From flight qualities to flight control law design : a simulation tool

Felix Antonio Claudio Mora-Camino, Karim Achaibou

FROM FLIGHT QUALITIES TO FLIGHT CONTROL LAW DESIGN

A SIMULATION TOOL

F. Mora-Camino, A. K. Achaibou

E.N.A.C., 7 Av. Edouard Belin, 31055 Toulouse, France

tel. :(33) 61 55 79 99 telefax : (33) 61 55 80 45

L.A.A.S.-C.N.R.S., 7 Av. Colonel Roche, 31077 Toulouse, France

tel. : (33) 61 33 62 00 telefax : (33) 61 55 35 77 e-mail : mora@laas.laas.fr

Abstract

In this communication we present a PC based simulation tool, ICARE, for realistic validation of flight control laws for a small aircraft. This tool which can be used for the training of advanced students in aeronautics has been developed in our laboratory recently.

The first step in the studies which can be carried with this software is the determination of natural flight qualities of an aircraft for a given operating point(flight envelope). The flight qualities of interest are static stability, dynamic stability and maneuverability, which can be derived from a state space representation of the linearized dynamics around the considered operating point while a qualitative scaling can be established for them. Then requirements issued in qualitative terms for the full behavior of the controlled aircraft can be taken in consideration.

ICARE provides a structure for the definition of the control laws which will meet these requirements. Also, robustness studies about these control laws over the entire flight envelope can be carried in qualitative terms with support of this software.

Since automatic flight operation is characterized by the frequent occurrence of mode shifts, it has been judged interesting to simulate these transients. So, ICARE allows the simulation of not only the response of the flight dynamics of the aircraft to autopilot inputs, but also of the operation of the Flight Control Unit and of the Mode Annonciator Pannel of the Autopilot. However, it is important to observe that ICARE is not a flight simulator package since no Attitude Director Indicator or Horizontal Situation Indicator is available on the screen.

1 Introduction

One of the main subjects taught in Aeronautical Engineering Schools is the Design of control laws for aircraft autopilots. This topic is often presented as the point of convergence of other basic disciplines(Aerodynamics, Flight Mechanics, Avionics and Control Theory) offered along the first years of graduate education.

However, often this topic which should represent a climax for the engineering student is poorly treated and is quite enough disappointing since it reduces to the application of classical control theory(in general pole location techniques) to the flight dynamics of a standard aircraft which are represented by a dubious single linear model. In general the link between this approach and the study of flight qualities remains thin and the resulting control laws don't provide too much confidence about the fulfillment of the flight quality requirements over the flight envelope.

Here we present a PC based full flight simulator for a light aircraft which gives support to a realistic flight control law design study which avoids the above limitations.

2 Flight Control Law Design Study

To design a flight control system, the first step is to know how the aircraft will respond dynamically to deliberate actions on its control surfaces or to random atmospheric disturbances. However, a sound knowledge of the dynamic response of an aircraft is necessary but not sufficient for a successful design: A knowledge of the quality of the aircraft response, from a pilot's point of view, is also important. Aircraft flying qualities are usually characterized by a set of parameters related with the modes(natural frequencies and damping ratios) of the linear dynamics resulting from the Small Disturbance Theory around pre-specified flight conditions. Their assessment can be related to the design parameters through a qualitative evaluation such as the one displayed below(Fig.1).

Handling qualities reflect the ease with which a pilot can carry out a manoeuver with an aircraft of given flight qualities. These handling qualities are appraised by test pilots which have the proper background and use well defined qualitative approaches to record their opinion.

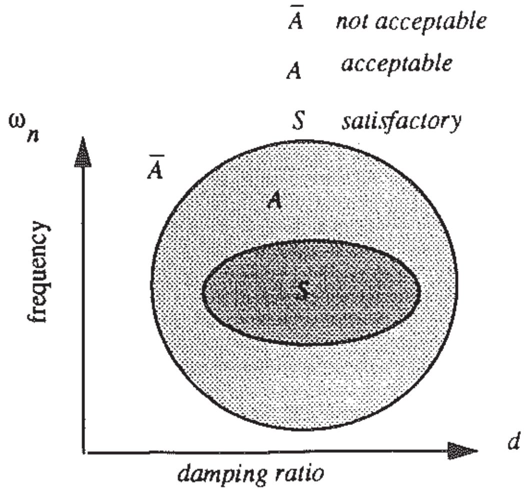


FIGURE 1.

