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A STUDY OF THE COMPUTER SECTION OF FLIGHT SIMULATORS

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1. INTRODUCTION

1:1 General

This report summarizes the results of a fifteen-month study of the computer section of training-type flight simulators. A previous report[1] described the results of the first nine months of the study program. On pages 3 and 4 of the previous report are given a number of specific recommendations growing out of the original study program. Our work since then has led us to emphasize further these recommendations, which for the convenience of the reader, are included again in the present report on pages 11-13 In addition, several recommendations with respect to specifications for dynamic performance of the trainer have been added in the present report (see page 14).

In order to help develop realistic dynamic specifications for flight-trainer performance a number of studies of the flight-equations of the F-86D and B-47 aircraft have been carried out. Specifically, computer solutions of both the lateral and longitudinal linearized flight equations of the F-86D have been obtained from a high-accuracy dc electronic differential analyzer.[2, 3] These solutions have been compared with flight-test data and results are summarized in a technical report.[4] In addition both the F-86D and B -47 longitudinal equations, including all important nonlinearities, have been simulated on the same dc equipment. Results of these tests are presented in another technical report.[5]

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[1] Numbered superscripts refer to similarly numbered references in the bibliography at the end of this report.

1.2 Scope of the Study Program

The following brief description of the scope of the study program is similar to the description in the first Final Report, and is included here for continuity.

Training-type flight simulators consist of a complete mock-up of the aircraft cockpit, a trouble console which allows the instructor to introduce various simulated malfunctions, and a computer which solves the aircraft flight equations and displays the results on the cockpit instruments. The present Air Force simulators are exhibiting excellent utility in training crews of bomber, fighter, and transport aircraft. Even more extensive use of this type of training device is anticipated in the future. However, the present simulators do require considerable maintenance, large amounts of electrical power, and often exhibit inadequate dynamic characteristics. With a view to improving the above difficulties by changing the methods of electronic computation or possibly by some standardization in the computer section, the present study program was initiated.

This program has fallen roughly into four parts; (1) a study of methods of computation used by the simulator manufacturers and by the computer industry in general; (2) a study of the flight equations used by the simulator manufacturers, the airframe manufacturers, and the guided-missile industry; (3) a study of the performance of the trainers at the various bases, including engineering tests, study of maintenance problems, pilot complaints, etc; (4) a study of the dynamic performance capabilities of computer-solutions of F-86D and B-47 aircraft and recommendations for dynamic specifications on flight-trainer performance.

Parts (1), (2), and (3) were summarized in the earlier final report[1], while part (4) is summarized in the two technical reports[4, 5] and in the present report.

2. THE LINEARIZED FLIGHT EQUATIONS

2.1 Summary of the Complete Flight Equations

As explained in the previous final report, the basic computational problem in the computer section of flight simulators involves the solution of equations which describe the position and angular orientation in space of a rigid body, namely the aircraft. These equations have as inputs the motion of the control stick, rudder pedals, engine controls, and other auxiliary devices, while the computed outputs such as airspeed, heading, attitude, rate of turn, altitude, engine rpm,, must be displayed on the cockpit instruments.

Essentially there are six dynamic equations which must be solved. These are the equations of motion representing translation along three axes and rotation about three axes. Each of the three equations for translation has input forces along its particular axis, forces which result from aerodynamic, propulsive, or gravity terms. The forces in turn cause accelerations along each of the axes, and these accelerations must be integrated to provide the velocities along the translational axes. In the same way each of the three equations for rotation has input moments about its particular axis. These moments cause angular accelerations about the axes, accelerations which must be integrated to obtain the angular velocities. By performing certain trigonometric operations on the angular velocities and integrating the resulting velocities, the orientation angles of the aircraft with respect to the earth (bank, attitude, and heading angles) are obtained. These angles are in turn used to resolve the three translational velocities described earlier into velocities north, east, and vertical (rate of climb), which after integration yields the aircraft position and altitude.

