Based Simulator

IFS dynamics and flight control law (including the VSS control law), the FBWA dynamics and flight control law. The model software is completely the same as those used in the pilot work station. The exception is a software new piece simulating the VSS control law, since unlike the pilot work station this simulator doesn't comprise the real onboard computer and relevant math model is realized in PC.

The test pilots were trained here before flight to evaluate the IFS behavior in the environmental conditions mostly resembling the IFS.

4. IN FLIGHT SIMULATION

4.1 In-Flight-Simulator Description

The IFS (Fig. 12)[3] is developed on the base of a single seat maneuverable aircraft. The IFS is originally operated through the standard redundant Fly-by-Wire Flight Control System in pitch (stabilizer) and roll (flaperon+differential stabilizer) channels, and mechanical flight control with highly augmented feedbacks in yaw (rudder).

The EDFBW(Experimental Digital FBW) is of triplex redundancy (computers No.1, 2 and 3) and utilizes the majority vote principle to identify the failed channel and switch it off. These computers (easily reprogrammable) provide the capability to simulate in flight the advanced aircraft/engine flight control laws and reproduce the dynamics of future even non-existent aircraft of wide spectrum dynamic configurations.

The forth experimental computer (No. 4, included into the same network with the three mentioned computers) is intended to collect and record the whole flight data pac kage and besides to transmit it in a real time scale to tel emetry station.

Thus in case of EDFBW failure or other emergency the pilot can shut the EDFBW off urgently and find himself immediately in a reliable standard direct link mode in all channels.

During the flights the flight research operational procedures will be monitored and controlled through the ground telemetry station and voice communication.

Fig. 12 IFS general view

4.2 VSS Control Law Operational Assessment and Validation

Since the IFS airframe and flight control math model may differ a bit from the FSF real characteristics a set of 4 options of gain ratios K_q and $K_{\int q}$ of VSS longitudinal control law was offered for flight test. Due to flight simulation data post-flight analysis results the proper combination of K_q and $K_{\int q}$ was selected providing the FBWA flight simulation acceptable quality and required stability margin of "IFS-actuator-VSS" closed control loop. Fig. 13 shows the examples of IFS responses to pitch stick step input abrupt commands of different amplitudes.

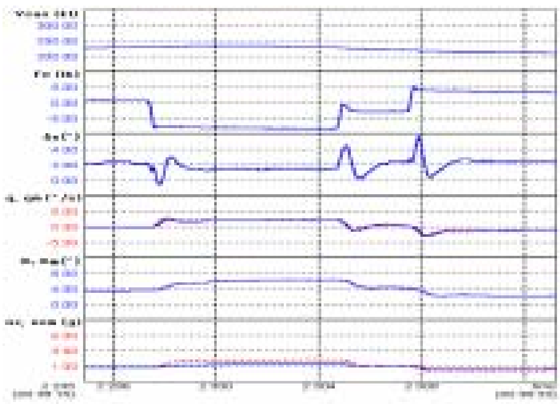

Fig. 13 Pitch channel. Response to step inputs command. In-Flight Simulation

After the VSS control law tuning in longitudinal channel the same procedure was performed in the lateral-directional channel where the flaperon and rudder were activated as VSS control surfaces. For this goal, basing on results of VSS control law math simulation a set of 4 combinations of VSS gain ratios $K_{\beta_{flaperon}}$, $K_{p_{flaperon}}$, $K_{\beta_{rudder}}$ and $K_{r_{rudder}}$ was selected for flight test.

These time histories demonstrate distinctly that VSS control law provides high accuracy of FBWA behavior flight simulation in FSF in case of roll. The similar situation (in terms of accuracy) may be observed in case of rudder pedal control. Aside the rest these results witness the flaperon and rudder adequate rate for simulation of FBWA rather high lateral-directional dynamics.

4.3 FBWA In-Flight Simulation and Handling Qualities Evaluation

The FBWA dynamic response assessment, it faced very specific flight test since it's intention was to simulate in flight the math model as much accurately as possible. To reach this matching the qualitative estimates of in-flight handling qualities must be fully equivalent to those of the ground math model. Since only rate attitudes have been in-flight simulated we were obliged to refer the pure math model response sometimes, if necessary. For instance, some longitudinal handling qualities are estimated in terms of g-load response. Since pitch rate but not g-load was in-flight simulated, the FBWA math model was referred to determine the relevant handling qualities. What concerns the pilot's subjective qualitative assessment it's fully justified in FBWA flight test and was performed. The pilot comment card (pilot's questionnaire) and Cooper-Harper rating scale was applied in this case.[4]

4.3.1 Handling Qualities Pilot's Evaluation

Pilots during PWS and ground based simulator training have noticed some minor effect. The matter is that pitch stick deflections per g-unit is nonlinear with reference to g-load demanded. The pilots evaluated the stick deflections per g-unit as too large in case of $0.5 < Nz < 1.5$ and normal, if $Nz > 0.5$. They perceived this nonlinear effect as some time delay followed by sharp and hardly predictable aircraft reaction. The assumption was made that this phenomenon can be attributed to parabolic pilot gain shaping for small inputs. This is confirmed by comparison of time response for very slow input Fig. 14 with step input time response Fig. 13.

