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Total In-Flight Simulator (TIFS)—A New Aircraft Design Tool

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TIFS is a newly developed, variable stability C-131 aircraft with the unique capability to vary its flying qualities in all six degrees of freedom. It also surpasses the utility of past variable stability aircraft through the realism possible in its separate, new evaluation cockpit. The capabilities and features of this in-flight simulator considerably broaden the ability of the designer to deal with difficult trade-offs in flying qualities problems. This paper describes the aircraft and its potential as a design tool. Physical characteristics as determined in flight and examples of simulation planning are given. Flight test records of model-following performance are included.

Nomenclature

C_L = lift coefficient
$C_{L\alpha}$ = lift curve slope
$C_{Y\beta}$ = sideforce curve slope
SHP = shaft horsepower
V = true airspeed
V_e = equivalent airspeed
W/S = wing loading
i_c = cockpit mounting incidence
n_y = side acceleration, g, positive right
n_z = normal acceleration, g, positive down
$\bar{q}$ = dynamic pressure
α_{FRL} = angle of attack of fuselage reference line
β = sideslip angle
γ = flight path angle in vertical plane
δ_F = Fowler flap deflection
δ_r = rudder deflection
δ_y = side force surface deflection, positive TE left
δ_z = direct lift flap deflection, positive TE down
θ = pitch angle
χ = flight path angle in horizontal plane
$(\ )_M$ = model motion variable or parameter
$(\ )_{EXT}$ = extremal value
$(\ )_{KTS}$ = quantity in knots
$(\ )_{DEG}$ = quantity in degrees

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Introduction

THE idea of applying the principles of automatic flight control to the development of variable stability airplanes has been established for more than twenty years. The concept has progressed from elementary variations in stability and control characteristics for research purposes to full simulation of the flight characteristics of all kinds of aircraft. The usefulness of the variable stability airplane for advancing knowledge and understanding in the areas of handling qualities and flight control is exemplified by the variable stability T-33, which has been engaged in research flying for over ten years. The Air Force Flight Dynamics Laboratory has now

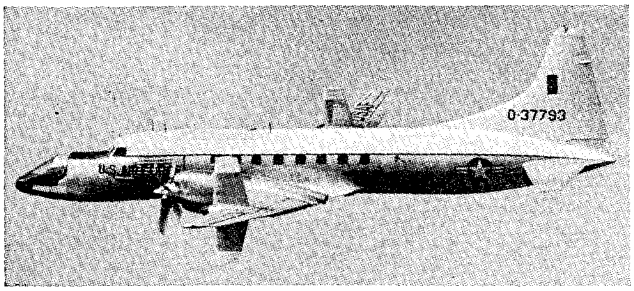

Fig. 1 TIFS aircraft in flight.

sponsored the development by the Cornell Aeronautical Laboratory of a much more advanced research airplane known as TIFS (Total In-Flight Simulator). A paper discussing the TIFS design was presented in 1968.[1] The development of this vehicle is now complete, and the TIFS airplane is proceeding to the research and development work for which it has been designed. A flight test phase has just been completed where all the systems have been operationally checked out, the modified airframe has been tested for flutter, and structural modifications have undergone flight integrity tests. Simulation modeling and flying quality evaluation flights are currently being conducted. Figure 1 shows TIFS flying during the testing phase. Its application to new airplane design and more details of its simulation capabilities will be discussed below.

General Description

TIFS is a research airplane developed for use in flight testing advanced flight control technology and for support in the development of new flight vehicles. The basic airplane is a C-131B (Convair 340), which has been converted to turboprop engines and extensively modified to accommodate the TIFS features. The basic features include the evaluation cockpit, direct lift flaps, side force surfaces, and variable stability system. These are shown in the system arrangement in Fig. 2. These features provide for the capability of six-degree-of-freedom dynamic simulation, in flight, and permit duplication of the flying characteristics of other flight vehicles.

The evaluation cockpit was added to the airplane in order to place the pilot flying the simulation in an environment which can duplicate the actual simulated airplane's cockpit. This particular cockpit does not represent any specific airplane cockpit, but is intended to be generally suitable for use in simulation of vehicles with a two place, side by side cockpit arrangement. It is easily replaceable by an entirely different cockpit from the adapter ring forward. The cockpit and the

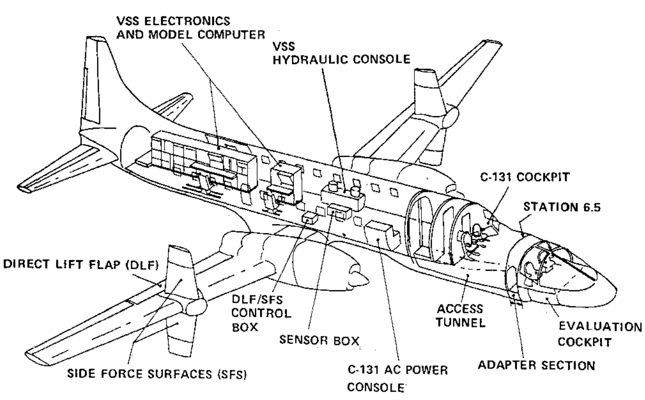

Fig. 2 System arrangement.

windshield are separately removable and can be replaced by other cockpit/windshield arrangements. It presently is equipped with two conventional wheel and column controllers and two rudder pedal units. The evaluation pilots fly these controls through variable electrohydraulic control feel systems, which are important parts of the simulation. The console contains a grouping of four engine throttles each of which can be mechanized to control the thrust of a single engine. The displays on the instrument panel are the major flight grouping of instruments developed under the Pilot Factors Program. Either computed information or actual flight data can be displayed on the flight instruments.

