AN ENGINEERING FLIGHT SIMULATOR FOR LIGHT AIRPLANES

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1. INTRODUCTION

The design and development of modern aircraft makes extensive use of flight simulations. A vast range of problems is open to investigation on simulators. The essential feature of all such investigations is to introduce the pilot into a closed loop control situation, so that account is taken of his capabilities and limitations. The expectation is that within the bounds of the experimental conditions, his behavior in the simulator matches his behavior in the flight situation.

It is important therefore, to establish the right simulator for the research investigation which is planned. Extensive simulation facilities are required throughout the procurement cycle of large and small aircraft projects. The choice of aircraft configuration will be influenced by early simulator evaluations; trade-off studies will determine the balance of airframe and equipment. At the design phase, aspects of stability and control, and the primary flight control options will be simulated. On the other hand, human factor considerations of the design, such as cockpit layout, control, displays and crew workload will be assessed. As hardware becomes available, it is incorporated into engineering simulators for evaluation, and before flight, the simulator will be used for pilot familiarization. Flight test clearance will be supplemented by parallel activities on ground-based simulators.

Engineering flight simulators are playing a more and more important role in the design and development of modern aircraft, research on the man-machine interface and for licensing, certification and accident investigations.

This paper discusses the mathematical modeling of the aerodynamic, flight control, propulsion, ground-handling and environmental characteristics of the airplane, starting from the general equations of airplane motion. The entire model is evolved and implemented on the parallel digital computer system constructed by a number of new VLSI single chip computers, TRANSPUTERs. The principles of computer generated image, computer display of aero-meters and sample systems are discussed. The paper deals with the hardware and software integration of the engineering flight simulator components and the testing of the complete flight simulator.

Finally, the successful applications of the flight simulator to the several kinds of light airplane are presented. The flight performances of the airplanes were determined on the simulator, and the responses to control inputs of flight of the AD200 light canard-configured airplane designed and manufactured by Nanjing University of Aeronautics & Astronautics (NUAA) were analyzed and compared with experimental data. The simulator can be used for certification and design development of light airplane, researching flying qualities and control system requirements, pilot training, and evaluation of competitive designs and operational procedures.

2. MATHEMATICAL MODELING OF AN AIRPLANE

The basis of any flight simulator – as mentioned before – is the mathematical model, including the data package describing the characteristic features of the airplane to be simulated. Airplane mathematical models may be obtained from theoretical analysis, wind-tunnel measurements and flight tests. This section presents the mathematical modeling of the aerodynamic, flight control, propulsion, ground-handling and environmental characteristics of the airplane, starting from the most general equations of airplane motion. The simulation of a complete mission, from take-off to landing, needs the non-linear equations of motion, covering the full flight envelope.

Equation of Motion

The motions of an airplane are affected by the external forces(F) and moments(M) resulting from flight through the atmosphere, engine thrust and landing gear forces during take-off and landing, acting on the airplane. The general equations of motion of a rigid aircraft in the body axes reference frame read (4)

$$\left.\begin{aligned} F_x &= -mg\sin\theta + X = m\cdot(\dot{u}+qw-rv)\\ F_y &= -mg\cos\theta\sin\varphi + Y = m\cdot(\dot{v}+ru-pw)\\ F_z &= -mg\cos\theta\cos\varphi + Z = m\cdot(\dot{w}+pv-qu)\end{aligned}\right\} \quad 1a$$

$$\left.\begin{aligned} M_x &= L = I_x\dot{p}-I_{yz}(q^2-r^2)-I_{xz}(\dot{r}+pq)-I_{xy}(\dot{q}-rp)-(I_y-I_z)qr\\ M_y &= M = I_y\dot{q}-I_{xz}(r^2-p^2)-I_{xy}(\dot{p}+qr)-I_{yz}(\dot{r}-pq)-(I_z-I_x)rp\\ M_z &= N = I_z\dot{r}-I_{xy}(p^2-q^2)-I_{yz}(\dot{q}+rp)-I_{xz}(\dot{p}-qr)-(I_x-I_y)pq\end{aligned}\right\} \quad 1b$$