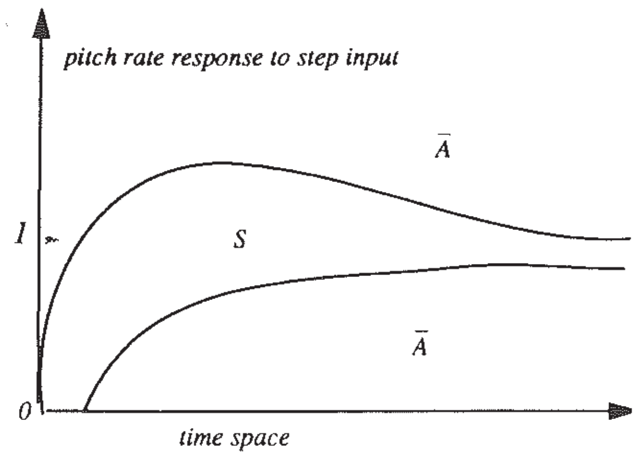


FIGURE 2.

In the academic field, flight training simulators able to reproduce handling qualities are not frequent while flying laboratories have turned today too expensive. So, numerical simulation may be a solution to fulfil this initial step of the design process.

Now, to sketch the classical approach for flight control law design, let us consider the problem of longitudinal flight augmentation.

The linearized longitudinal dynamics of an aircraft can be written in a state space form:

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

where $\underline{x} = (\Delta u, \Delta\alpha, \Delta\theta, \Delta q)'$ and $\underline{u} = (\Delta\delta, \Delta\pi)'$ with:

Δu: variation of longitudinal speed,
$\Delta\alpha$: variation of angle of attack,
$\Delta\theta$: variation of pitch angle,
Δq: variation of pitch rate,
$\Delta\delta$: variation of elevator deflection,
$\Delta\pi$: variation of thrust.

The eigenvalues of A are characteric of the stability and oscillatory modes of the aircraft in free regime, while controllability matrice $[B|\,AB|\ldots A^{n-1}B]$ determines its handling capabilities. To change these flying qualities, a state feedback control law can be used:

$$\underline{u} = -G\underline{x} + \underline{v}$$

where v is the input from the pilot or from the autopilot.

Then, the dynamics are now governed by the state equation:

$$\dot{\underline{x}} = (A - BG)\underline{x} + B\underline{v}$$

So the spectrum of A is replaced by the spectrum of (A-BG). Different modal control techniques are available to chose G such that the eigenvalues of (A-BG) are placed adequately in the complex plane.

This approach has a consequence over the handling qualities of the aircraft : The equilibrium state $\underline{x}_e$ associated to input v_e is such that $(A - BG)\underline{x}_e + B\underline{v}_e = \underline{o}$
and now with (A-BG) stable, $\underline{x}_e = -(A - BG)^{-1}B\underline{v}_e$

So, the equilibrium state is altered by the flight augmentation procedure.
Let $\underline{y} = C\underline{x}$ be the output vector of interest for the pilot with $\dim(p) \le 4$. Then $\underline{y}_e = Cx_e$ and if we define handling coefficients by

$$M_{ij} = \frac{dy_{ie}}{dv_{je}}, i = 1, \ldots, p\,;\, j = .1,2$$

we have :

- unaugmented case: $M = -CA^{-1}B$ if A is invertible.

- augmented case : $\tilde{M} = -C(A - BG)^{-1}B$ if A is stable.

So, a dilemma may appear in the design of a flight augmentation system between stability and handling around a modified equilibrium situation.

In general, in the academic field, this study ends with some simulation runs which show the obvious: the dynamics of a linear multivariable system whose modes are already know. Thus, important aspects remain untackled:

What is the effective robustness of the proposed solution?

What is the influence of neglected nonlinearities over the performance?

What is the behavior of the aircraft during transients resulting from shifts in automatic modes?

