01 Apr 1991

Development of a Large Commercial Transport Model for a Real-Time Digital Flight Simulator

John Francis Winkler

Recommended Citation

Winkler, John Francis, "Development of a Large Commercial Transport Model for a Real-Time Digital Flight Simulator" (1991). *Opportunities for Undergraduate Research Experience Program (OURE)*. 124.
https://scholarsmine.mst.edu/oure/124

DEVELOPMENT OF A LARGE COMMERCIAL TRANSPORT MODEL FOR A REAL-TIME DIGITAL FLIGHT SIMULATOR

John Francis Winkler

Abstract

In order to test the adaptability of the University of Missouri-Rolla's flight simulator to different types of aircraft, a basic mathematical model of a large commercial transport aircraft is developed. The original aircraft model is based on the Cessna 210, and in order to accommodate the drastic differences between the Cessna 210 and the Boeing 747, many changes are made to the simulation code. The aircraft geometric data, stability and control derivatives, and weights data are altered to match those of the 747. Changes are made within the various subroutines to include thrust reversal, spoilers, and a variable incidence horizontal stabilizer. In order to simplify the model, various modifications to the 747's lift, moment, and drag data are made based on an order of magnitude analysis.

This paper gives an overview of the procedure used in creating the new mathematical model and the various problems encountered during the model's implementation. The various assumptions that are made to simplify the modeling of the transport aircraft and the reasoning behind each assumption are discussed in detail. Finally, the flight characteristics of the developed model are compared with those of a real-world aircraft to determine the validity of the model.

It appears from flight testing that the final model does indeed offer the flight characteristics of a large transport aircraft.

Introduction

Recent rises in fuel costs make the need for practical and realistic flight simulation extremely important. With a well-designed flight simulator, industry can train pilots on the ground, thereby saving flight time and fuel. An engineer can model a slight configuration change on an aircraft and immediately see its effects on the flight characteristics. Moreover, by changing the magnitude of the stability and control derivatives, one may be able to see the difference in the handling of the aircraft. Large aerospace companies are currently using advanced flight simulators to optimize the flight characteristics of an aircraft in the initial design stage. In this sense, they may eliminate a large number of problems before the aircraft is ever built. Test pilots are now finding that the test aircraft are flying very close to the simulator model on which they were trained.

The University of Missouri-Rolla flight simulator project was started in 1987 by graduate student Michael Sinnett, and a mathematical model of a Cessna 210 general aviation type aircraft was completed in 1989. The computer code for the simulator is written in FORTRAN and runs on an Apollo 10000vs workstation. The program itself is divided into two major routines: the math model and the graphics model. Each model runs on a different central processing unit, and they communicate with one another through a shared memory location. An instruments program runs interactively with the math model and graphics model on an Apollo 4500 workstation. The graphics are displayed on a 10' diagonal glass screen with an overhead rear projector. At this time the pilot input is read in through the use of a joystick, mouse, and keyboard.

Since the completion of the Cessna model in 1989, new graphic scenes have been added and a weather model containing wind, turbulence, and microbursts was developed to enhance the realism of the simulation.[6] Furthermore, an interest has come about in being able to develop mathematical models for different types of aircraft.

The purpose of this project was to develop a mathematical model of a large commercial transport type aircraft for the digital flight simulator at the University of Missouri-Rolla. The large transport aircraft model is based on the Boeing 747, and it is clearly apparent that this aircraft is much different and much more complex than the Cessna 210. Many changes had to be made to the Cessna model to accommodate the drastic differences between the two aircraft.

This report discusses the differences between the Cessna 210 and the Boeing 747 and the changes that have to be made to model the 747 properly, and it gives a very basic overview of the various problems encountered during the model's implementation. The various assumptions that are made to simplify the modeling of the transport aircraft and the reasoning behind each assumption are discussed in detail. Finally, the flight characteristics of the developed model are compared with those of a real-world aircraft to determine the validity of the model.