Thus the solution of the flight equations involves summation, integration with respect to time, multiplication, and trigonometric resolution. In addition, the calculation of the aerodynamic translational forces and moments involves generation of arbitrary functions (e.g., functions of Mach number, altitude, etc.) and division. Solution of the propulsion equations which give such outputs as thrust, rpm, etc., may involve function generation, integration, summation, and multiplication.

The simultaneous solution of all these equations is a formidable task, as witnessed by the complexity of the computer section of flight simulators. For example, in Appendix V of the first final report[1] it is estimated that a typical fighter aircraft simulator requires 62 summing amplifiers, 16 integrating amplifiers, and 18 servos for multiplication, function generation, and trigonometric resolution.

2.2 The Simplified Linearized Flight Equations

In order to avoid the considerable complication of the above equations and still obtain useful information on the dynamic behavior of the aircraft, it has been the practice for many years in the aircraft industry to work with the linearized flight equations. To do this we assume that the six dynamic aircraft variables (forward, vertical, and side velocities in the aircraft axes, and roll, pitch, and yaw rates) are perturbed only slightly from their steady-state values.[4] When this assumption is made it turns out that the equations involving variables for lateral motion (roll rate, yaw rate, and side velocity) can be separated from the equations involving variables for longitudinal motion (forward velocity, vertical velocity, and pitch rate). Each of these sets of linear equations is only fourth order and can be solved on a rather modest computer installation.

From the solutions of linearized lateral flight equations the period and time to damp to half amplitude of the oscillatory lateral "Dutch roll" motion can be obtained, as well as the time-constant of the spiral motion. These solutions should agree with the lateral transients observed in the final complete simulator which, includes all nonlinearities, since these nonlinearities are relatively unimportant as long as the lateral transients are small. Similarly, from solutions of the linearized longitudinal flight equations the period and time to damp of the short period and long period (phugoid) pitching motion can be obtained. Again these should agree with the final trainer performance in simulation of small pitching motions. Since the pilot normally flies with small motion perturbations from steady flight, we feel that these comparisons are significant and important.

2.3 Formulas for Calculating Approved Data for Dynamic Specifications

It seems clear from the above discussion that the solutions to the linearized flight equations might well be used as the approved data for dynamic performance specifications of the flight simulators. Thus the period and time to damp to half amplitude of the lateral and longitudinal motions as obtained from the linearized equations can be used to check on the final dynamic performance of the trainer.

In many cases an exact computer solution of the linearized flight equations may not be necessary to determine period and time to damp of the oscillatory lateral and longitudinal motions. Peterson has shown[4] that for a conventional fighter aircraft, such as the **F-86D**, approximate formulas can be used to compute these quantities directly from the usual stability derivatives furnished by the airframe company.

2.3.1 Short-Period Pitching Oscillation

For example, consider the short-period pitching motion. A fairly accurate formula for the period T_o of the damped oscillation is given on page 24 of Peterson's report[4]. Thus

$$T_o = \frac{2\pi}{V_o}\sqrt{\frac{2I_{yy}}{\rho Sc(-C_{m_\alpha} - \frac{\rho Sc}{4m} C_{L_\alpha} C_{m_q}}} \qquad (1)$$

where T_o = period of oscillation, seconds

V_o = aircraft velocity, feet per second

I_{yy} = aircraft inertia about the y body axis, slug feet squared

ρ = density of air, slugs per cubic foot

S = aircraft wing area, square feet

c = mean aerodynamic chord, feet

m = airplane mass, slugs

C_{m_α} = moment curve slope coefficient

C_{L_α} = lift curve slope coefficient

C_{m_q} = damping in pitch coefficient

All the above quantities are furnished by the airframe company. The accuracy of Equation (1) is in general better than the accuracy requirement in the dynamic specification, so that it could be used directly (at least for conventional aircraft) to calculate the approved period data for the short-period pitching oscillation. Also from Peterson's report, page 24, we have for the damping ratio ζ of the short-period pitching motion the following approximate formula:

