A FLIGHT SIMULATION APPLIED TO THRUST CONTROL

Hildebrando Ferreira de Castro Filho
Instituto Tecnológica de Aeronáutica – ITA
hfcastrof@yahoo.com.br

Pedro Paglione
Instituto Tecnológica de Aeronáutica – ITA
paglione@aer.ita.br

Abstract. The ERJ-145 airplane, produced by EMBRAER, has two engines to provide thrust. This arrangement allows the use of thrust only as an alternative emergency control system. The automation of this system, referred to as **CVE**, for "*Controle de Vôo por Empuxo*" (Flight Controlled by Thrust), was developed to help the pilot to maintain controlled flight and to land in case of partial or total loss of authority in its primary flight control surfaces. The qualitative verification of degree of controlability is performed by EMBRAER and Brazilian Air Force pilots in simulated flights performed in EMBRAER's Full Flight Simulator, installed at INFRAERO, in São José dos Campos.

Keywords. *Aircraft simulation. Aircraft control. Thrust-only control. Real-time operating systems.*

1. Introduction

One of the classes of accidents involving airplanes is related to the loss of authority in their primary flight control surfaces (ailerons, elevator and rudder) caused by hydraulic, mechanical, electrical or electronic failures or collision with other objects. The control of an airplane without authority or with partial loss of authority on these surfaces turns out to be a great problem for the pilot, who will have to maintain stable flight and then try to land the airplane.

On airplanes that have more than one source of thrust thrust-only control or control aided by thrust is a viable alternative but difficult to be carried on by the pilot because of the different response times involved and because of the lack of training for this type of situation.

NASA Dryden (Burcham, 1998), (Burcham, 1999) has developed a similar type of control to the F-15 and MD-11 airplanes. Another contribution (Bull, 1995) extended the investigation to mid-size jet transport airplanes.

An effort using both propulsion and aerodynamic actuation for safe flight operation in the presence of actuator failures with actuator reallocation is presented in (Idan, 2001). Another paper (Bramesfeld, 2001) demonstrates the potential of quickly finding and evaluating alternative longitudinal and lateral-directional control strategies for a damaged transport airplane.

NASA Dryden (Burcham, 1991) has briefly flight tested a similar type of control in a Gates Learjet 24, an executive jet with two engines. The Learjet geometrically resembles the ERJ-145 because of the high engine placement. In this configuration a thrust increase causes a nose-down pitch. This configuration was considered "extremely difficult" for longitudinal control and that "the phugoid was almost impossible to damp with throttle inputs".

Thrust-only control is promising but there are difficulties in its implementation due to the great diversity of airplane models and control systems and the different aerodynamic reactions to this actuation model. The goal of this paper is to present the simulation of automatic controls to evaluate the degree of control exhibited by the ERJ-145 airplane under loss of full or partial authority in its primary flight control surfaces using thrust control only.

2. The ERJ-145 airplane

The ERJ-145 (EMBRAER, 2000) is a medium-sized airplane operating in short, medium and long distances, available in various models and configurations, to civilian and military uses (Airbone Early Warning and Control, Ground Surveillance, Remote Sensing and Maritime Patrol). This airplane has two engines and its length is 29.87m, 20.04m wing span, maximum take-off weight is 20.600Kg and maximum landing weight is 18.700Kg. Table (1) shows its derivatives.

Table 1. ERJ-145 Models.

Model	Use	Function
ERJ-145 STD	Civil	Regional Transportation
ERJ-145 LR	Civil	Long Range Regional Transportation
ERJ-145 ER	Civil	Extended Range Regional Transportation

ERJ-145 XR	Civil	Extra Long Range Regional Transportation
EMB-145 AEW&C	Military	Airbone Early Warning and Control
EMB-145 RS/AGS	Military	Ground Surveillance and Remote Sensing
EMB-145 MP/ASW	Military	Maritime Patrol and Anti-Submarine Warfare

2.1 ERJ-145 Flight Controls

The ERJ-145 primary flight controls are the elevators, ailerons and double rudders. The elevators are mechanically commanded and actuated and are redundant. Ailerons and rudders are mechanically commanded and hidraulically actuated and have mechanical reversion in case of hydraulic power loss. Steady flight control and trimming are available to all axis.

Flight spoilers are available to increase descent rate and deaccelerate the airplane. Ground spoilers break lift and help the landing gear to brake. These two surfaces are electrically commanded and hidraulically actuated.