Problem Formulation

As it was previously mentioned, UMR's flight simulator was originally designed to model a Cessna 210 general aviation aircraft. The Cessna is a fairly simple plane driven by a single Propeller engine, and it contains only the basic required control surfaces (Figure 1). Ailerons are used for roll control; simple flaps are used to augment the lift, and a basic elevator and rudder are used for pitch and yaw control, respectively. Moreover, this aircraft flies in the low subsonic flight regime where lift, drag, and moment calculations are relatively simple to perform.

The Boeing 747, however, is a very large and complicated jet aircraft (See Figure 2). It is Propelled by 4 turbofan engines, and it contains numerous control surfaces. Outboard ailerons are used for low-speed roll control while inboard ailerons are used for high-speed roll control. The flap system on the 747 is very complicated, containing a combination of leading edge Krueger flaps and triple-slotted trailing edge flaps which can be used together to augment the lift. This larger aircraft also possesses inboard and outboard elevators for pitch control along with a split rudder for yaw control at different speeds. The flight envelope of the 747 is much greater, as it may fly at altitudes up to 45000 feet above sea level and at speeds around 800 nautical miles per hour. Its maximum cruise speed lies within the transonic regime. and therefore supersonic pockets may form on the wings, complicating lift, drag, and moment calculations.

Although the simulator was originally written in a fairly general format, it is easy to see that several changes and additions will have to be made to model the more complex Boeing 747 aircraft. It should be noted here that the original intent of this project was to model a large commercial transport based on the 747, and hence the final developed model was not intended to behave exactly like the Boeing aircraft. Nevertheless. many changes still had to be made in order to develop a simplified generic commercial aircraft.

Mmodeling Data and Table Lookups

The original Cessna model only has a few different table lookups due to the lack of a large amount of information, as it is very difficult to get companies to release detailed and accurate information pertaining to the lift, drag, and moments acting on their aircraft. Therefore the Cessna model has only four one-dimensional lookups to determine the atmospheric temperature based on altitude. the atmospheric density based on altitude, the change in the zero-lift pitching moment due to flap deflection, and the ground effect on drag based on