To the Equations (1) the kinematic Equations (2) should be added, expressing the relations between the rates of change of the airplane's attitude angles and the angular velocities about the airplane body axes

$$\left.\begin{aligned} \dot{\psi} &= q\sin\varphi\sec\theta + r\cos\varphi\sec\theta\\ \dot{\theta} &= q\cos\varphi - r\sin\varphi\\ \dot{\varphi} &= p + q\sin\varphi\tan\theta + r\cos\varphi\tan\theta\end{aligned}\right\} \quad 2$$

The Aerodynamic Model

The aerodynamic forces and moments in Equations (1) result from flight through a volume of ambient air *at rest*, relative to earth. Adding the contributions of the forces and moments due to atmospheric turbulence (g), engine operation (T) and landing gear ground contact (LG), results in the following general equations for the external forces and moments in body axes

$$\left.\begin{aligned} X &= \tfrac{1}{2}\rho V^2 S(C_{x_a}) + X_{LG} + X_T\\ Y &= \tfrac{1}{2}\rho V^2 S(C_{y_a}) + Y_{LG} + Y_T\\ Z &= \tfrac{1}{2}\rho V^2 S(C_{z_a}) + Z_{LG} + Z_T\\ L &= \tfrac{1}{2}\rho V^2 Sb(C_{l_a}) + L_{LG} + L_T\\ M &= \tfrac{1}{2}\rho V^2 S\bar{c}(C_{m_a}) + M_{LG} + M_T\\ N &= \tfrac{1}{2}\rho V^2 Sb(C_{n_a}) + N_{LG} + N_T\end{aligned}\right\} \quad 3$$

The general non-linear aerodynamic model of light airplane, in terms of dimensionless force and moment coefficients in Equations (3) becomes

$$\left.\begin{aligned} C_L &= C_{L_0} + C_{L_\alpha}\cdot\alpha + C_{L_u}\cdot(\tfrac{u}{V}) + C_{L_{\dot\alpha}}(\tfrac{\dot\alpha\bar{c}}{2V}) + C_{L_q}\cdot(\tfrac{q\bar{c}}{2V})\\ &\quad + C_{L_{\delta_F}}\cdot\delta_F + C_{L_{\delta_E}}\cdot\delta_E + (\Delta C_L)_{GE}\\ C_D &= C_{D_0} + C_{D_\alpha}\cdot\alpha + C_{D_u}\cdot(\tfrac{u}{V}) + C_{D_{\dot\alpha}}(\tfrac{\dot\alpha\bar{c}}{2V}) + C_{D_q}\cdot(\tfrac{q\bar{c}}{2V})\\ &\quad + C_{D_{\delta_F}}\cdot\delta_F + C_{D_{\delta_E}}\cdot\delta_E + C_{D_{\delta_A}}\cdot\delta_A + (\Delta C_D)_{GE}\\ C_Y &= \quad C_{Y_\beta}\cdot\beta + C_{Y_p}\cdot(\tfrac{pb}{2V}) + C_{Y_r}\cdot(\tfrac{rb}{2V}) + C_{Y_{\delta_R}}\cdot\delta_R\\ C_l &= \quad C_{l_\beta}\cdot\beta + C_{l_p}\cdot(\tfrac{pb}{2V}) + C_{l_r}\cdot(\tfrac{rb}{2V}) + C_{l_{\delta_A}}\cdot\delta_A + C_{l_{\delta_R}}\cdot\delta_R\\ C_m &= C_{m_0} + C_{m_\alpha}\cdot\alpha + C_{m_{\dot\alpha}}\cdot(\tfrac{\dot\alpha\bar{c}}{2V}) + C_{m_u}\cdot(\tfrac{u}{V}) + C_{m_q}\cdot(\tfrac{q\bar{c}}{2V})\\ &\quad + C_{m_{\delta_F}}\cdot\delta_F + C_{m_{\delta_E}}\cdot\delta_E + (\Delta C_m)_{GE}\\ C_n &= \quad C_{n_\beta}\cdot\beta + C_{n_p}\cdot(\tfrac{pb}{2V}) + C_{n_r}\cdot(\tfrac{rb}{2V}) + C_{n_{\delta_A}}\cdot\delta_A + C_{n_{\delta_R}}\cdot\delta_R\end{aligned}\right\} \quad 4$$

To obtain the aerodynamic forces and moments, a systematic empirical approach (11), based on the Datacom (8) incorporating some results of reference (7), was developed to predict the stability, control and hinge moment derivatives in the preliminary design phase of general aviation airplanes of conventional, canard or tri-surface configuration with a satisfying accuracy.