3. The Real-Time Simulation

EMBRAER uses a Gould computer to drive its EMB-120 Brasilia Full-Flight Simulator located in São José dos Campos, Brazil. This simulator was adapted to function as an ERJ-145 simulator. The aerodynamics is changed to reflect the new airplane but the panel remains that of the EMB-120.

FORTRAN routines describing the ERJ-145 dynamics were transferred from the Gould to a microcomputer, edited and compiled. The QNX operating system was chosen to host the routines. The Gould *Datapool*, a structure that stores variables, was emulated, a task scheduler was created and the converted routines were finally validated.

QNX Neutrino OS 6.2 is a real-time multi-task multi-threading operating system with priority pre-emptive scheduling ant fast context change. It is freely available on the Internet (www.qnx.com) for non-commercial applications.

One of the scheduling structures available in QNX is based on threads, channels, timers and pulses.

The logic to the scheduler realization is:

- One thread is created to each execution line, that is, a thread to each block of routines that will run on a certain frequency;
- In each thread a channel is created. A channel is a structure able to accept connections;
- A connection is created within this channel;
- A timer is created with the desired execution frequency;
- The timer is configured to send pulses to the newly created connection;
- A loop starts monitoring the channel and when a pulse is received the block routines are executed.

A flag is set in case the thread is to end. When this happens the loop ends, the timer is deleted, the connection ended and the channel destroyed.

One difficulty was the unavailability of a FORTRAN compiler to QNX. The solution found was to use the FORTRAN GNU 77 compiler, freely available in the Internet which runs in operating systems that are compatible with Unix.

The FORTRAN programs were migrated and compiled in a microcomputer running Linux RedHat 7.2 Enigma and GNU 77.

Since Gould does itself the initialization of the *Datapool* variables the programs had to be rewritten to incorporate the variables initialization clauses.

After the compilation, the object modules were copied to QNX and tested. Since there was binary correspondence between the operating systems there were no problems in the use of these modules.

The *Datapool* had to be emulated in the QXN environment. The chosen way was the creation of a unique structure in C language (*struct* clause) that contained all the variables that had to be interchanged among the different simulation modules.

After the FORTRAN routines were converted to QNX, programs were created to:

- integrate these routines;
- specify different flight conditions;
- present the results of the simulation runs.

These modules were written in ANSI C to guarantee portability.

Validation was accomplished through the comparison of the values of key variables obtained in different runs of the microcomputer simulations with the values of EMBRAER “off-line” routines tested and guaranteed as valid.

Figure (1) shows the graphical interface in QNX.