$$\zeta = \frac{T_o \rho V_o S c^2}{16\pi I_{yy}} \left(\frac{2I_{yy}}{mc^2} C_{L_\alpha} - C_{m_q} - C_{m_\alpha} \right). \qquad (2)$$

where ζ is related to $T_{1/2}$, the time to damp to half amplitude, by the formula

$$T_{1/2} = \frac{T_o \ln 2}{2\pi\zeta} = 0.11 \frac{T_o}{\zeta} \qquad (3)$$

Based on the F-86D results, it would again appear that Equation (2) is considerably more accurate than the dynamic specification requirements, and hence could be used directly to calculate the approved damping time for the specifications.

2.3.2 Long-Period (Phugoid) Pitching Oscillation

It has been shown that the long-period (phugoid) oscillation in pitch can be represented accurately by the following formula (see reference 4, page 25).

$$T_o = \sqrt{2}\pi V_o/g = V_o/7.25 \qquad (4)$$

where T_o = period, seconds
V_o = aircraft velocity, feet per second
g = gravity acceleration, 32.2 feet per second squared

A simplified formula for the damping ratio ζ for the phugoid oscillation is also available[4]. Here a specification on the ratio **R** of the successive amplitude peaks (one positive maximum to the next positive maximum) is probably more effective. R is simply given by

$$R = e^{2\pi\zeta}, \quad \zeta << 1 \tag{5}$$

Note that Equation (4) for the phugoid period T_o depends only on the aircraft velocity, V_o and is independent of any other aircraft parameters. Our field tests on the present ac trainers with regard to phugoid period were unsuccessful on the F-86D and C-124A simulators due to difficulty in trimming the trainer for level flight (see reference 1, page 19). We believe that the phugoid performance is a critical measure of simulator resolution and performance in longitudinal motion simulation, and that many pilot complaints of lack of trainer stability stem from poor resolution and performance in longitudinal motion.

2.3.3 Lateral Dynamic Oscillations

The linearized flight equation for lateral dynamics (side velocity, roll rate, and yaw rate) exhibit damped oscillatory transients, often referred to as "Dutch roll" in the actual aircraft. On page 25 of Peterson's report[4] are the period T_o and the damping ratio ζ of this lateral motion. Thus

$$T_o \cong \frac{2\pi}{V_o} \sqrt{\frac{2I_{zz}}{\rho Sb\left(C_{n_\beta} + \frac{\rho Sb}{4m} C_{Y_\beta} C_{n_r}\right)}} \tag{6}$$

and

$$\zeta = \frac{T_o \rho V_o S b^2}{16\pi I_{zz}} \left(-\frac{2I_{zz}}{mb^2} C_{Y_\beta} - C_{n_r} \right) \qquad (7)$$

where I_{zz} = aircraft inertia about the z body axis, slug feet squared

b = aircraft wing span, feet

C_{Y_β} = side force due to yaw coefficient

C_{n_β} = yawing moment due to sideslip coefficient

C_{n_r} = damping in yaw coefficient

The remainder of the parameters in Equations (6) and (7) are defined in Section 2.3.1. The time to damp to one-half amplitude can be calculated from ζ by use of Equation (3).

For the F-86D the approximation in Equation (6) gives periods for the lateral dynamics which agree with the exact flight-equation solutions to better than 10 percent[4]. Thus Equation (6), at least for this conventional-type aircraft, could be used to establish approved-data for the period of lateral dynamics. Equation (7) for the damping ratio is a less-accurate approximation, and based on the F-86D results[4] its usefulness for other aircraft is questionable.

In deriving Equations (6) and (7) the effect of the product of inertia I_{xz} was neglected. This is probably valid for many aircraft, but may become fairly important for some aircraft with more unconventional configurations.