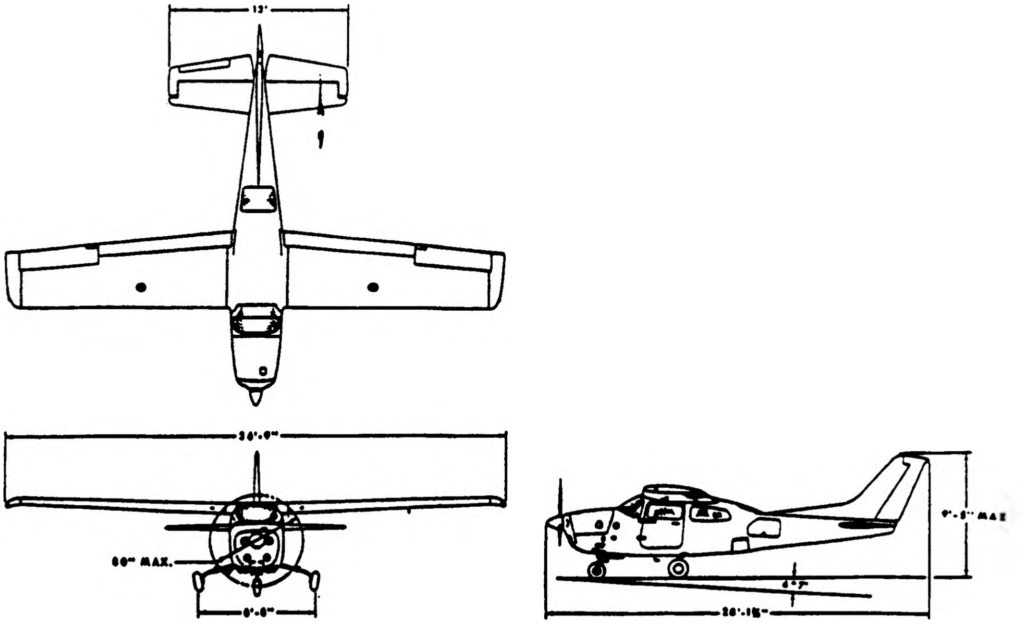

Figure 1 - Cessna 210

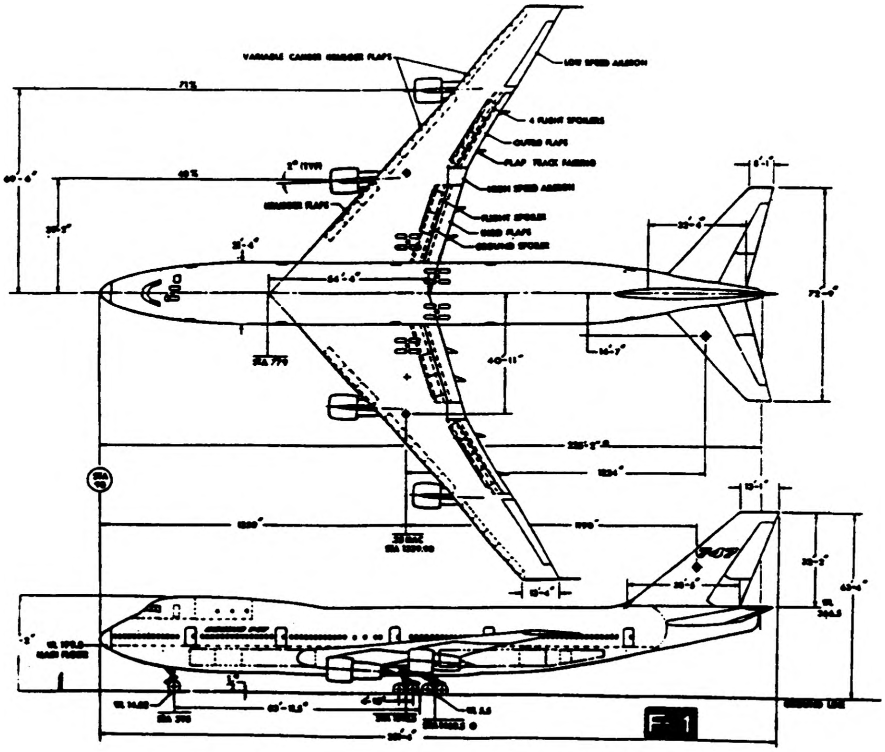

Figure 2 - Boeing 747

the height above the ground. It also has two three-dimensional lookups to determine the lift coefficient and drag coefficient based on angle of attack, flap deflection, and Mach number.

Lack of data was not a problem for the commercial transport model, as Boeing[1] provided the same data that its engineers initially used to model the 747 in a NASA simulator. Lift, drag, moment, and ground effect data are all given in graphical form. This graphical data was employed to generate tables that can be utilized by the computer code. The procedure for creating tables of data from graphical data was used to create tables for the lift, drag, and moment coefficients as functions of angle of attack and Mach number and as functions of angle of attack and flap deflection.

All in all. the commercial transport model contains the original one dimensional lookups to determine the atmospheric temperature and pressure based on altitude, and 10 two-dimensional lookups to determine the values of the above variables. This extra data involved setting up new variable arrays and adding them to the common blocks in the subroutines. The data tables and new variable arrays can be seen in the Subroutine Aero-load. found in Winkler.[11]

Aircraft Geometry Changes

The areas and dimensions of the aircraft were taken from Boeing,[2] stored in a data file, and read into a menu structure. These values may be changed within the menu substructure to see the effect on the flight characteristics of the aircraft, but the default values may always be restored from the data file.

Weight Properties

Aircraft Weight and Balance

The maximum takeoff weight for a Boeing 747 aircraft varies anywhere from 620000 lb to 820000 lb depending on the model and configuration (See Janes[9]). A value of 660000 lb was chosen for simulation use. In reality, this weight would depend on the number of passengers, the amount of payload, and the amount of fuel. Moreover, over a long range flight, the weight of the aircraft would vary as fuel is used up.