Engine Model

An engine model must first produce the correct value of steady thrust to correspond with the pilot's demand through his power level.

In the case of piston engined airplanes, the computation of the contributions of the propeller/engine combination to the external forces and moments can be found in the references (7) - (9).

Engine power as a function of the engine speed, manifold pressure and air density are obtained from the 'engine power chart', as given by the engine manufacturer.

Ground-handling Model

Ground-handling simulation became an important item, since the arrival of visual simulation systems. For the simulation of taxying, take-off and landing, the mathematical model of the aircraft-undercarriage is necessary. Providing simple ground reactions sufficient to balance the airplane's weight can be done by a simple spring and damper model, with extra damping on recoil. For some tasks, however, a more detailed model may be necessary, to include tires and brakes, anti-skid systems and nose-wheel steering (1). Additional features may need to be included to represent such influences as 'ground effect' (5), (8), whereby the presence of the ground close to the airplane during take-off and landing so constrains the airflow around the airplane that the forces acting differ markedly from those applicable to the same configuration in free air.

Turbulence and Windshear

Atmospheric turbulence, wind and windshear disturb the aircraft motions. Models describing these phenomena are therefore essential in flight simulation (1).

A full atmospheric model needs to represent a number of properties. The starting point is the variation of air density and temperature with altitude, as defined by the International Standard Atmosphere. These properties may be called atmospheric statics. A wind environment is also needed, in terms of mean surface wind for take-off and landing, and winds at altitude as they affect performance on a route schedule, for example. Associated with wind, there is usually turbulence, the effect of which can range from a distraction and disturbance in a precise task, to a design case for control authority or for crew ride comfort. Methods of modeling turbulence have improved in recent years (3), (6) as a result of active research into the real world environment. More extreme atmospheric phenomena are also now being modeled. Wind shear has caused several major accidents and is a legitimate item to be simulated, either for research into aircraft design or for training pilots to recognize and counter it effectively.

IMPLEMENTATION ON TRANSPUTERS

The mathematical models of airplanes mentioned above are described by systems of ordinary differential equations. These equations must be solved to learn more about the model, to study the effect of varying parameters, or to control the system.

Historically, analog, digital and hybrid computers have been used to obtain solutions of this mathematical model. A single processor digital computer is the most widely used alternative at the current time. On this, as the model becomes more complex and the solution time increases. Parallel digital processing can also be used to obtain the solution. Due to the high hardware costs and programming difficulties only a few such systems are in use today. However, recent developments in VLSI technology are rapidly moving in favor of parallel digital processing.

The entire model is evolved and implemented on the parallel digital computer system constructed by a number of new VLSI single chip computers, TRANSPUTERs. This paper deals with the hardware and software integration of the engineering flight simulator components and the testing of the complete flight simulator.

Figure 1 is a block diagram of the engineering flight simulator with fixed-base, in which a Transputer net receives airplane position and attitude data from the root computer and data representing the terrain, airfield etc. over which the flight takes place. In the CGI system of the simulator the appropriate part of the visual data base is selected and passed to the geometric and display processors. Transputer net generates the video signals representing the sense and the deflection signal to projectors for projecting on the screen.

The Transputer and Occam

The Transputer is one of a family of new VLSI single chip computers built by INMOS Corporation. The T800 Transputer contains a 10 MIP (millions of instructions per second) 32-bit processor, 4k bytes of on chip RAM memory, I/O interfaces, and a timer. The Transputer is packaged in a pin grid array about one inch square. If necessary RAM and I/O can be expanded using additional external devices (12). The Transputer has the distinction of being one of the first designs to incorporate several hardware features to support parallel processing. This permits any number of Transputers to be arranged together to construct a parallel processing system. Existing languages require a few extensions to support parallel processing primitives. To do this INMOS has developed Occam, a high-level language supported on the Transputer. Occam is a simple block-structured language that supports both sequential and parallel programming on one or more Transputers (12). State-

