FLIGHT SIMULATION OF MULTIPLE AIRCRAFT AND HELICOPTERS USING A SINGLE HIGH—PERFORMANCE COMPUTER

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Abstract

This paper describes the simultaneous simulation of multiple airframes in real time using a single high—speed computer, the AD 100. Examples include the simulation of up to 32 aircraft over their full flight envelopes, 8 helicopters with each helicopter simulated using the blade element method, the simultaneous simulation of multiple fighter aircraft together with six—degree—of—freedom missile simulations, and the simultaneous simulation of airframes and turbofan engine dynamics. A simple method for handling separate integration mode control (reset, operate, hold) for each of the airframes is also described.

1. Introduction

Flight simulation of the engagement of multiple piloted aircraft for both training and weapons system evaluation is becoming widespread. Full flight envelope simulation of high—performance aircraft requires large numbers of multivariable aerodynamic functions, which can consume considerable processor time on general purpose computers. If the flight control system is also included in the simulation, the required integration frame rates for satisfactory dynamic accuracy can become quite high. The net result is that a single, comprehensive airframe simulation can tax the speed capabilities of very fast general purpose computers. In fact, there are a number of examples where two or more general purpose computers have been required for the real—time simulation of a single aircraft. It follows that the simulation of multiple airframes can require a large number of general purposes computers, which in turn can introduce programming and timing problems, especially in a real—time environment.

In this paper we describe the use of the Applied Dynamics AD 100 computer for the simulation of airframes. The AD 100 is a multiprocessor with special architecture and software which has been optimized for the solution of ordinary, nonlinear differential equations. The computer uses emitter—coupled (ECL) logic with floating—point word lengths of 56 bits and 65 bits. It can perform 10 million multiplies and 10 million adds per second. The total time required for a 56 bit floating point multiply is 0.075 microseconds, and for a 65 bit floating point add is 0.1 microseconds. The eqivalent overall instruction rate exceeds 100 million instructions per second. Because of the short multiply and add times, and the special architecture, the AD 100 is extremely fast in

the solution of scalar problems. The Function Memory Unit (FMU) in the AD 100 includes a solid—state memory of 2.097 million 65 bit words and is designed to be especially efficient in the generation of multi—variable functions. The AD 100 interface can handle up to 5 megawords per second. In the examples which follow we will see how the above characteristics can be utilized in the real—time simulation of multiple complex airframes within only one AD 100.

2. Multiple Aircraft Simulation

As a first example we consider the simulation of an aircraft with six degrees of freedom, along with a simplified flight control system. The rotational equations of motion are written using aircraft body axes, while the translational equations of motion are written using flight—path axes. [1] Quaternions are used to represent the angular orientation of the aircraft. Conventional Euler angles are computed from the quaternions for display purposes. There are 13 state variables associated with the six degrees of freedom of the rigid airframe (the 4 quaternions introduce a redundant state). The flight control system includes 7 state variables and six limiter—type nonlinearities. The count of multivariable functions used in the simulation to represent aerodynamic coefficients is the following:

2 one—variable functions

5 two—variable functions

3 three—variable functions

6 four—variable functions

The time required on the AD 100 for a single pass through the airframe equations (i.e., one integration step when using a single—pass integration method) is 128.7 microseconds. The highest frequency in the simulation is the 5 hertz frequency of the control—surface actuators. With the AB—2 (second—order Adams—Bashforth) integration algorithm, an integration step size of 8 milliseconds gives a dynamic accuracy of roughly one percent in the actuator simulation. [2] The highest frequency for the rigid airframe in our example here is the 1 hertz associated with the short—period longitudinal motion at maximim dynamic pressure. In this case the dynamic error resulting from the 8 millisecond integration step size will be much less than one percent. Since the AD 100 requires only 128.7 microseconds for one integration step, the aircraft simulation can be run at 8000/128.7 or 62.16 times

real time. The use of multiple frame—rate integration for the 5 hertz actuator loops could be used to further speed up the simulation.