For simulator purposes, however, the weight is assumed to remain constant throughout the flight time. One will normally not be flying the simulator for a long period of time that will cause the weight to change substantially. For short flight times on the order of an hour or so, this kind of assumption appears to be relatively valid.

According to Boeing,[1] the center of gravity (cg) may vary anywhere from about 14% of the mean aerodynamic chord to about 33% of the mean aerodynamic chord. The center of gravity will depend on the number and positioning of passengers, the amount and location of payload, and the amount and location of fuel.

The simulation of the commercial aircraft assumes the cg to remain constant at 25% of the mean aerodynamic chord, which is 1250 inches from the nose of the aircraft (See Boeing[2]). Again, one will probably not be flying the simulator for a long period of time. and hence the weight and location of the fuel will not change drastically enough to warrant changing the aircraft cg. Moreover, it can be assumed with reasonable accuracy that the majority of the passengers will remain in their seats during the flight and hence the cg will remain relatively constant.

Aircraft Moments of Inertia

The aircraft moments of inertia are required by the simulation to integrate the equations of motion. The values of Ixx, Iyy, Izz, and Ixz will change with the weight distribution of the aircraft. For the Cessna model, it was a valid assumption to make Ixz = 0, but because of size of the 747 and the nonsymmetrical weight distribution in its xz plane, this is not true for the 747. Values of the moments of inertia for landing gear up and landing gear down were obtained from Roskam.[7].

Stability and Control Derivatives

The original Cessna model assumes that the stability and control derivatives remain constant throughout the flight envelope. For the low altitude and low speed envelope of the Cessna 210, this is a reasonable assumption. The 747, however, has a much larger flight envelope; it can cruise at altitudes up to 45000 feet and Mach numbers up to 0.92. Because many of the basic stability and control derivatives are functions of both Mach number and altitude, some way had to be devised to take the compressibility effects into account.

The Cessna 210 is equipped with one set of ailerons, one elevator, and one rudder. Hence, the Cessna model is only set up to model this simple case. The 747, however, is equipped with inboard and outboard ailerons, inboard and outboard elevators, and a split rudder. This is to insure that the aircraft will have good control characteristics over its entire flight regime. At lower speeds, the outboard ailerons are used to roll the aircraft, and at high speeds, the inboard ailerons are used for roll control. The elevators and split rudder are used likewise.

These multiple control surfaces cause their respective control derivatives to vary substantially with velocity. The values of the important stability and control derivatives were obtained from Roskam[7] for three different flight conditions and can be found in Winkler.[11] Each flight condition pertains to a specific velocity. In order to include the effect of these multiple control surfaces. an expression is set up to vary the magnitude of the aileron, elevator, and rudder control derivatives with velocity as per each flight condition. Because the control derivative for the aileron, elevator, and rudder varies automatically with velocity, it is in effect modeling both the inboard and outboard control surfaces. Hence. the single control derivative for the ailerons can be thought of as an average of the control derivatives of the inboard and outboard ailerons, and this removes the requirement of having two separate derivatives – one for the inboard ailerons and one for the outboard ailerons. The same analysis applies to the split rudder and the inboard and outboard elevators.

Aerodynamic Forces and Moments

The original equations for the total lift, drag, and pitching moment coefficients in the Cessna model had to be altered for the commercial transport model because of the different type of data that was obtained from Boeing.[1] The Boeing data was very detailed, and in order to simplify the model, the higher order terms for each force and moment coefficient were thrown out. Because the purpose of this project was to develop a basic model of a commercial transport, neglecting the higher order terms seems to be reasonable. A detailed analysis of the changes made in the calculation of each coefficient is given in Winkler.[11].

Landing Gear

The original Cessna model uses a simple landing gear setup with one nose gear and two main gear. When retracted, the main gear rotates inward and then backward, and the nose gear rotates forward.

Only the nose gear and the inside back main gear were modeled for the commercial transport aircraft. This simplification was made in order to keep from having to rewrite the entire Ground Subroutine. The aircraft model will still take off and land without problems, and such a simplification does not affect the flight characteristics.

