MODEL FOLLOWING TOTAL IN FLIGHT SIMULATOR AS AN EDUCATIONAL TOOL

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Abstract

One of the important and difficult problems in aeronautics students' education is shaping of aircraft dynamic properties from handling qualities point of view. Theoretical study, engineering calculations, computer simulation and flight simulator experiments are using for synthesis of aircraft dynamic characteristics. However these tools not taking into consideration all specific conditions and restrictions typical for true flight. Total in Flight Simulator (TIFS) is a real aircraft equipped with a special kind of indirect (fly-by-wire) software based flight control system whose properties can be modify by researchers. TIFS should be very useful didactic tool in the aeronautics students' education. Practical experiences, like test flights, constitute a very important element of the professional preparation for aviation designer and research engineers. There is a kind of flying laboratory or flying classroom. The most sophisticated experiments concern indirect flight control system applied for aircraft handling qualities evaluation. In this case, the flying laboratory plays a role of Simplified Total in Flight Simulator.

1 Introduction

The European Universities use the flying classrooms, for example Cranfield University uses two Jetstream 100 aircraft as an Integrated Digital Measurement and Control Systems for Teaching and Research, and Delft University of Technology employs Cessna Citation II as a Flying Classroom Instrumentation System. These aircrafts were adapted to teaching functions 20 years ago and they are still used as flying laboratories. On-board equipment has been improved and airplanes play the important role in didactic process, but these aircrafts are not equipped with indirect flight control system and modification of dynamic properties is not possible.

This paper presents main properties of the project, which has been worked out by Department of Avionics and Control Systems staff and students. This project offers a great opportunity for students' education in fields of on-board system design, flight control systems analysis and synthesis, and flight testing procedures. The main and the most important part of the project is software developing for simulation in real time different dynamic properties of the aircraft. Another words, TIFS models different types of aircraft during a real flight.

The PZL M20 "Mewa" – 6 seats, twin-engine propeller aircraft will be used as a flying laboratory. Adaptation is based on employing special on-board equipment for measuring and recording of flight data. The next step is to equip the aircraft with digital autopilot and experimental indirect (fly-by-wire) flight control system which will be used for testing different control laws from handling qualities of aircraft point of view. In particular, the proposed flying laboratory will be used as didactic tool for in-flight simulation of different aircraft dynamic characteristics.

Practical training plays a very important role in aeronautics engineers' education. This function is performed by laboratory exercises. However, laboratory stands, including flight simulators, do not emulate many unique characteristics and properties of aircraft and its on-board equipment. Test flights cover many special psychological aspects, that students' participation in real flight experiments is an essential element of the process of establishing their engineering intuition. Rzeszów University of Technology instructs aeronautics designers and pilots; the Pilot Training Center employs training airplanes. One of these aircraft, the PZL M20 "Mewa", will be used as a flying didactic laboratory. This paper describes the preliminary project of the PZL M20 aircraft control system modification for obtain the in-flight simulator.

2 The Project Assumptions

The PZL M20 aircraft will be equipped with complete set of sensors, navigation systems, and an on-board computer to integrate all modules of the system. First, the aircraft will be equipped with measuring equipment and a computer system designed for storing, processing and displaying information. Next, a digital flight control system will be included. In the third stage, an indirect (fly-by-wire) control system will be installed which will allow modifications of aircraft's dynamic and handling properties. In this way we can name the aircraft as simplified TIFS - Total In-Flight Simulator. Evaluator will be able control the aircraft using an additional steering panel and side-stick. The mechanical linkage will be used as safety control system.

From the main goal of the project point of view, the most important is flight control computer and its software. The different dynamic properties and handling qualities of the aircraft are shape by the control law synthesis for desired properties of the aircraft in-flight simulation obtaining. This task will be performed by application of the indirect flight control system (fly-by-wire), used to obtain the possibility of control system property modification. As a result, handling qualities of the airplane will be shaped. Implementation of the indirect flight control system means that airplane can be used as a simplified in-flight simulator. This idea has been applied in aviation research for many years (for example [1] and [2]) but there are no known applications this solution for aeronautics students' education. Experiences in the field of indirect flight control systems designing for light airplanes will be used in the construction of the experimental control system described in [3] and [4].