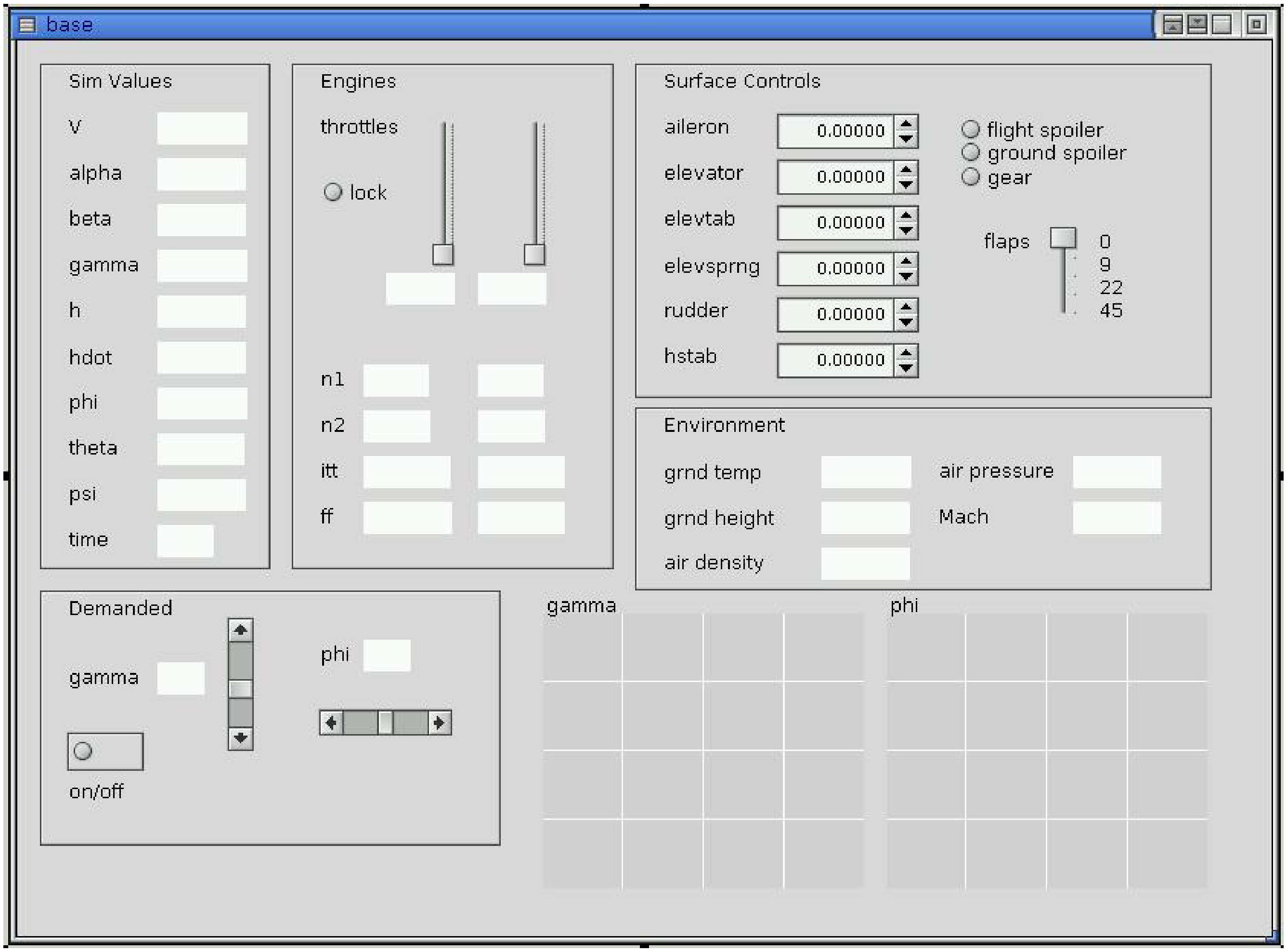

Figure 1. Simulator graphical interface in QNX.

4. Controllers Design and Development

Three controllers were designed, developed and implemented in the simulation. One controller of the PID type (Karl, 1995) was designed to control the longitudinal mode. Another PI controller was designed to control the lateral-directional mode. Heading control was implemented in cascade with the lateral-directional controller.

The IAE (Integral of the Absolute Error) optimal criterium was used to design the controllers (Karl, 1995). The IAE was calculated in the simulation runs. Performance criteria weren't readily available so the airplane dynamics couldn't be easily modeled. The controllers diagram is shown in Fig. (2).

The signals in Fig. (2) are presented in Tab. (2). FADEC means Full-Authority Digital Engine Control.