The simulation code was altered slightly to change the rotation of the gear. The nose gear on the 747 rotates backward during retraction while the inside main gear rotate forward. The spring constants and damping coefficients for each set of gear were increased until the gear provided a reasonable response during landing and takeoff (See Winkler[11]).

VISUAL OUTPUT

The cockpit of the original Cessna model is set about 3 feet above the ground; the Boeing 747 cockpit, however, is about 27 feet above the ground, and therefore the visual output had to be modified. This was accomplished by adding an increment of height to the altitude which is sent to the Graphics Model.

The instruments on the original Cessna model have maximum values that apply to that particular aircraft. The airspeed indicator has a maximum value of 200 knots, while the rate of climb indicator has a maximum value of 200 feet per minute. Since the Boeing 747 can fly at speeds over 500 knots (See Janes[9]) and climb at a maximum rate of 16000 feet per minute (See Boeing[1]), the maximum value on the airspeed indicator was therefore changed to 600 knots, and the maximum/minimum values on the rate of climb indicator were changed to 16000 feet per minute.

The original simulation world has several small aviation airports with 2000 foot runways. These runways can easily handle the small Cessna for takeoff and landings, but they realistically cannot handle an aircraft the size of the 747. According to Janes,[9] a fully loaded 747 may take just over 10000 feet to take off and clear a 36 foot obstacle. In order to compensate for this takeoff distance, a 10000 foot runway was created and placed in a large commercial airport.

Flight Controls

It was desired to employ spoilers, thrust reversal, and a variable incidence stabilizer on the commercial transport model to simulate the 747 more accurately. Changes are therefore made in the Crew Station Subroutine so that a stabilizer switch can be set, thrust reversal can be turned on or off, and spoilers can be deflected or retracted.

Additional code was added to the flight Controls Subroutine so that it can calculate the stabilizer position based on the information calculated in the modified Crew Station Subroutine.

The subroutine checks to see if the flaps are deflected past their maximum value for a given airspeed, and if they are, it automatically retracts them to the next lower setting. The maximum speed for any flap deflection can be found in TWA.[3] The Flight Controls Subroutine also keeps the control surfaces from deflecting past their maximum deflections. The maximum values of deflection for the rudder, aileron, and elevator for the 747 were obtained from Boeing[1] and can be found in Winkler,[11] along with the previously mentioned subroutines.

Engine Routine

The original engine model is a very simple subroutine which calculates thrust based on throttle position and density. At full throttle setting and sea level, the thrust calculated will basically be equal to the static sea level thrust of the engine. As altitude increases, the thrust of the engine is decreased by the density ratio factor. For the commercial transport model, a check was added to see if reverse thrust is being employed to slow the aircraft during landing. If so, the sign of the thrust is made negative.

The engine options for the Boeing 747 are numerous, and Janes[9] lists several different types along with their maximum static sea level thrust. The Rolls-Royce RB211-524D4 engine with a static sea level thrust of 53110 pounds was chosen for the simulation. Hence, with four of these engines, the simulation model is able to develop 212440 pounds of thrust at sea level.

Performance Evaluation

There is really no exact method for evaluating the performance of the commercial transport model on the simulator. It was easy to get a pilot's opinion on the simulator's realism for the Cessna model, as general aviation pilots are numerous and easy to find. Boeing 747 pilots, on the other hand, are too few and extremely hard to find, and there were none available to test the flight characteristics of the simulator model. The model does seem to behave like a large aircraft would, as it appears to react slower than the corresponding Cessna model. The following performance of characteristics of the commercial transport were evaluated and compared with the corresponding characteristics of the Boeing 747.

- **Takeoff Distance** - The takeoff distance obviously varies between the different models of the 747, and it depends immensely on the takeoff weight. According to Janes,[9] the 747-100B takes 10000 feet to take off and clear a 35 ft high obstacle, while the 747-200 will take as much as 10,800 ft to take off and clear a 35 ft high obstacle, depending on the version. The commercial transport model, with the horizontal stabilizer deflected downward, will lift off before the end of the 10.000 ft runway. The exact ground roll distance depends on the deflection of the stabilizer. The aircraft climbs rather quickly after takeoff, and it therefore will clear a 35 ft high obstacle right around 10000 ft.

