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ABSTRACT

A flight simulator was recently developed at the University of Missouri–Rolla for a single engine aircraft. The need soon arose for a higher performance aircraft. After exploring several possibilities, a Learjet Model 24D was chosen to include the high performance aircraft.

The purpose of this project was to develop a model for the Learjet 24D. This was accomplished by examining the computer code previously written and determining the changes needed. The code for the simulation is located in various subroutines. Each subroutine was analyzed to determine if changes needed to be made. When a modification was needed, appropriate methods were used to determine the parameter. When this process was complete, the aircraft was flown on the simulator. Each flight was used to analyze the performance of the aircraft and then compared to the Operating Manual for the Learjet. After evaluating the performance of the flights, changes were again made to meet the performance of the Learjet. Several assumptions were made in this process with the end justification being the performance of the simulation. The completed Learjet model has produced a simulation which flies much like the actual aircraft.

This report will outline the steps employed to develop the Learjet model, the assumptions made, and the results of evaluating the model performance.

1. Introduction

Flight Simulation is becoming an increasing alternative to the high cost of aircraft operational costs, and is being used by industry to train new pilots, refresh veteran pilots, and train emergency techniques that are too dangerous to perform in actual operations. For university students, the flight simulator can be used as an inexpensive and safe way to teach the basic principles of piloting an aircraft, as well as to reinforce principles of performance and stability & control learned in the classroom. Based on these motivations a set of computer programs, written in Fortran and run on an Apollo DN10000VS computer were developed. The Apollo computer is capable of operating at speeds which allow the simulation to occur in real time. The simulator setup is designed to receive input from the pilot through a keyboard, mouse, and joystick and display graphics output to the user via a 10 foot projection screen and a computer terminal. The computer terminal is used to display a basic instrument cluster consisting of five instruments and sixteen text outputs. The instruments include an airspeed indicator, an artificial horizon, a clock, a vertical compass, and a vertical speed indicator. The text instruments are capable of being changed to read practically anything the pilot desires to see.

The flight simulator was originally developed modeling a single engine propeller driven Cessna 210. The need for a high performance aircraft was considered and found to be an appropriate addition to the simulator. Work began in January 1990 on the modeling of a small business jet. After looking at several aircraft, a Learjet Model 24D was chosen to fulfill the role.

2. Simulation Process

As shown in the block diagram of Figure 1, the simulation begins by accessing shared memory. Shared memory access prepares the shared memory between the aircraft and graphics programs for parallel processing. The next step in the simulation is initializing the timing mechanism, which defines the rate at which the simulation is ran. Aero_Load and Atmos_Load subroutines initialize variables needed in the simulation. Aero_Load loads the lift, drag, and moment data tables, and Atmos_Load loads the standard atmosphere tables. Table_prep prepares these tables for the simulator to use.

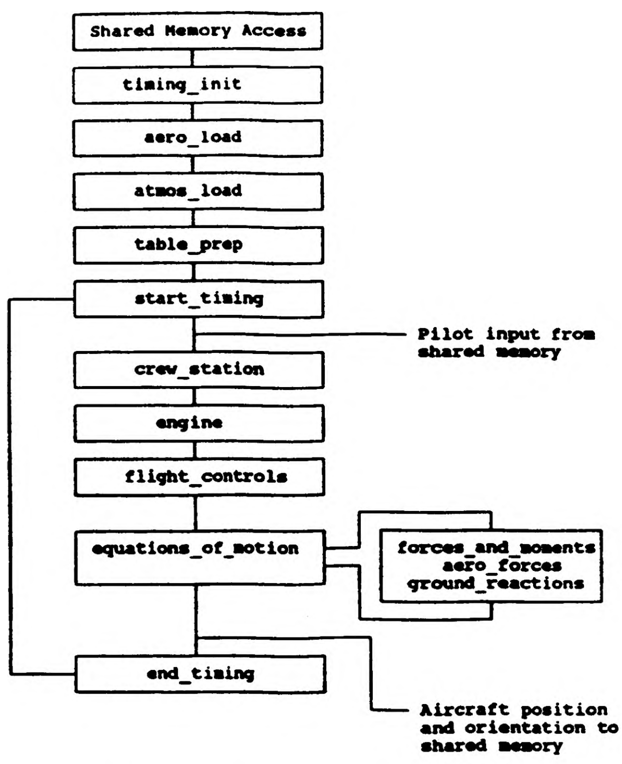

Figure 1. Simulation Process Flowchart

The real–time portion of the simulation is begun with the start_timing block. A real-time process is one in which the execution time of the computer is synchronized with the actual time of the system being modeled. If the computer calculates all the information needed it must wait until the next pass is required. This process is accomplished in the timing mechanism of the program.