Fig. 1. General aviation aircraft PZL M-20 "Mewa" as an educational Total in Flight Simulator

The properties of the optimal controller were calculated applying the indirect (implicit) model following method. In particular, the modified version based on the computer simulations was used. Model following method allows shaping properties of the flight control systems that satisfactorily approximate those of the desired model of controlled aircraft. In this way, the expected handling qualities can be reached. Choosing the different models of desired aircraft we can test the new control laws, which are proposed for implementation in the control systems dedicated for different types of aircraft, see [5] and [6].

Establishing desired properties of pilot-controlled, but automatically augmented aircraft, requires selecting proper control system structure. On the basis of to-date experiments, a direct model-following control structure, presented in figure 2, has been chosen. Model-following design technique is a well-known method for a control system synthesis, and it is very often used in design practice (for example [7] - [10]). In this project the modified version of the direct model-following method is applied, which was described in the previous publications [11] and [12]. This method is chosen for shaping dynamic properties and handling qualities of the total-in-flight simulator as a very useful solution from didactic point of view. It is a new instance of a previous approach applied in [12] and [13].

Model of aircraft and gain matrices ($K=[K_P, K_M, K_A]$) are adjusted to selected control option and flight conditions. Figure 2 presents only the basic, simplified system structure. It should be supplemented with diagnostic, supervising, and warning systems to ensure proper cooperation between the pilot and control system.

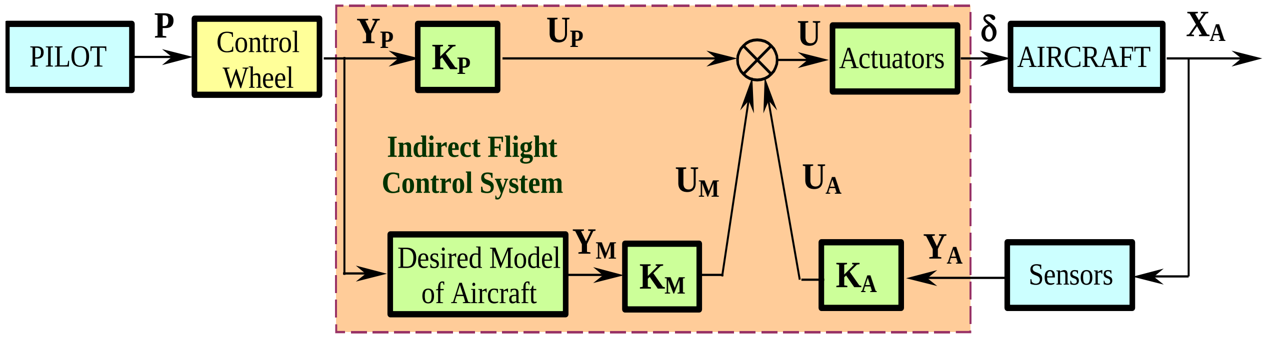

Fig. 2. Diagram of the model-following control system

For the case of the flight with almost constant airspeed, a linear model of aircraft dynamics may be assumed, with separate equations of longitudinal motion and lateral motion.

The most important students' experiments are calculation control laws and evaluation of indirect flight control system. In general, we will consider two versions of the controller:

- Full state feedback, optimal indirect model following controller (IMF),
- Suboptimal simplified model following controller with feedback from observability output signals (SMF).

The optimal IMF controller needs the full state feedback control. It means that all states should be measured or the state observer must be used; this fact increases number of calculations that have to be performed in real time [10]. From the practical point of view, it would be profitable to employ a simplified model following (SMF) controller, which would only consider feedback on measurable state variables [12]. The first version of the controller is calculated as typical theoretical exercises and results can be evaluated on the basis of computer simulations. In flight, the simplified version of the controller should be used. To summarize, the basic part of the test flights preparing is calculation of suboptimal controller properties as control laws defined by matrix of coefficient $K=[K_P, K_M, K_A]$. Calculated coefficients will be applied on flight computer and handling qualities of aircraft can be evaluated.