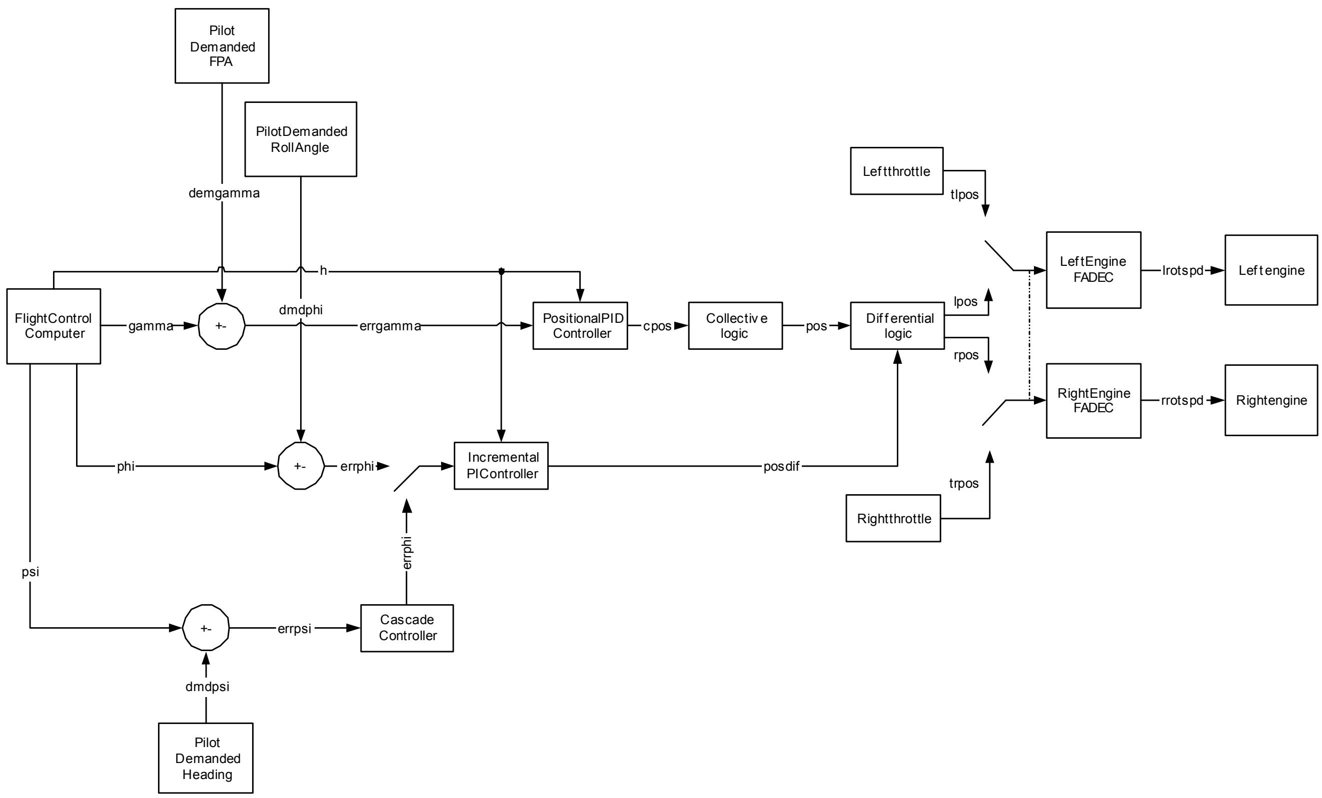

Figure 2. CVE Diagram.

Table 2. Signals in Fig. (2).

Signal	Description
gamma	Airplane's FPA (Flight Path Angle)
phi	Airplane's roll angle
psi	Airplane's heading
dmdgamma	FPA demanded by pilot
dmdphi	Roll angle demanded by pilot
dmdpsi	Heading angle demanded by pilot
h	Airplane's height above M.S.L. (Mean Sea Level)
errgamma	Deviation in FPA between demanded and actual
errphi	Deviation in roll between demanded and actual
errpsi	Deviation in heading between demanded and actual
cpos	Calculated collective throttle position
pos	Calculated throttle position after collective logic
posdif	Calculated difference between throttle positions
lpos	Final calculated left throttle position
rpos	Final calculated right throttle position
tlpos	Throttle left position
trpos	Throttle right position
lrotspd	Left engine rotation speed (FADEC)
rrotspd	Right engine rotation speed (FADEC)

4.1. CVE in the Simulation

When the CVE is activated the FADEC is automatically set to MTO (Maximum Take-Off) mode. The MTO mode provides more thrust so there is a more responsive airplane.

The roll angle control and the heading control can only be activated one at a time because of their cascade configuration.

The CVE writes the calculated left and right throttle positions in the *Datapool*. The engines and FADEC calculation routines read the throttle positions from the *Datapool* and proceed accordingly. The throttle angles that were being read by the I/O routines from the simulated cabin are now ignored. Figure (3) shows this configuration.

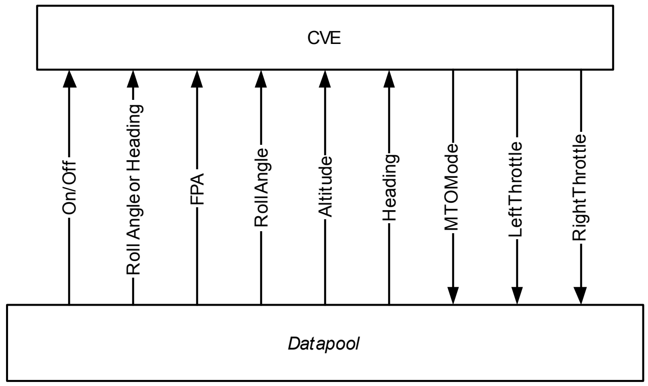

Figure 3. Communication between the CVE and the Datapool.