- **Maximum level speed** - The maximum level speed for the Boeing 747-100B at an altitude of 80,000 ft above sea level is given by Janes[9] as 525 knots, and the maximum level speed for the 747-200 ranges from 623 knots to 630 knots, depending on the version. The commercial transport model has shown its capability of reaching a level speed of right around 520 knots at a 30,000 ft altitude.

Concluding Remarks

A simplified model based on Boeing 747 that will give the flight characteristics of a large commercial transport aircraft was developed for the University of Missouri-Rolla flight simulator. This model met the performance characteristics of the 747 with reasonable accuracy.

With this new model, students in aerospace engineering should be able to get a better feeling of how a large commercial transport actually flies through "hands on experience." By using the menu structure, they can change various stability and control derivatives and see what happens to the flight characteristics of the aircraft. Through altering the flight conditions, the students ought to be able to see how varying the altitude, velocity, and weather conditions affect the aircraft's performance. Moreover, with this new model, students could learn more about how and why wind shear has caused various airliner accidents during takeoff and landing.

In the future, if one wanted to change the model from a generic transport model to a more exact representation of the 747, several things could be done. The engine subroutine could be rewritten to calculate thrust as a function of throttle position, Mach number, and altitude. A new subroutine could be written that would calculate the stability derivatives as a function of Mach number and altitude to take compressibility into account, thus bypassing the menu structure. Lastly, one could include the higher order terms that were neglected in the various coefficient calculations. The task of obtaining an exact model of the 747 would take a long time and a lot of hard work, but it may be well worth attempting.

Flight simulation is becoming more and more important as the rising fuel and maintenance costs make actual flight testing of aircraft extremely expensive. The more work that can be accomplished through simulation, the larger the savings will be to industry. The development of flight simulation on the university level is therefore extremely important, as new research may bring forth many advances in the modeling of various aircraft. The advancement and continuation of flight simulation research will clearly benefit not only industry and education, but the entire scientific community.

Acknowledgments

The author would like to thank Doctors Kamran Rohkaz and Fathi Finaish, and graduate student Marcus Adkins for their continued support throughout the project. The grant from OURE is greatly appreciated.

References

1. Boeing. The Simulation of Jumbo Jet Transport Aircraft. Volume 2: Modeling Data. Boeing Company. Wichita. Kansas. Sep 70.

2. Boeing. General Arrangement Model 747P Passenger. Boeing Drawing J5B00090. Revision C. Boeing Company, Renton, Washington, Oct. 67.

3. TWA 747 FLIGHT HANDBOOK. TRANS WORLD AIRLINES. Kansas City. Missouri.

4. Sinnett. M. "The Development of a Real-Time Digital Flight Simulator on the Apollo DN10000VS". M.S. Thesis, University of Missouri-Rolla, 1990.

5. Adkins. M. "Development of a Turbulent Atmospheric Model For An Experimental Flight Simulator." M.S. Thesis. University of Missouri-Rolla, 1990.

6. Sinnett, M. "Notes on UMR's Flight Simulation Facility." Unpublished notes, University of Missouri-Rolla, 1990.

7. Roskam, J. Airplane Flight Dynamics and Automatic Flight Controls. Roskam Aviation and Engineering Corporation. Ottawa. Kansas.

8. Etkin, B. Dynamics of Flight - Stability and Control. New York: John Wiley and Sons, Inc., 1982.

9. Janes. Jane's All The World's Aircraft. Jane's Information Group Limited. Sentinel House, United Kingdom. 1990.

10. Anderson, J. Introduction To Flight. New York: McGraw-Hill Book Company, 1989.

11. Winkler, J. "Development of a Flight Simulation Model for a Large Commercial Transport Aircraft." Department of Mechanical and Aerospace Engineering and Engineering Mechanics, University of Missouri-Rolla, 1991.