3 Suboptimal Indirect Model Following Controller (SMF)

The properties of the optimal controller were calculated applying the indirect (implicit) model following method [12], and in particular the modified version described in the previous paper was used [11]. Model following method allows shaping properties of the flight control systems that satisfactorily approximate those of the desired model of controlled aircraft. Selection of the model is the important stage of this method. Chosen model can contain desired dynamic properties of the plane (for example the "ideal model with good performance" [10]) or it can describe the performance of the known real aircraft.

The difference between the real aircraft and the desired model performance is defined as (see Fig. 2)

$$\mathbf{E}(t) = \dot{\mathbf{Y}}_M - \dot{\mathbf{Y}}_A \tag{1}$$

This kind of error between desired (modeled) and real output signals represents differences on dynamic reaction of modeled and real aircraft. In general, the steady-state performance of aircraft should be established in another way. The control function **U**(t) will be chosen to minimize the value of a quality control index

$$\mathbf{J} = \int_{0}^{\infty} \left(\mathbf{E}^T \mathbf{Q}\,\mathbf{E} + \mathbf{U}^T \mathbf{R}\,\mathbf{U}\right) \mathbf{dt} \tag{2}$$

For suboptimal simplified model following controller with feedback from observability output signals (**SMF**) the control law is described by the following equation (see Fig. 2):

$$\begin{gathered}\mathbf{U} = \mathbf{K_P Y_P} + \mathbf{K_M Y_M} + \mathbf{K_A Y_A} \quad \textit{or} \\ \mathbf{U} = \mathbf{KY}; \quad \mathbf{K} = [\mathbf{K_P}, \mathbf{K_M}, \mathbf{K_A}], \ \ \mathbf{Y} = [\mathbf{Y_P}, \mathbf{Y_M}, \mathbf{Y_A}]^T\end{gathered} \tag{3}$$

SMF controller matrices $\mathbf{K_i}$ are calculated using the simulation method of model following control system synthesis [12]. The method based on the computer simulation. For the purpose of solving the IMF controller for linear control problem we must use the methods, which require solving of algebraic matrices non-linear equations.

For the real dimensions of the state equations, the calculation time rises to a level that makes it profitable to employ the direct methods of the searching for the minimum of the performance index. The practical application becomes even more evident if we consider that in such a case a simplified linear model of the object's dynamics may be replaced with the full non-linear model. It is also possible to take into consideration many real-life restrictions, e.g. those concerning control signals. The solution of the classical linear problem for the problem's simplified version may be used as a first approximation of the desired solution. Finally, the non-linear programming method with the inequality constraint functions will be used for the sub-optimal control laws choosing [14]:

$$\mathbf{J(K)} = \int_{0}^{T_f} (\mathbf{E}^T \mathbf{Q}\,\mathbf{E} + \mathbf{U}^T \mathbf{R}\,\mathbf{U})\mathrm{dt} \tag{4}$$

where: $\mathbf{K} \in [\ \mathbf{K}^{\mathbf{min}}, \mathbf{K}^{\mathbf{max}}]$ – suboptimal value of the control matrix, lower and upper limitations of the gain matrix, respectively, T_f - finite period of integration, it is approximate equal period of the phugoid mode or the largest of the time constant of the aircraft motion.

In practice, because of the stability requirements, the modified version of performance index $\mathbf{J_W}$ is used

$$\mathbf{J_W}(\mathbf{K}) = \mathbf{J}(\mathbf{K}) + \mathrm{d}\sum_{j=1}^{p} \mathrm{g}^{r_j} \qquad r_j = \mathrm{real}(\lambda_j) \tag{5}$$

where: λ_j - eigenvalue of the linear approximation of the closed-loop control system, p – number of eigenvalues with real(λ_i)≥0, d, g – parameters (weighting coefficients).

It is necessary to check if simplifying control laws leads to significant deterioration in the attitude stabilization quality and a transition process. For this purpose, the computer simulation is particularly convenient, as a part of the synthesis method.