This could be implemented in the real airplane acording to Fig. (4). Bold boxes are new devices to the airplane. The dashed box means a modification in the device.

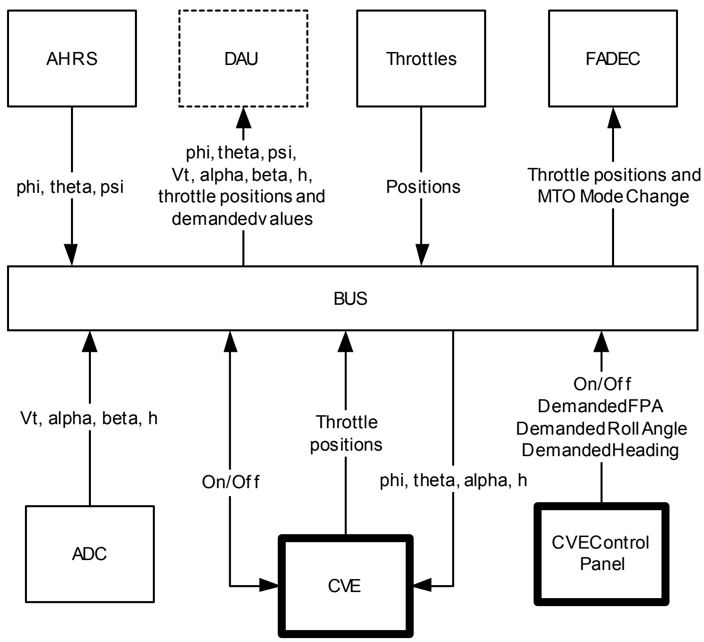

Figure 4. Diagram of the CVE if implemented in the airplane.

Table 3. Function of the devices shown in Fig. (4).

Device	Meaning	Function
AHRS	Attitude Heading and Reference System	To supply the Euler angles
DAU	Data Acquisition Unit	To centralize and distributate data
ADC	Air Data Computer	To calculate α, β and Vt
BUS		Airplane data bus

In the ERJ-145 the CVE would change a flag in the DAU to start operation. This flag would signalize that the FADEC should change its mode to MTO and that the throttle angles from the cabin are to be ignored.

The CVE would read α, θ and *h* (angle of attack, pitch attitude and altitude) from the ADC and calculate γ (FPA, Flight Path Angle). Roll angle ϕ is available from the AHRS.

The values demanded by the pilot are sent from the CVE control panel to the DAU via the BUS. The CVE would execute the control logic and would write the new throttle positions in the DAU. The FADEC continuosly reads the throttle positions from the DAU.

4.2. Reference Flights and Gain Scheduling

Eight simulated flights were created to the gain scheduling mechanism. Gain scheduling was used to absorb the different aerodynamic and engine reactions due to differences in altitude. Table (4) and Tab. (5) shows the conditions of each flight.

Table 4. Reference flight conditions.

Flight	Altitude [feet]	Calibrated Airspeed [knots]	Throttle [deg]	Elevator [deg]
1	500	250	52.5	1.9°
2	1000	250	45.3	1.5°
3	5000	250	48	1.2°
4	10000	250	50	1.5°
5	15000	300	50	1.3°
6	20000	300	46	0.8°
7	25000	375	60	1.4°
8	30000	300	70	1.9°

Table 5. Collective flight conditions.

Surface, Equipment or Condition	Position
Aileron	0°
Rudder	0°
Flap	0°
Flight Spoiler	0°
Landing Gear	Retracted
Weight	18.000 Kg
Center of Gravity	25% m.a.c.
Horizontal Stabilizer	-2°

The gain scheduler was designed using the Matlab (Matlab, 2002) *polyfit* function. The *polyfit* function finds the coefficients of a P(X) polynomial of degree N that better adjusts the input values in a least-squares sense.

Five polynomials were derived, three to the FPA controller (Kc, Ki and Kd) and two to the roll angle controller (Kp and Ki).

4.3. Throttle Positioning Logic

The calculations carried out by the FPA controller are sent to the roll angle controller to then be sent to the FADEC. An actuation logic was developed so that both the longitudinal and the lateral-directional modes could be simultaneously controlled.

The FPA controller generates collective positional values to the throttles. That means the two throttles would have to be be in the same computed position. This would cause the roll control inoperable so the average position of the throttles is changed. The absolute angular difference between them is preserved.