In relation to the first point, the control law must be robust with respect to operational variations(flight level, airspeed, centering, flap and landing gear configuration) and today intrincate methods(H_2/H_∞ control techniques) exist to design robust control laws. Unfortunately, since there is no clear relation between operational variations and structural changes in the linear models of the first order flight dynamics, this approach, which till now has not been adopted by the industry, remains unrealistic.

In relation to the second point, the nonlinearities of the flight mechanics affect not only the robustness of the proposed solution but also the dynamic behavior of the system and unless a full flight simulator is available, these points cannot be investigated. The same observation arises in relation to the third point.

For all these reasons, a numerical full flight simulation should be welcome to support a realistic flight control law design study.

3 The Full Flight Simulator

Icare is a numerical simulator for the flight dynamics of a light aircraft(Trinidad TB-20). This aircraft is currently used for pilot training at the aeroclub of ENAC. Also a real time (Bus VME, microprocessor 6800) training simulator for the cockpit of this same aircraft has been realized at ENAC for practical teaching. At this time an analytical data package (aerodynamics and propulsion) was built from raw test data. This data package has been repeatedly validated by skilled flight instructors used to fly TB-20.

Then to give a sound support to the teaching of flight control law design techniques, a new simulation software, based on this data package has been developed: ICARE.

This software device originally written in Pascal and currently rewritten in C can be run on PC compatible microcomputers. Many engineering students have been involved through academic projects during the last three years in its construction while now it has become a teaching tool for new incoming students.

ICARE can be used in several different ways:

-As a full flight simulator with entries (stick, rudder bar and thrust lever) from the microcomputer keyboard although its outputs record graphics of the variation with time of preselected variables from three possible categories(trajectory, aerodynamics and attitude angles).

-As a tool to get the flight and handling qualities of the either uncontrolled or controlled aircraft for any point within the flight envelope and for any allowed configuration. Thus this gives ground to a study of the variability of flight and handling quality indexes and to the design of the control structure which should cover every flight condition.

-As a full flight simulator which permits the progressive building of a full flight control system (stabilizers, basic and higher automatic modes for longitudinal and lateral motion) whose effectiveness can be thoroughly examined: flight qualities of the controlled aircraft, robustness of the control law, nonlinear effects, coupling between longitudinal and lateral modes,...

ICARE can generate data which can be used as input to control design softwares such as the Matlab Control Toolbox so that the candidate control laws can be obtained in an easier and clear way following well established methods.

When the user informs ICARE with a reference situation(point of the flight envelope and aircraft configuration), it computes the corresponding trim conditions(actuator deflections and equilibrium thrust), establishes a linear model of the flight dynamics around this nominal situation and calculates the flight and handling quality indexes. At this point the user can leave the simulation process to select with the help of any control design package the flight control laws which will be applied to the flight dynamics. At the present time, only linear state feedback control laws can be introduced while saturations for computed reference values are considered with tunable time delays for the changes in reference values so that sharp transients are avoided. This is representative of current practice in this field of application of Control Theory.

When a flight control law is under test, the graphical display presents not only records of preselected test variables(angle of attack, airspeed, altitude, ...) and of current values for other relevant variables(load factor, vertical speed, actuator deflections, thrust ...) but also the operational state of the flight control system whose active control modes can be changed by selection on the keyboard. Standard color codes are used to inform the operational state of each control subsystem. Also, during a simulation run reference values for the target variables of the active control modes can be changed through the keyboard as in Control Wheel Steering mode which is available on modern commercial aircraft(A310).

4 Conclusion

ICARE is at the present time used by graduate students of ENAC who at the end of the discipline "Automatic Flight Control Systems" have to work out an autopilot for this aircraft. ICARE has also be used by advanced research students to try to understand why classical PID control laws present surprisingly some robustness properties when applied to this class of nonlinear systems.

Since ICARE simulates the flight dynamics of a light aircraft which in fact has no real need of a full autopilot now we are involved in the development of an equivalent device for an heavy aircraft(Airbus A300). However the data package of this aircraft is far more complex and consists of tens of discrete data tables. The adopted approach here is to use advanced processing techniques:

Tabulated data is translated into a set of neural nets while trim conditions are obtained by the use of a genetic algorithm. So here again, the building of this new device will be an occasion for students to cope with advanced numerical techniques.