It should be noted that the number of multivariable aerodynamic functions required for a full flight envelope simulation of a complex, high performance aircraft may be considerably larger than the function count listed above. Table 1 shows a tabulation of the exection times required by the AD 100 for the computation of multivariable functions using table lookup and linear interpolation. The table consists of two sections. The first section shows the execution times for the binary search required to identify the largest breakpoint contained in each function input variable. Three binary searches are mechanized simultaneously, with the total execution time for each trio dependant on the number of breakpoints. The second section lists the total execution time for function evaluation using linear interpolation. For example, the 16 aerodynamic functions listed above have 8 different input variables which require the following binary search kernals: one 65—breakpoint kernal (2.8 microseconds), one 17—breakpoint kernal (2.2 microseconds) and two 9—breakpoint kernals (3.8 microseconds) for a total execution time of 8.8 microseconds. Total execution time for the function evaluation kernals is given by $2(.6) + 5(1.1) + 3(1.9) + 6(3.5) = 33.4$ microseconds. Thus the overall AD 100 execution time for computing the 16 multivariable aerodynamic functions in our example aircraft simulation is $8.8 + 33.4 = 42.2$ microseconds. It is clear from this example and Table 1 that a much larger number of multivariable functions could be handled by the AD 100 and still have the overall integration frame time remain under several hundred microseconds.

Table 1. AD 100 execution times for multivariable function generation

Binary Search Kernals

3 binary searches for	3	breakpoints	1.3	microsec.
3 binary searches for	5	breakpoints	1.6	microsec.
3 binary searches for	9	breakpoints	1.9	microsec.
3 binary searches for	17	breakpoints	2.2	microsec.
3 binary searches for	33	breakpoints	2.5	microsec.
3 binary searches for	65	breakpoints	2.8	microsec.
3 binary searches for	129	breakpoints	3.1	microsec.
3 binary searches for	257	breakpoints	3.4	microsec.

Function Evaluation Kernals

Evaluation of a 1—variable function	.6	microsec.
Evaluation of a 2—variable function	1.1	microsec.
Evaluation of a 3—variable function	1.9	microsec.
Evaluation of a 4—variable function	3.5	microsec.
Evaluation of a 5—variable function	6.9	microsec.
Evaluation of a 6—variable function	13.5	microsec.
Evaluation of a 7—variable function	26.5	microsec.

It should be noted that the 128.7 microsecond frame time for the aircraft example described above includes 17.5 microseconds of overhead associated with the AD 100 simulation executive, called SIMEXEC. Thus the net execution time per integration frame is 128.7—17.5 or 111.2 microseconds. This means that each additional airframe in a multiple aircraft simu—

lation will require only 111.2 microseconds. For illustrative purposes, let us assume that a more complex airframe simulation requires three times the 16 multi—variable functions listed at the beginning of this section (this adds 66.8 microseconds). Let us also assume that a much more complex flight control system adds another 50 microseconds, and that 100 input/output channels add still another 20 microseconds. Then the overall integration frame time for each aircraft would be $111.2 + 66.8, + 50 + 20 = 248$ microseconds. If the required real—time step size is 8 milliseconds, as assumed above, then the AD 100 could in principle simulate up to 8000/248 or 32 aircraft simultaneously in real time. As noted earlier, the use of multiple integration frame rates for the high—frequency flight control subsystems would permit an overall real—time step size considerably larger than 8 milliseconds. This would in turn increase even further the number of simultaneous aircraft which could be simulated.