4.4. Speed Control

When the flight control surfaces of a given airplane are locked in a certain position the trim speed is weakly affected by thrust. Retrimming to a different speed can be realized with other techniques such as moving the horizontal stabilizer, changing the airplane's c.g., moving flaps, changing the landing gear configuration or releasing weight. Therefore the CVE does not control speed. Nevertheless speed tests were conducted by the pilots, to realize if the V_{ref} (landing reference speed) could be achieved.

4.5. Controllers Limits

The controllers were evaluated against different flight surfaces locking positions, c.g. and weight to reference flight number 4. The demanded values were -2° to FPA and 10° to roll angle. Table (6) shows the conditions to this flight and Tab. (7) shows the limits.

Table 6. Flight condition to the controllers evaluation.

Item	Value
Altitude	10.000 feet
Calibrated Airspeed	300 knots
Elevator	+1.5°
Horizontal Stabilizer	-2°
Weight	18.000 Kg
Center of Gravity	25% m.a.c.

Table 7. Controllers limits.

Item	Airplane Minimum	Airplane Maximum	Min. with success (automatic)	Max. with success (automatic)
Ailerons	-25°	+15°	-1°	+1°
Rudder	-15°	+15°	-6°	+6°
Elevators	-27°	+14°	-8°	+3.5°
Horizontal Stabilizer	-10°	+4°	-3°	-2°
Weight	15.000 Kg	18.700 Kg	15.000 Kg	18.700 Kg
Center of Gravity	15%	43%	15%	37%
Lateral Wind	0 knots	30 knots	0 knots	10 knots
Longitudinal Wind	0 knots	30 knots	0 knots	10 knots
Oblique Wind	0 knots	30 knots	0 knots	10 knots

One difficulty found for the lateral-direction control of the ERJ-145 is related to the relative angles of the horizontal stabilizer and elevators. Even though these surfaces are not directly related to the lateral-directional aspect, deflections of the stabilizer of less than -3° would make the roll angle control critical. In this situation the roll angle control could only be achieved if the elevators were locked in a pitched down position (+3° or more). This was found to be due to the negative contribution of the vertical fin to the rolling moment and involves complex aerodynamic interactions among these surfaces that were not thoroughly investigated in this work. Figure (5) presents the roll angle controller response with the fin contribution and Fig. (6) without the fin contribution. The removal of the fin contribution was made in the simulation program for the analysis of this problem.

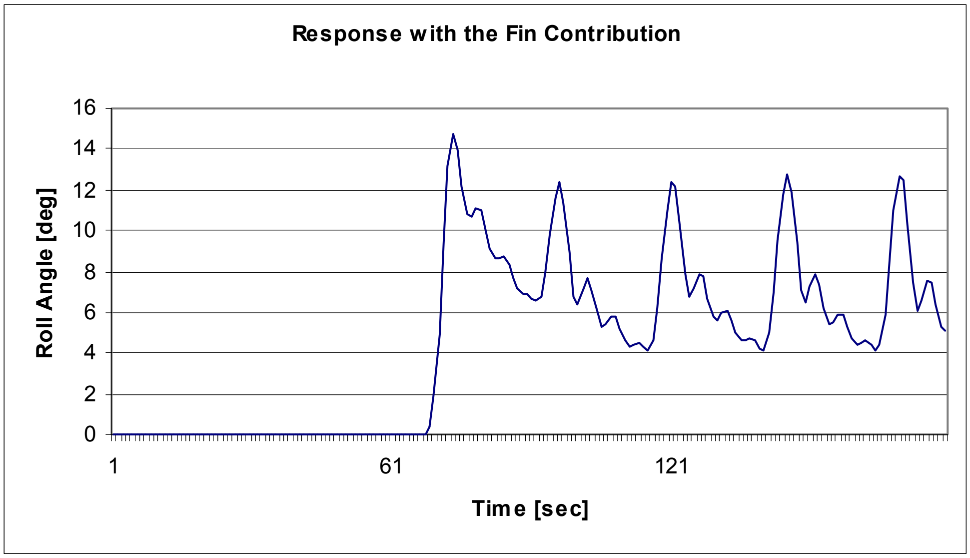

Figure 5. Roll angle controller response with the fin contribution.