5 References

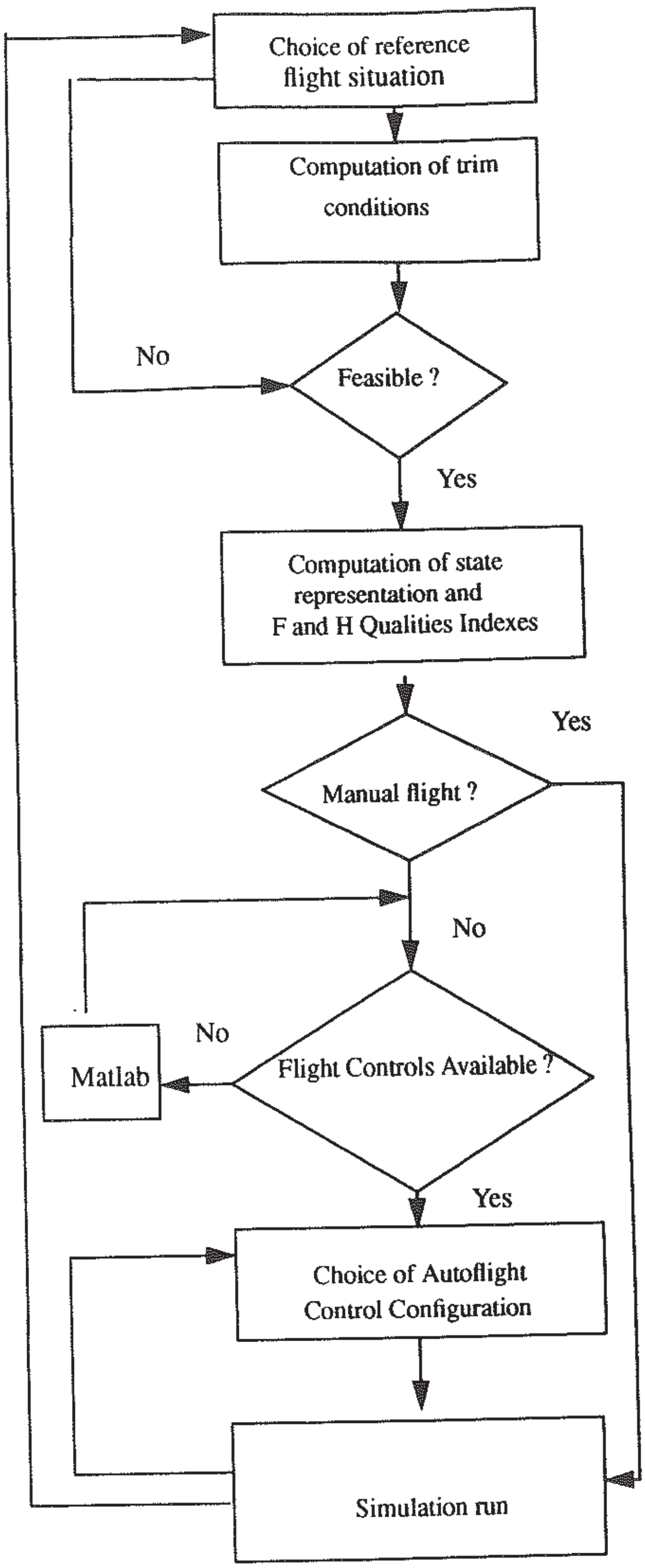
[1] D. McLean, 1990. " Automatic Flight Control Systems ", Prentice Hall.

[2] A. K. Achaibou, F. Mora-Camino, J. Aguilar-Martin, 1994." A Fuzzy Approach to Flying Qualities Enhancement ", Tempus Impact Workshop, Fuzzy Duisburg'94, (April) .

[3] ICARE, 1994 . " Manuel d'utilisation ", ENAC.

[4] F. Mora-Camino, A. K. Achaibou,R. Asep, T. J. Shen, 1994." Robust LQ Gain Schedulling using a Set Covering Approach ", IFAC Symposium on Robust Control Design, Rio de Janeiro, (september).

[5] P.Da Silva, 1994. "Lois de commande en vitesse pour le pilotage automatique", DEA report, LAAS-CNRS/ENAC, (july).



Interactive utilisation of ICARE