The pilot inputs generated by the stick, mouse, and keyboard are supplied to the shared memory. According to this pilot input data, the subroutine Crew_station then calculates stick, throttle, rudder pedal, and flap switch position. The engine subroutine is then called to calculate the engine thrust based on throttle position and altitude. The flight controls subroutine then calculates the aileron, rudder, elevator, and flap positions. The next subroutine called is equations of motion, which then calls Ac_forces_and_moments to determine the total forces and moments acting on the aircraft. This subroutine then calls the aero subroutine to calculate the aerodynamic forces and moments. Ac_forces_and_moments also calls the ground reactions subroutine which calculates the forces due to inertia, friction, braking, and nose wheel steering while the aircraft is on the ground. Once these subroutines have been called, the equations of motion subroutine integrates the angular and linear acceleration equations once to yield linear and angular velocities and again to yield positions and orientations. The velocities and orientations are then sent to shared memory for use by the graphics to update the visual displays. End timing determines whether it is time to begin a new pass through the simulation. This process is then repeated until the pilot elects to stop the simulation.

This brief review of the flight simulation should be enough to give a basic understanding of how the simulator operates. It is not the purpose of this report to outline the entire operation of the flight simulator. For additional details, the reader may refer to [1].

3. The Learjet Model 24D

The Learjet is designed to carry 8–10 people, cruise at Mach numbers around 0.8, Velocities around 470 knots, and at altitudes up to 45,000 feet. There is a single low wing which is swept back to allow operation at high speeds. The aircraft is equipped with two engines mounted on the aft fuselage, each capable of producing 2,950 pounds of thrust at sea level. The total amount of fuel carried is approximately 5,590 pounds. With full fuel the aircraft has a maximum takeoff weight of 13,000 pounds. The jet incorporates conventional control surfaces: ailerons, elevator, and a rudder. Flaps can be used to aid in takeoff and landing.

4. Modifications

4.1 Stability and Control Derivatives

Stability derivatives are changes in aerodynamic forces or moments due to motion about one of the aircraft axes. Several of the derivatives for this simulation were obtained from

[2], many of these are located in a namelist called s_and_c.nml in the Learjet_data directory. For this simulation many of the stability derivatives were assumed to be constant over the range of speeds and weights the aircraft will operate. This assumption is justified in part by the fact that many of the derivatives change very little throughout the flight envelope. The derivatives, which do change, were taken as the values at the high speed end of the flight envelope. This was done in part because this is where the majority of the simulation time will be spent. Normally the aircraft will takeoff then cruise at speeds where the derivatives are correct. Another reason for choosing the high speed derivatives was the handling qualities of the aircraft. At high speeds the plane became hard to control if the low speed values were used.

Some of the derivatives are located in the aero subroutine. These derivatives are changed through each pass of the simulation. One major difference in the Learjet model and the Cessna model is the coefficient of lift. The Cessna model uses table lookups to determine this value, but the Learjet model calculates the value. All equations for modifications came from either [3] or [4].

Another difference between the two models is the moment curve slope. The slope for this simulation is allowed to change with a change in the center of gravity location. At stall, a decrease in lift should cause a pitching down of the nose. Since the lift and moments are calculated separately, the decrease in lift near stall did not directly cause a nose down pitching moment. To overcome this problem a new variable, cm_stall was selected. Below stall, cm_stall equals zero, but at stall and above, cm_stall takes on a value to cause the needed moment to pitch the nose down.

4.2 Control Surfaces

The Learjet has a movable horizontal stabilizer which is used to trim the plane. The input for this horizontal stabilizer deflection is located in the Cst.sub subroutine. The movable horizontal stabilizer allows the pilot to fly the simulator without constantly holding the stick forward, which is what would have to be done when flying at high speed. The trim tab was developed for the Learjet, but was also installed on the Cessna model. The keys to activate the trim tab are: 'u' for nose down, 'j' to zero the tab, and 'm' for nose up. The variable introduced to accomplish this task was called delta_tab. The deflection of delta_tab is limited to five degrees up and down.

The actual control surface deflections are calculated in the flight controls subroutine, Fc.sub. The Learjet has different ranges of control surface deflections than the Cessna so all these had to be changed. The deflections are: aileron 18 degrees, elevator 15 degrees, and rudder 30 degrees, these deflections were obtained from [6]. The flap operating speeds are also located in this subroutine. The flaps are extended by two settings. The maximum speed to extend the flaps to eight degrees is 190 knots, the maximum speed to extend the flaps to 40 degrees is 153 knots.

To ease the pilot in controlling the aircraft with the small joystick at high speeds, the elevator and aileron deflections are scaled above 200 knots by the ratio of the aircraft velocity to 200 knots. A similar equation is used for delta_a, the aileron deflection.

4.3 Forces and Moments

Forces and moments are dealt with in f_m.sub and ground.sub. F_m.sub contains the equations that compute the forces and moments while the aircraft is in the air. Two values that had to be changed in this subroutine were the maximum structural g's the aircraft could withstand. The values from [5] are +4.5 to -1.5 g's. These values were not used in the simulation due to the joystick. The joystick is so sensitive that at high speeds with the low values of g limitation the wings were to easily torn off. For this reason slightly higher values of +5 to -2 were chosen.