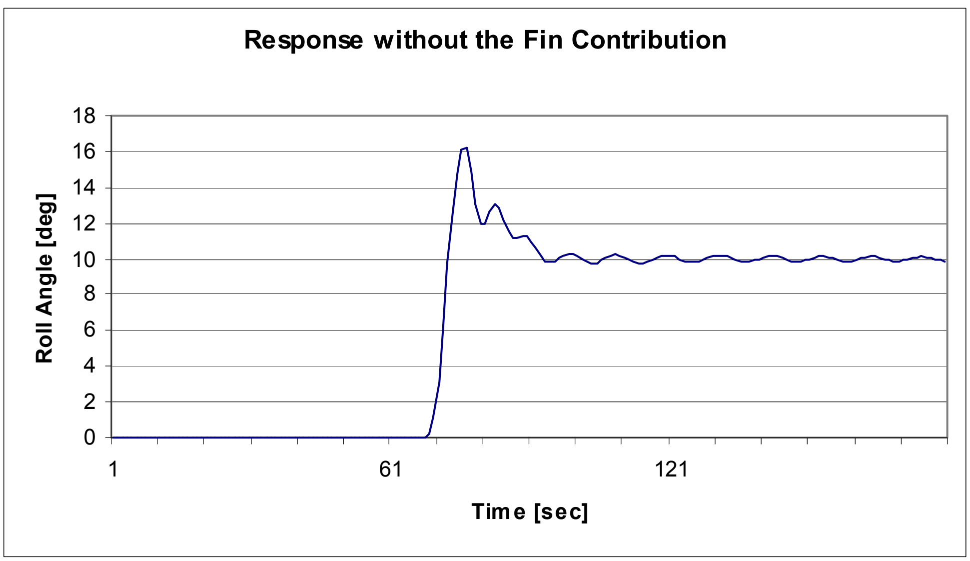

Figure 6. Roll angle controller response without the fin contribution.

Another set of aerodynamic interactions that influences the thrust-only control is the relative position of the flaps and the horizontal stabilizer. When the flaps are deflected the horizontal stabilizer may be deflected less than -10° and this is what allows speeds close to V_{ref} for landing. If the flaps are not deflected the minimum for the horizontal stabilizer would be –3° and V_{ref} could not be achieved.

The flaps themselves impose another constraint. Deflections of the flaps of less than -9° would cause an unstable situation to the controllers due to $Cl\beta$ (rolling moment due to side slip). In this configuration small sideslips would cause strong rolling moments that were beyond the capacity of the engines to overcome. Figure (7) shows the rolling moment due to different flap positions.

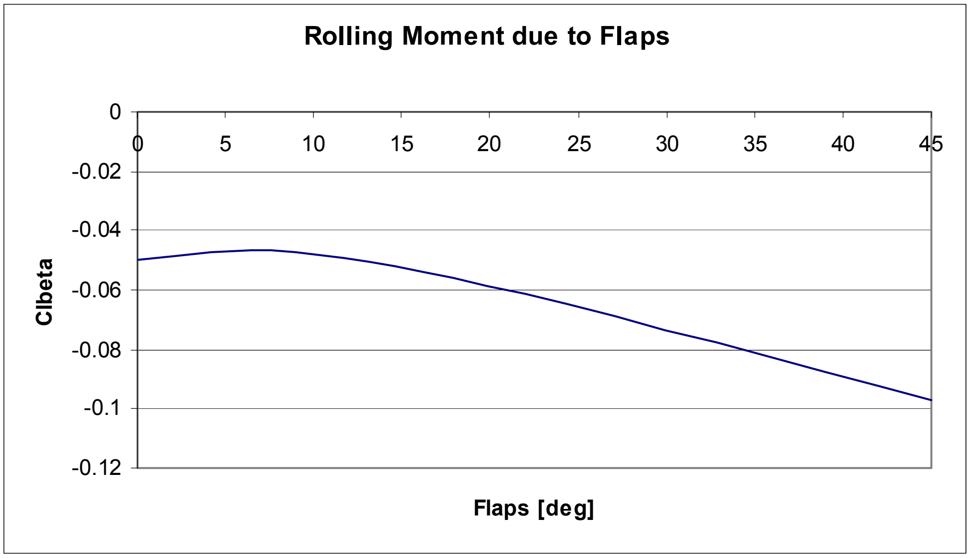

Figure 7. Rolling moment due to Flaps.

The wind tests didn't include oscillatory or randomic disturbances, such as the Dryden wind model. Winds are considered constant.