4 Numerical Example

The numerical example concerns the synthesis of desired dynamic properties and handling qualities of the general aviation aircraft PZL-M20 "Mewa" equipped with indirect (FBW) experimental flight control system. The task is the following: choosing the properties of the control laws in this way that reaction in longitudinal motion of the aircraft for pilot's control wheel displacement should be the similar to reaction of three different aircrafts: commuter aircraft PZL M28 "Skytruck" [12], airliner DC-8 and fighter F-89 [15]. In the experimental aircraft model the properties of the real actuators were applied and control of engine power is used. In case of modeled aircraft, an inertia of mechanical control system is involved, end engine control system is switched off. The short period dynamic properties will be shaped, therefore power control of M20 aircraft engines is not used (no power levers displacement).

Handling qualities evaluation is planned during flight of PZL M20 with maneuver speed V_A=62.8 m/s on altitude H_{STD}=500 m, mass m=2040 kg, medium center of gravity position.

Fig. 3. Commuter aircraft PZL M28 "Skytruck"

Calculations were performed with MATLAB-Simulink package. For longitudinal motion modeled PZL M28 dynamic properties, the results of applying the SMF controller are presented in Figure 4. Plots show the time-history of the pitch rate and pitch angle after displacement of the control wheel causes elevator rotation of modeled aircraft. The pilot's control signal has a typical trapezoidal shape (signal U20 on upper left pictures). Plots in Figure 3 show reaction of flying laboratory (line M20) and modeled aircraft PZL M28 (line Model) for cruiser flight configuration on the same pilot's control signal. If control system is switched on, the same pilot action causes different control signal generation which activates actuator of elevator (line U20, pictures on the right). The delay causes by actuator inertia is visible. Pitch rates and pitch angles of the modeled and real aircraft are very similar. In this way, from pilot point of view the PZL M20 general aviation aircraft reaction on control wheel displacement is similar to PZL M28 aircraft reaction on the same pilot action. It is possible to say that handling properties concern attitude orientation of the experimental aircraft is similar to modeled commuter aircraft. Of course, increments of airspeed and load factor are different; they strongly depend on performance of modeled and real aircraft. In lateral motion we can observe a good conformability of modeled aircraft and flying laboratory reaction on the pilot steering, as well.

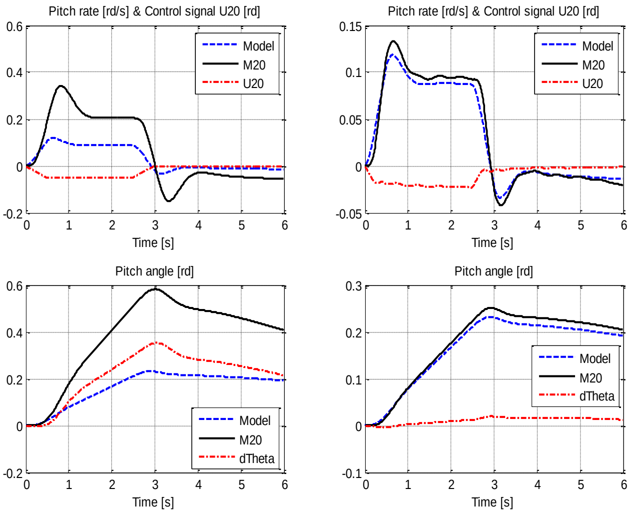

Fig. 4. The time-history of the state variables with the model-following control system switched off *(on the left)* and switched on *(on the right)*, where: M20 – PZL M20 "Mewa" general aviation aircraft and Model - PZL M28 "Skytruck" commuter aircraft in cruiser configuration (V_{IAS}=106.4 m/s, H_{STD}=3000 m), U20 – control signal of M20 elevator actuator, dTheta – pitch angle difference between modeled aircraft and total in-flight simulator