3. Separate Mode Control for Individual Airframes

In a multiple engagement simulation it may be desirable to control separately in real time the integrator modes (reset, operate, hold) for each individual airframe. In the AD 100 this can be accomplished by appropriate modification of SIMEXEC. Another approach is to maintain the simulation of every aircraft in the operate mode at all times, but with the integration formulas for each state variable modified to accomplish individual mode control. To illustrate the method, assume that we are using the second—order predictor algorithm, AB—2, which is one of the most popular real—time methods. Then the difference equation for integrating the state equation, $dX/dt = F$, is given by

$$X_{n+1} = X_n + .5h*(3*F_n - F_{n-1})$$

where h is the integration step size. To allow separate mode control we modify the difference equation to the following form:

$$X_{n+1} = X_n + K1*.5h*(3*F_n - F_{n-1}) + K2*(X_0 - X_n)$$

The constants K1 and K2, in the form of real—time inputs each integration frame, control the integrator mode. Thus with $K1 = 1$ and $K2 = 0$ the integrator is in the operate mode. With $K1 = 0$ and $K2 = 0$, the integrator is in the hold mode. Finally, with $K1 = 0$ and $K2 = 1$, the integrator is in the reset mode, where in the next step the state X_{n+1} will take on the initial condition X_0. If each integration for a given airframe simulation is programmed with this formula, the integration modes for that airframe can be controlled separately from all other airframes by appropriate setting of the real—time inputs K1 and K2.

Note that in either the reset or hold mode, the state variable derivative F will be evaluated each frame using the same fixed state variables. Thus F_{n-1} will be equal to F_n. When the integration is then switched to the operate mode with $K1 = 1$ and $K2 = 0$, the difference equation for the first integration step will be given by

$$X_{n+1} = X_n + .5h*(3*F_n - F_n) = X_n + h*F_n$$

which is simply Euler integration. Subsequent steps, for which F_{n+1} in general is not equal to F_n, will revert to AB—2 integration. Actually, the usual startup method for AB—2 integration is Euler for the first step, so that the above technique should not cause any significant error in a real—time environment.

4. Multiple Helicopter Simulation

Our next example is the real—time simulation a helicopter using the blade element method. In the blade element method each rotor blade is divided into a number of segments or elements. The aerodynamic lift, drag and moment acting on each segment are calculated from the angle of attack and Mach number of the segments using two—variable aerodynamic functions. These forces and moments are then summed to obtain the overall aerodynamic forces and moments acting on the blade, which are used to integrate the blade equations of motion and to calculate the rotor forces acting on the airframe.

The angle of attack and Mach number at each blade segment are determined by computing the velocity components of the segment center of pressure with respect to the local air. These velocity components depend not only on the flapping and lagging motion of the blade, but also the rotor inflow and the trans—lational and rotational velocities and accelerations of the airframe. The overall calculations are very com—putationally intensive.[3] The real—time simulation is further complicated by the need to use high integration frame rates. For reasonable performance and dynamic handling accuracy Houck has shown that 4 to 6 segments per blade are required, and that each integration step should correspond to no more than 12 to 18 degrees of azimuthal motion of the rotor.[4] For a rotor with an angular frequency of 27 radians per second this translates into an integration step size of between 8 and 12 milliseconds for the rotor simulation.

The equations of motion of the Sikorsky UH—60A helicopter have been programmed on the AD 100 com—puter using the Sikorsky Gen Hel engineering simulation program.[5] The simulation includes the main rotor, tail rotor, empennage, fuselage, flight controls, landing gear, engine/fuel control, and ground effects. Overall frame time on the AD 100 is approximately 1 milli—second. It follows that up to 8 such helicopter simulations could be run in real time on a single AD 100.

It should be noted here that the AD 100 uses a programming language called ADSIM, which is similar to such continuous system simulation languages as ACSL and CSSL. In the current version 5.0 of ADSIM a real—time multiple airframe simulation is limited more by the size of the ECL program memory in the AD 100 than the speed requirements. Under version 5.0 of ADSIM and with the current size of program mem—ory in the AD 100, the UH—60A simulation described above would be limited to 4 airframes. Version 6.0 of ADSIM, which is about to be released, will support hardware subroutining as well as the software sub—routining currently supported by version 5.0. This will then remove any size restrictions in the real—time simulation of multiple airframes.