Several other values that had to be changed in this subroutine dealt with geometric distances involving the landing gear. A drawing of the meaning of the geometric data can be found in [1]. The geometric distances for the Learjet were obtained from [6]. Some of these distances include the x, y, and z positions of the gear fully retracted and fully extended. These distances are needed to perform the simulation of the gear being raised and lowered. The gear in the Cessna move in two motions, first moving in, then back to stow in the fuselage. The gear on the Learjet only move up into the wings so this process had to be changed.

The ground subroutine contains the forces acting on the aircraft when the aircraft is on the ground. Several variables in this subroutine had to be modified. There are some geometric distances in this subroutine as well as f_m.sub, which had to be changed. The damping coefficients and the spring constants of the landing gear had to be modified. Two values of each constant were used, one for small displacements of the struts and one for larger displacements. These values were determined by trial and error. The values had to be larger for this aircraft, but care had to be taken in raising them.

4.4 Additional Modifications

The weight and balance subroutine contains information about the loading of the aircraft and the moments of inertia. The aircraft for this simulation is loaded with 4 people, 414 gallons of fuel, and 50 pounds of baggage. This brings the takeoff weight to 11000 pounds, which would be a typical configuration for this aircraft. Provisions have been made to easily modify the weight by simply choosing a different passenger loading. The center of gravity is also calculated in this subroutine. The ac_moment needed for the center of gravity calculation is acquired by adding the weights of different components multiplied by there moment arm. The weights of the components as well as the moment arms are listed in [5]. The moments of inertia were obtained from [2].

The engine subroutine contains the equation for thrust. The method used for determining thrust assumes that the thrust of the engines varies directly with air density. This subroutine was changed to reflect the Learjets more powerful engines.

The instrument panel for a Learjet is much different than a Cessna's, so two instruments were changed. The airspeed indicator for the Cessna went to 200 knots, the maximum speed of the Learjet is much faster, so the airspeed was increased to 600 knots. The code for the airspeed indicator is located in the instruments directory in the file airspeed.ftn. Similar adjustments for the vertical speed indicator were also performed. The Cessna vertical speed indicator range was between -2000 feet per minute and 2000 feet per minute, this was changed to ± 6000 feet per minute. All the other instruments were compatible with the Learjet.

Another modification made to the simulator was not specific to the Learjet model. A new scene was created. For details on how to create a new scene, see [7]. The scene created was a night scene, which included a lighted runway and lighted cities.

5. Results

The purpose of this project was to create a model of the Learjet for the existing simulator at UMR. The justification for all the changes made, rested in the final performance of the simulation. The main analysis for the results came from flying the aircraft and checking the performance against the Operating Handbook, [5]. Several phases of flight were evaluated in great detail. These were takeoff, cruise, landing, and flight at slow speeds, including the stall. Final flight tests indicated the simulation performs very close to the actual aircraft. A table of comparisons between actual and simulation performance numbers appears below.

Table I
Results

Performance Parameters	Flight Manual	Simulation Results
takeoff speed (knots)	115	118
takeoff ground roll (feet)	2250	2050
maximum Mach number	0.82	0.82
landing ground roll (feet)	1500	1450
stall speed, flaps at 0° (knots)	107.0	110.0
stall speed, flaps at 8° (knots)	95.0	93.0
stall speed, flaps at 40° (knots)	86.0	83.0
climb gradient at 10000 feet (%)	3.2	3.3
climb gradient at 20000 feet (%)	0.5	0.55

6. Conclusions and Recommendations

The purpose of this project was to modify existing code to perform similar to a high performance aircraft, the aircraft chosen was the Learjet Model 24D. Steps were taken to analyze and determine the changes needed in the original code, then obtain new information for the simulator by various methods. The performance of the aircraft was then compared with the Operating Manual. Once the performance tests were completed, changes were made to correct the simulation to more closely match the performance numbers in the Manual. Final flight tests indicate a very good simulation of a high performance aircraft has been developed. In the future, this simulation will be used with the other models currently in the simulator to benefit all Aerospace Engineering students at the University of Missouri–Rolla.

The simulation could be greatly improved with the addition of a cockpit and real controls. The joystick does not provide the feel of an actual control stick. The rudder controls are currently on the keyboard, which does not allow the pilot of feeling the position of the rudder. With the addition of a cockpit, a q–feel system could be incorporated into the model. Q–feel is a system by which the velocity of the aircraft is felt in the controls. As it is now, the pilot can move the stick as easily at 500 knots as can be done at 100 knots, which is not the case in an aircraft. The cockpit would also give more of an impression of flying, than is currently felt with the simulation.

One of the most important uses for the simulator could be the simulation of aircraft being designed in the senior design class. With the aid of this paper and reference [8] it should be a fairly simple task to modify the code to fit a generic model. This would benefit the design students, and offer something that very few, if any other university could offer a senior design student.

Acknowledgements

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