In addition to the oscillatory lateral transients discussed above the lateral dynamics include a short-period exponential decay term and a long-period exponential term which may decay or build up, depending on whether the aircraft is spirally stable or unstable. Accurate approximate formulas are given by Peterson[4] for the time constants of both motions.

3. SOLUTIONS OF THE COMPLETE LONGITUDINAL FLIGHT EQUATIONS

3.1 Importance of Good Longitudinal Simulation

A number of the pilot complaints about simulator performance at the different bases visited could be traced to inadequate simulator performance in longitudinal (pitching) motion. Due to poor resolution in attitude (pitch) angle it is difficult to trim the ac trainers for level flight, or to set up a fixed rate of climb or descent. This poor resolution is the result of backlash, dry friction, and tachometer inaccuracies in the ac electromechanical integrators as well as granularity in the pick-off potentiometers.

3.2 DC Analogue Computer Solution of the Longitudinal Flight Equations

In order to demonstrate the performance of dc analogue computers employing electronic integration for solving the longitudinal flight equations, these equations were set up for both the F-86D and B-47 aircraft, including all important nonlinearities. The results of this simulation are presented by E. G. Gilbert in a technical report[5]. The solutions exhibited a rate of climb resolution of 50 feet per minute or better, extreme ease in trimming the aircraft for level flight or given rates of descent, and faithful reproduction of both short-period and long period (phugoid) pitching oscillations.

As a result of these tests it seems evident that much more satisfactory simulator performance in longitudinal motions is obtainable with a dc system than with the present ac systems. As stated before, the longitudinal simulation is the most critical in solving the flight equations, so that an overall dc system should be smoother and more stable than an ac system.

4. RECOMMENDATIONS

4.1 Recommendations from the Previous Final Report

The following recommendations were presented in the final report summarizing the first 9 months of this study program[1]. They are repeated here for the convenience of the reader. They represent not only recommendations regarding the type of electronic computing devices to be used but also suggestions which should improve the development time and costs along with the effectiveness of future trainers. Engineering support for the recommendations is contained in the bulk of the first final report.

(1) It is recommended that the present ac 60 cycle carrier analog computing systems in the trainers be replaced by dc analog systems in future trainers. The dc systems will exhibit greatly improved dynamic performance, decreased development time for each new trainer, decreased calibration and check-out time, more opportunity for built-in automatic checking devices, easier maintenance, and easier incorporation of modifications of the flight equations once the trainer is in the field. It should not be necessary to drift stabilize the bulk of the dc amplifiers in the computer.

(2) Centrally located power supplies, preferably of the motor-generator type, should be employed.

(3) For multiplication, servo-driven potentiometers still seem to be the most reliable and easily maintained arrangement. 400 cycle motors driven by magnetic amplifiers appear to be the best combination. Tapped potentiometers are recommended for function generation.

(4) It is recommended that self-testing circuits be incorporated in the computer section, circuits which will check amplifier balance, gain,

and overall static performance of the computer. This is readily possible with a dc system, and the circuits can be designed so that a failure in the testing device will not affect operation of the simulator.

(5) Stick forces should be provided by means of a torque-producing device employing feedback, such as a torque tube.

(6) Portions of the computer dealing with simulation of the fire-control system should not employ the actual GFE aircraft fire-control equipment, since the latter is not, in general, intended for continuous duty and does not have the advantage of many of the physical input data available in the trainer. A more reliable and satisfactory simulation of the fire-control problem can be mechanized in a portion of the computer section of the trainer.

(7) It is recommended that in the future a much closer liason between simulator and airframe manufacturer be maintained. This is particularly important where the airframe manufacturer is doing considerable simulation work himself as a design and analysis aid. Such liason should in all cases result in more accurate and up-to-date aircraft data being furnished to the simulator manufacturer.