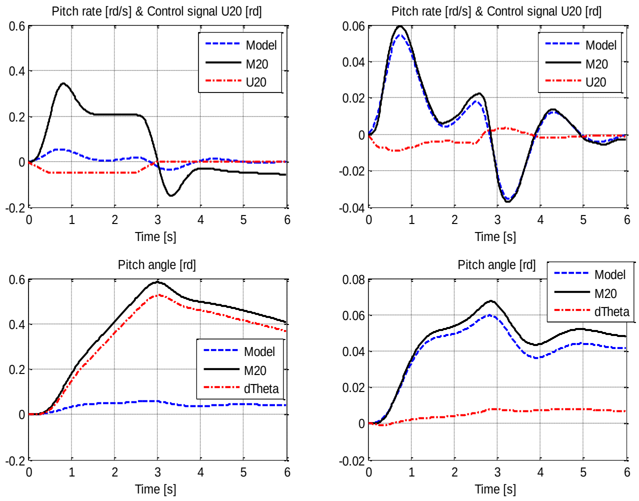

Fig. 5. The time-history of the state variables with the model-following control system switched off (*on the left*) and switched on (*on the right*), where: M20 – PZL M20 "Mewa" general aviation aircraft and Model – modeled DC-8 airliner aircraft in cruiser configuration (V_{IAS}=251.2 m/s, H_{STD}=10000 m), U20 – control signal of M20 elevator actuator, dTheta – pitch angle difference between modeled aircraft and TIFS

Figures 5 and 6 present reactions of the PZL M20 aircraft as in-flight-simulator of DC-8 and F-89 aircraft. In this way, the main handling characteristics and dynamic properties of different aircrafts can be simulated during the real flight. General aircraft PZL M20 has the same dynamic performance from pilot point of view as airliner DC-8 or fighter F-89.

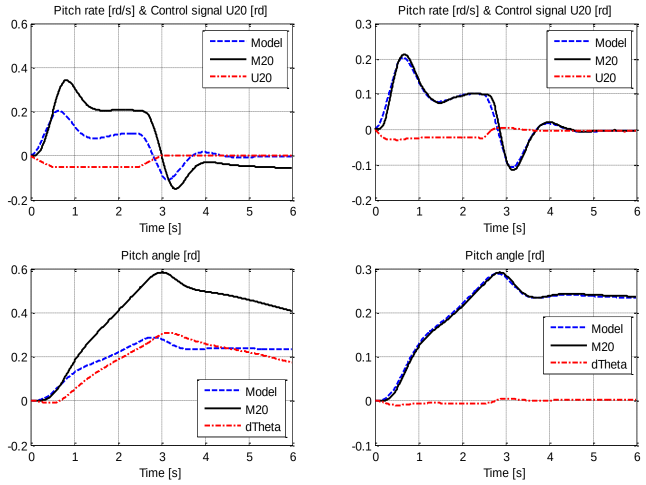

Fig. 6. The time-history for modeling of F-89 fighter aircraft handling performance in cruiser configuration (V_{IAS}=201 m/s, H_{STD}=6100 m); SMF controller switched off *(left)* and switched on *(right)*

5 Summary

The total in-flight simulator should be very useful didactic tool in the aeronautics students' education. Practical experience, like in-flight experiments, constitute a very important element of the professional preparation for aviation designer and research engineers.

Experiments described in this article are the most sophisticated example of students' exercises. The flying laboratory will assist the process of student education in many ways, for instance [16]:

- Supporting education of aerodynamics, flight mechanics and aircraft performance, on-board instruments and systems, navigation aides, flight control systems, flight test methodology,
- In-flight testing of instruments and systems prepared by students as a course and diploma projects,
- User's modified automatic flight control system.

Active student participation in preparing and conducting measurement flights is an important didactic task. The following students' activities in a frame of the flight test experiments are executed:

- Theoretical study and total-in-flight simulator control laws synthesis for chosen real aircraft or designed one,
- Preparing a plan of the test flight: flight conditions, kind of aircraft maneuvers, list of displayed and stored signals,
- Observation the chosen parameters during the flight and active participation in the experiment,
- Post flight data analysis and conclusions (written report).

The numerical example concerns the synthesis of desired handling qualities of the general aviation aircraft PZL-M20 "Mewa" equipped with indirect (FBW) experimental flight control system. Results of the calculation show that reaction in longitudinal motion of the aircraft for pilot's control wheel displacement should be the similar to reaction of the modeled aircraft. The same features of simplified TIFS are observed in lateral motion of aircraft. It is possible to say that handling properties concern attitude orientation of the experimental aircraft is similar to modeled aircraft. The flying laboratory has at choice modeled properties, and it should be very interesting experiment for students.

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