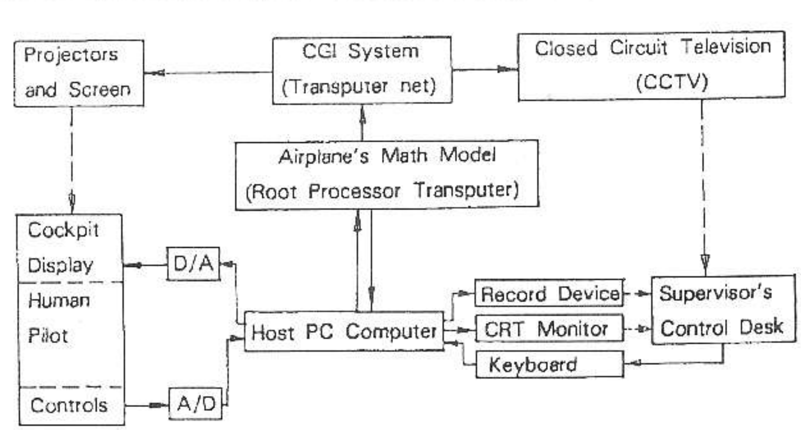

FIGURE 1. Block diagram of software and hardware modules of the engineering flight simulator.

Table 1. The comparison of "flight" performances on the simulator and flight test results at the same flight condition.

	AD200			AD100		AD100T	
Data index*	1	2	3	1	3	1	3
Takeoff (m)	131	126	120	66	60	107	NA
Landing (m)	160	154	140	73	68	137	NA
Vmax(km/h)	144	141	135	128	120	111	NA
Vstall(km/h)	69	67	68	53	51.9	64	NA
Vymax(m/s)	1.9	2.2	1.83	2.5	2.7	1.5	NA
Vvymax(km/h)	85	84	90	66	69.6	88	NA
Rmin (m)	70	77	NA	63	53	67	NA

*where data index 1 is simulating flight performances based on the empirical approach[1];
2 is simulating flight performances based on the windtunnel tests[13];
3 is real flight test results.
NA is not available

portant here. In this engineering flight simulator, a CRT (cathode ray tube) is used to simulate the flight instrument panel, including a number of aero-meters, for replacing the real instruments.

Sampling System

The sampling system is used for getting the pilot's control input signals (analog), and converting them to digital values. Measuremental devices are installed on various points of the flighy controls, fuel controls and so on.

Integration and Validation

The complexity of a flight simulator, either for training or research and development, is obvious from the above elaborations. Before integration, the main components are initially tested on a stand-alone basis. So individual testing of the simulator components starts by establishing a functioning computer, which controls all remaining flight simulator components. Next each software module is individually tested. Simultaneously with the simulation software testing above, stand-alone testing of the remaining flight simulator components may be carried out, starting with the individual components, accommodated in the flight simulator cockpit.

The out-of-the-window visual simulation system can be tested stand-alone with the display CRTs or projectors separated from the infinity optics.

After completion of the above and of calibration tests, the real-time flight simulator software may be loaded into the digital computer and the flight simulator is ready for 'flight' testing. In order to demonstrate that the flight simulator accurately duplicates the flight test data of the airplane to be simulated, a number of specific flight test maneuvers are needed to compare the characteristic behavior of the actual airplane with that of the flight simulator as discussed in the following section.

ments that are to be executed in sequential order are placed in a SEQ block. Statements that are to be executed in parallel order are placed in a PAR block. An Occam program can be run on any number of Transputers. If there are more parallel processes than Transputers, multiprocessing is used to simulate parallel processing. Thus, one version of a program can be written so that it will run on one or a number of Transputers. Only the small section of Occam program that assigns processes to processors would require modifications.

Computer Generated Image

An essential part of flight simulation is the generation and display to the pilot of a simulated perspective view of the outside world. The visual system which accomplishes this receives inputs from the computer which is computing the position and attitude of the airplane as it moves along the simulated flight path and must continuously provide the view appropriate to each position and attitude.

Computer-generated imagery (CGI) is far more versatile, CGI systems can generate and display terrain of unlimited size, and a growing number of jet-fighter simulators even use scenes generated by computer.