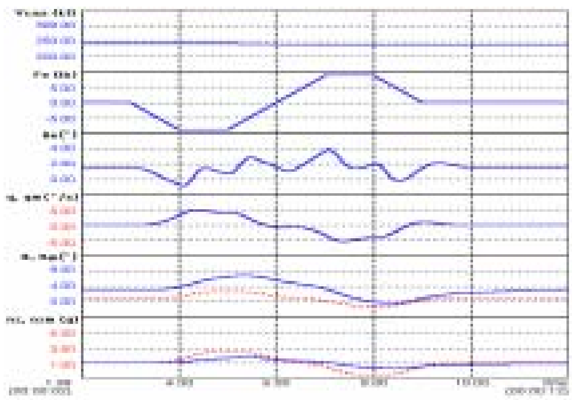

Fig. 14 Pitch channel. Response to very slow stick input. Math simulation, H=18,000 ft, VCAS=243 kt

During test flights special frequency sweep excitations (large and small pilot inputs amplitude) were applied in longitudinal channel for frequency domain handling qualities analysis. Using this data, the frequency characteristics of FBWA in longitudinal channel were calculated, namely input pilot stick movement, output pitch angle.

As far as the lateral-directional is concerned, it was revealed that a rudder pedal gain ratio is rather high. It was reduced down to pilot's acceptable value, but it is very difficult to suggest now any concrete value, because actual (FBWA) rudder pedal kinematics (force/displacement) characteristics were not simulated.

4.3.2 FBWA Dynamics Quantitative Assessment

For FBWA handling qualities assessment, the relevant criteria from the MiLS Aircraft Flying Qualities Design Guide Document were applied. Assumptions are made the aircraft is in Normal State (i.e. no failures) and simulation relates to non-terminal Flight Phase category B, Loiter (LO). Angular rates of FBWA are only simulated in IFS for the given flight regime (Vcas = const) being within the operational flight envelope.(Table 2)

Table 2 Handling Qualities Assessment

Category	IFS Results	MIL-STD	Comments
Short-Period	$\omega nSP = 4.55$ rad/sec, $n/\alpha = 58.0$ g/rad, $\zeta SP = 1.1 \quad 1.2$	$\zeta SP = 0.3 \quad 2.0$	Level 1
Residual Oscillations	None	Nz < 0.05g	
Longitudinal Pilot-Induced scillations	None	No tendency	
Bandwidth Criterion	$\omega bw = 3.5$ rad/sec, $\tau p = 0.05$ sec.		Level 1 Fig. 15
Gibson Criterion	Acceptable		Fig. 16
Dutch Roll	$\omega nd = 3.2$ rad / sec, $\zeta d = 0.47$	$\omega nd = 3.2$ rad/ sec, $\zeta d = 0.19$	
Roll mode	$\tau R = 0.97$ sec	$\tau Rmax = 1.0$ sec	
Coupled Roll-Spiral Oscillation	None	$\zeta RS * \omega nRS >$ 0.5 rad/sec	
Lateral/Directional Pilot Induced Oscillations	None	No tendency	
Linearity of Roll Response	None	No objectionable nonlinearities	

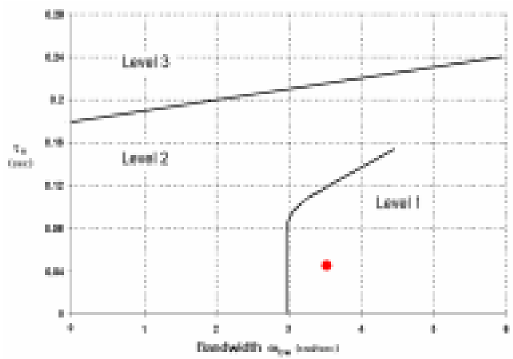

Fig. 15 Bandwidth Criterion Results(Most Unstable Region)

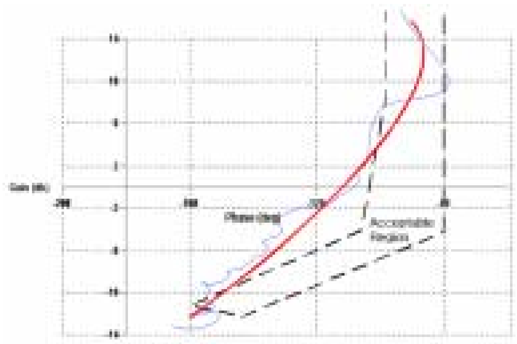

Fig. 16 Gibson's Criterion Results(Most Unstable Region)

5. CONCLUSIONS

The control law was designed for the most unstable FBWA configuration flight and it's dynamics are evaluated. The ground based simulation including math-model, real-time pilot-in-the-loop and iron bird simulation were used for validation of the control law before the experimental in flight simulation. It shows that the real time simulation of FBWA dynamics didn't featured very specific or unsafe behavior of aircraft during maneuvering in vicinity of the given regime of FBWA flight envelope.

The VSS control law applied in the IFS utilized the Model Following System technique. The flight test results showed the VSS control law validity and accuracy and demonstrated a very acceptable matching of FBWA real time math model simulated and IFS actual flight responses (with reference to the attitude rates). The matching of high accuracy was kept up within the wide range of test pilot input commands and changes of IFS airspeed occurred during the flight research. The in-flight simulation of FBWA didn't reveal any serious deficiencies of flight control law.

As a whole, the FBWA dynamics was evaluated as acceptable and being within the limits of maneuverable airplane behavior. The FBWA handling qualities were rated by the test pilot as:

- Level 3.5 4.5 in longitudinal channel (primarily because of the aircraft response to pilot input command non-linearity perceived as a time delay),
- Level 2 3 in roll channel,
- Level 4 5 in yaw channel (primarily due to extremely high roll rate response to rudder).

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