5. Security

The CVE cannot be activated at any time. If flaps are lowered more than 9° or when at least one engine is in failure thrust control is useless.

6. The Simulated Flights

The cockpit in the FFS (Full-Flight Simulator) was instrumented to the controllers tests. The aileron trim dial and the rudder trim dial were reconfigured to read the desired FPA and roll angle, respectively. Their values were shown in the EMB-120 torque indicators that weren't being used.

Five pilots, A to E, (three from EMBRAER and two from the Brazilian Air Force) executed tests with the controllers implemented in EMBRAER's Full-Flight Simulator. Four documented flights were conducted, each one four hours long. Their impressions were collected and analyzed. Table 8 shows the tasks that were realized, using thrust-only control, both automatic and manual.

Table 8. Tasks conducted by the pilots.

Task	Description
1	Maintain FPA with a "clean" airplane
2	Maintain FPA with a "dirty" airplane
3	Acquire a certain FPA
4	Maintain heading
5	Acquire a certain heading
6	Acquire the ILS Localizer
7	Acquire the ILS Glideslope
8	Maintain the ILS Localizer and Glideslope
9	Maintain FPA and velocity and changing flaps
10	Acquire Vref
11	Acquirir zero lateral error with runway
12	Land

The qualitative results and comments from the pilots to the automatic control varied from "sluggish" to "excellent", depending on airplane configuration. Their comments to human control varied from "hard" to "impossible". This showed that gains can be achieved with the use of such controllers. Landings were accomplished within standard values of descent rate and airspeed, close to an airplane without failure in its primary flight controls.

Pilots A, B and E commented on the difference of performance between the controllers. The lateral-directional control of the ERJ-145 is harder to be executed because of the weak moments generated by the short lateral distance between the engines. Nonetheless the longitudinal control is nicely accomplished, even though the engines are located higher than its longitudinal axis and therefore generate an initial negative pitch moment.

The CVE in the simulation runs and in the simulated flights helped the pilots counter the phugoid (longitudinal slow oscillatory mode). Pilots D and E declared the automatic longitudinal control as "excellent".

7. Conclusion

The automatic controllers realized their intent: to help the pilot to regain control of an ERJ-145 with loss or partial loss of authority in its primary flight surfaces using only thrust.

There are restrictions to the CVE operation due to the relative locking positions of the primary flight surfaces in case of failure or damage.

This work showed that the ERJ-145 thrust-only control as an aid to the pilot in emergency situations is possible.

The qualitative results of the simulated flights showed that landing is possible and even "easily accomplished" (according to pilot D), depending on airplane configuration and damaged surfaces lock position. Pilot D also opiniated that "training and familiarity with the device is all that is demanded".

The resuls demonstrated the potential to improve this airplane's controlability and increase the chance of survival in many simulated conditions of loss or partial loss of the primary control surfaces.

8. References

Burcham Jr, Frank, et al., 1991, "Controlling Crippled Aircraft: With Throttles", NASA/TM-104238.

Burcham Jr., Frank et al., 1998, "Using Engine Thrust For Emergency Flight Control: MD-11 and B-747 Results", NASA Dryden Flight Research Center, NASA/TM-1998-206552.

Burcham Jr., Frank, et al., 1999, "Simulator Evaluation of Simplified Propulsion-Only Emergency Flight Control Systems on Transport Aircraft", NASA Dryden Flight Research Center, NASA/TM-1999-206578.

Bramesfeld, Götz, 2001, "An Investigation of Strategies For Controlling Damaged Transport Aircraft", The Pennsylvania State University.

Bull, John, et al., 1995, "Piloted Simulation Tests of Propulsion Control as Backup to Loss of Primary Flight Controls for a Mid-Size Jet Transport", NASA/TM-110374.

EMBRAER, 2000, "ERJ-145 Airplane Operations Manual", EMBRAER, São José dos Campos, Brazil.

Idan, Moshe et al., 2001, "Intelligent Aerodynamic/Propulsion Flight Control For Flight Safety: A Nonlinear Adaptive Approach", in American Control Conference, Arlington, VA.

Karl J. Aström, Tore Hägglund, 1995, "PID Controllers: Theory, Design, and Tuning", The Instrumentation, Systems and Automation Society.

Using MATLAB, 2002, The Mathworks Inc.

Wittenmark, Björn et al., 1990, "Computer Control: An Overview", Department of Automatic Control, Lund Institute of Technology, Sweden.

9. Copyright notice