5. Simulation of Multiple Airframes and Missiles

In this section we consider a comprehensive six—degree—of—freedom simulation of a tactical missile, with the possibility of simulating multiple missiles and aircraft in multiple engagements. The example missile considered here is the Hellfire, which can be launched from conventional aircraft or heli—copters against surface or air targets. The system being simulated consists of the missile airframe, guidance system and flight control system, including pneumatic servos which control each of four fins. A total of 53 state variables is required in the simulation. The count of multivariable functions used in the simulation is the following:

18	1—variable functions
17	2—variable functions
7	3—variable functions

Net execution time on the AD 100 for one integration frame is 267 microseconds. The frame time required for an accurate solution in real time is four times this. Thus up to 4 Hellfire missiles can be simulated in real time on a single AD 100. More importantly, one AD 100 can be used to simulate two or three missiles as well as multiple airframes. In section 2 we saw that an integration frame time of 8 milliseconds was rep—resentative of the real—time requirement for a high performance aircraft, including its flight control and avionics system. The 1 millisecond real—time frame requirement for the missile suggests that we compute 8 integration steps for the missile per integration step for the aircraft. If we simulate 2 missiles, the requir—ed AD 100 execution time per 8 millisecond frame of the aircraft simulation is $2(277)(8) = 4432$ micro—seconds. This leaves $8000 - 4432 = 3568$ microsec—onds for simulating multiple aircraft. At 248 micro—seconds per aircraft, which is the AD 100 frame time we calculated at the end of Section 2, this would allow a simulation of up to 3568/248 or 14 aircraft in addition to the two missiles.

Consider next the simultaneous simulation of hel—icopters and two missiles. In Section 4 we saw that the AD 100 frame time per helicopter when using the blade element method is 1 millisecond, whereas the require—ment for real time is again 8 milliseconds. Now the 3568 microseconds available per 8 millisecond frame can be used to simulate three helicopters in addition to the two missiles, all with a single AD 100.

In the above two illustrations it should be noted that the tactical missiles have a flight time of only a few seconds. When the simulated flight of a given missile has terminated, the simulation of another missile can be initiated. Thus the capability of simulating multiple aircraft as well as two missiles simultaneously in no way precludes the overall succesive simulation of many more missiles in a prolonged engagement.

6. Simulation of Airframes plus Jet Engines

Real—time high fidelity dynamic simulations of jet engines are used extensively for the design and test—ing of engine controllers. In high performance aircraft the engine dynamics can interact significantly with the airframe dynamics. This is especially true in helicop—ters, where engine interaction with the rotor often forces redesign of the engine control system. It is therefore desirable to be able to combine comprehen—sive simulations of airframe and engines in real time.

The AD 100 has been used extensively to simulate turbofan engines using sophisticated high—fidelity models which include compressor maps, turbine maps, etc.. Typical execution time for one integration frame for a high—bypasss turbofan is 110 microseconds. The required integration step size for a real—time sim—ulation of the same engine is 1 millisecond. If we again use 8 milliseconds as the step size for the airframe, this suggests that we should take 8 integration steps in the engine simulation for each step in the airframe simulation. If we assume two engines per airframe, three airframes would require $2(3)(110) = 660$ mi—croseconds per integration step in simulating the engines, or $8(660) = 5280$ microseconds per 8 milli—second frame for the airframes. This leaves 2720 milliseconds for simultaneous simulation of three air—frames, which at 250 microseconds per airframe presents no problem for the AD 100.

7. Conclusions

We have seen how computers like the AD 100 with architecture optimized for the solution of scalar—type ordinary differential equations are capable of simu—lating many airframes simultaneously in real time. In particular we have shown that 30 or more six—degree—of—freedom comprehensive simulations of conven—tional aircraft, including flight control and avionics systems, and be simulated simultaneously in real time.
We have also shown that up to 8 helicopters can be simulated in real time using the blade element method. Engineering level six—degre—of—freedom missiles can also be simulated in real time simultaneously with the airframe simulations. Finally, comprehensive jet engine dynamic simulations can be combined with up to three real—time airframe simulations, all on a single AD 100 computer.

8. References

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