(8) The dynamic flight equations, at least in linearized form, should be set up and solved on accurate analog computing equipment before a final computer mechanization for the trainer is decided upon. This is essential to determine the relative importance of various aerodynamic terms, which terms can be eliminated, importance of things like products of inertia, correlation with preliminary flight test data when available, possible errors in the data furnished by the airframe manufacturer, etc.

(9) Specifications on the performance of trainers should not, in general, include increased absolute accuracy but should be increased in comprehensiveness to include dynamic requirements, resolution requirements, and slope as well as magnitude requirements in such things as stick-force versus displacement simulation.

(10) It is recommended that support for research and development of digital computer sections for flight simulators be provided. Only by actual using experience with this type of computer and the many analog to digital and digital to analog conversions necessary for operation as a flight simulator will an ultimate comparison of the digital system with present or projected analog system be possible.

4.2 Recommendations Regarding the Use of 400 Cycle AC Computing Systems

On the basis of power consumed, size, interchangeability with actual aircraft equipment, and dynamic capabilities it can be shown that a 400 cycle ac analogue computer section would be superior to the current 60 cycle systems[6]. However, all the undesirable characteristics of ac computers such as electromechanical integrators, phase-shift errors, low impedance requirements, critical lead locations, difficulty of automatic checking etc., are aggravated even more when 400 cycle rather than 60 cycle is employed. For this reason we feel that going to 400 cycle analogue computer systems would be a serious mistake.

4.3 Suggested Specifications for Stick-Force Simulation

The usual stick-force specification requires that the force at any displacement be within a fixed percentage (say 25 percent) of the approved data or within a fixed poundage, which ever yields the greater tolerance. One difficulty with this type of specification is that it allows very uneven or rough stick-force simulation to still lie within the regions of tolerance. It is suggested that to the above specification be added the requirement that the slope of the actual stick force versus displacement curve, as determined by successive force measurements over distance intervals as small as one percent of full scale, be within 25 percent of the slope of the approved-data curve.

4.4 Suggested Dynamic Specifications

It has already been pointed out that pilots normally fly their aircraft with small perturbations from steady-state flight. For this reason, good simulator performance for small motions is important. If such performance is good then the simulator will reproduce faithfully the dynamic transients following small perturbations from level flight. To help check simulator performance in this regard the following suggestions are made for incorporation into the dynamic specifications of the trainer.

4.5 Suggested Longitudinal Dynamic Specifications

In Section 2.3.1 and 2.3.2 it was stated that the longitudinal dynamic behavior of the aircraft exhibits both a short-period and a long-period dynamic oscillation. It is suggested that the specified period of the short-term oscillation, as measured from the pitch-rate Q, be within 25 percent of the period given by the approved data, while the time to damp to half-amplitude be within 35 percent. The period and time to damp should be within the above limits for amplitudes of pitch-rate from 5 percent to one percent of maximum pitch-rate.

It is suggested that the long-term(phugoid) period, as measured by the rate of climb, be specified to lie within 25 percent of the period given by the approved data, while the ratio of successive peak amplitudes (one maximum rate of climb to the next maximum) be within 20 percent of the approved data. These tolerances should be maintained for maximum rate of climb variations between ±2000 feet per minute and ±1000 feet per minute. At no time during these tests should the recorded rate of climb indicate jumps or discontinuities larger than 150 feet per minute.

4.6 Suggested Lateral Dynamic Specifications

It is suggested that the period of the oscillatory lateral (dutch-roll) transients, as measured by the roll rate, be specified to be within 25 percent of the approved data, while the ratio R of successive amplitudes of oscillation should be within 10 percent of the approved data. Whenever $R > 1.4$, the specification would be better if placed on the damping ratio ζ, say within 25 percent of the approved ζ. These specifications should be met for roll-rate amplitudes of 5 percent to one percent of the maximum roll rate.

The spiral stability, as measured by the bank angle, is a long-term exponential in behavior, and either builds up or decays, depending on whether the aircraft is spirally stable. A dynamic specification of 35 percent on the time constant of this spiral motion is suggested.

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