Computer Display of Aero-Instructors

The requirements for objective fidelity in the cockpit of the flight simulator vary with its objectives. However, the general assertion can be made that the character and the workload of the pilot's task in the simulator should be representative of those seen in flight. Hence the emphasis on perceptual fidelity. Research and development simulators should have high environmental cue fidelity, while equipment cue fidelity may be less im-

4. EXAMPLES

Examination of Light Aircraft Flight Performances

Three light canard-configured airplanes AD200, AD100 and AD100T, which were designed and manufactured by NUAA, were tested on the flight simulator in the same conditions as in the real flight tests. The comparison of "flight" performances with aerodynamic forces and moments gained by the systematic empirical approach (1) and the flight tests (13) is shown in Table 1.

Response to Control Inputs

Figure 2 shows the responses of the non-linear AD200 model to an elevator deflection. Thick lines refer to wind tunnel test data (13), and thin lines to the empirical approach (1). The responses of the angle of attack (al-

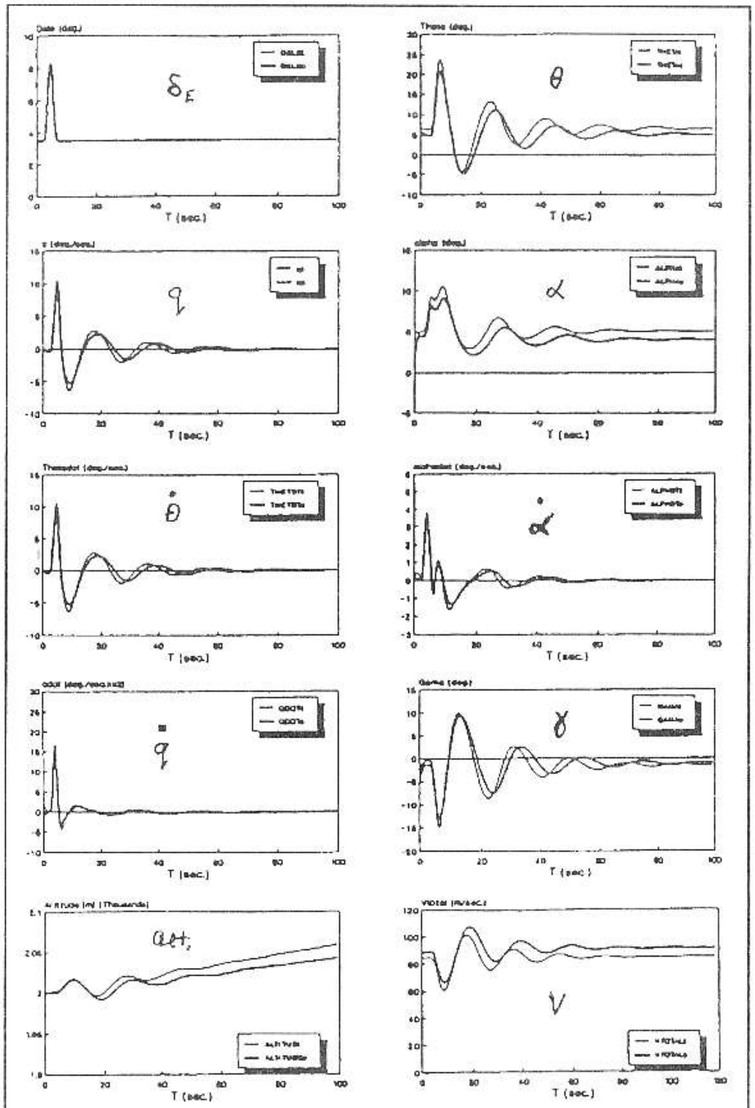

FIGURE 2. The response of AD200 on a elevator deflection.

pha), pitch rate (q) and derivative of alpha (alphadot) show the 'short period' motion of the AD200. The 'phugoid' is visible in the responses of the total velocity relative to the earth with the undisturbed air (Vtotal), the pitch angle (Theta), the flight path angle (Gama) and the altitude (Altitude).

5. SUMMARY

This paper discusses the mathematical modeling of the aerodynamic, flight control, propulsion, ground-handling and environmental characteristics of the airplane, starting from the general equations of airplane motion. The entire model is evolved and implemented on the parallel digital computer system constructed by a number of new VLSI single chip computers, TRANSPUTERs. The principles of computer generated image, computer display and sample system are discussed. The paper deals with the hardware and software integration of the engineering flight simulator components and the testing of the complete flight simulator.

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