The variable stability system in the TIFS airplane has more capability than any built and flown in the past. Using the special control surfaces, the side force surfaces, and the direct lift flaps, in conjunction with the normal control surfaces and servo-operated throttles, all three forces and three moments on the airplane can be independently controlled. Side force control is obtained from the all-moving vertical surfaces mounted above and below each wing positioned in front of the main wing spar and outboard of the engines. These surfaces have a total area of 100 ft^2 with $\pm 30°$ of deflection. A simple hinged flap mounted in place of the outboard Fowler flap, extending from the engine nacelle to the aileron, provides direct control of lift. These flaps have a total area of 108 ft^2 and can be deflected $\pm 40°$. High performance linear electrohydraulic servo actuators drive the special and normal control surfaces in order to obtain the response necessary for good simulation.

The computer installation is shown in Fig. 2. Its features include a special-purpose analog computer with 584 operational amplifiers and a 60-channel digital data recording system. Two test engineers operate this equipment in flight—one primarily responsible for the computing functions and the other for the data recording. The computer was specially designed and built for this variable stability system. The recording system is digital for ease in data processing. The data can be directly analyzed by IBM 370 or played into a strip chart recorder immediately after a flight to select the sections for detailed analysis. The portion of the computer producing the model vehicle to be simulated contains roughly 330 amplifiers, a sizeable number of which are used in function generators, multipliers, and other nonlinear circuits. It can be used to study airplane motion or flight control system behavior in combination with rigid body motion.

The TIFS airplane is always under command of the pilots in the normal C-131 cockpit even when being flown from the evaluation cockpit. The controls in the safety cockpit are mechanically connected to the airplane's control surfaces and therefore always indicate the motion of each surface. This, plus the panel for monitoring system operation mounted near the center of the instrument panel, allows the command pilots to closely follow the motions of the airplane and assume control in the event a hazardous (hazardous for the C-131) flight condition occurs. A single button disengages the variable stability system and leaves the pilot with the characteristics of a C-131. Other automatic monitoring circuits are programmed to prevent hardover signal inputs to the control surfaces and to prevent inadvertently exceeding structural limits. The system engage panel, located on the aft portion of the center console, allows the command pilot to engage and disengage the variable stability system and select the servos he desires for the operation.

TIFS as an Aircraft Design Tool

There is no need to embark on a lengthy discussion about the use of simulation in design of new flight vehicles. Simulators are used in the modern airplane development in the early stages when criteria are being developed for the general class of vehicle, through evaluation of the flying qualities of the airplane as the design takes shape and on into the design of the stability augmentation systems. They are even being used for developing criteria by which to certify supersonic transports for commercial operation. Simulation facilities are becoming more sophisticated and complex to keep abreast of the requirements for better, more realistic simulations. Great strides have been made improving ground-based simulators' motion capabilities and VFR visual displays. In spite of all the improvements, little research exists on the question of just what cues and information are important to the pilot and how real must the reproduction of these inputs be to provide results reliable enough to help the designer.

TIFS has taken a step toward realism in simulation not previously available to the airplane design world. With independent control of all the moments and forces about the three axes, it is now possible to do a six-degree-of-freedom simulation with realistic dynamic responses duplicating the flying characteristics of an airplane in development. Once this has been realized, we can turn to the factors which make TIFS such a revolutionary tool. A simulation in TIFS places the pilot evaluating an airplane under design in an actual flight environment with actual vision cues. No current visual attachment provides the depth perception and the peripheral cues (with a moving base) a pilot has in flight. Picture the pilot flying with an engine out to the end of a runway after breaking out at 500 ft offset from the centerline. The visual cues are of vital importance. His performance is undoubtedly also influenced by the vestibular and proprioceptive cues he experiences from the actual motion environment.

The role of an in-flight simulator in developing criteria for new airplanes under design can be important. In the procurement of new military airplanes, MIL-F-8785B[2] is used as a basis for determining an airplane's acceptability. The detail design specification for a new airplane is written using −8785B as a guide for using previous experience with similar airplanes and specific mission requirements to determine a definitive specification. There are further latitudes provided in −8785B where qualitative phrases such as "objectionable flight characteristics" and "normal pilot technique" are used to describe certain criteria. The intent is to avoid the inclusion of numerical bounds when the basis for such numbers is not yet well defined. For the large flight vehicles, this job of writing a detailed design specification may be more difficult. There is a lack of experience and data on which to base a specification. Here is an area where TIFS may be ideally applied. By simulating the general class of airplane being developed and varying the parameters which may be critical to a design, a systematic study can be done to determine reasonable design criteria specifications from which detail and type specifications are derived.

An example of how this technique may be applied can be seen from previous work. The Air Force originally specified a roll angle of 8° in the first second for the C-5A in landing approach. There was a great deal of discussion of this by competing development contractors. Two separate in-flight simulation studies were conducted by Cornell Aeronautical Laboratory (CAL) for the Air Force Flight Dynamics Laboratory using CAL's variable stability B-26. In the conclusions for each of these studies, it was determined that a roll angle of between 4 and 5° in the first second was sufficient.[3,4] The roll angle on the completed C-5A has turned out to be approximately 5.5° and pilots who are flying it feel this is sufficient for the job.[5]

Look next at a more close involvement of TIFS in airplane design. In past airplane development, little consideration was given to the influence on other design aspects the flight control system might have in the early stage of the design. In the past, flight control technology was not available to change this approach. Recently, however, the scene has been changing. Consideration is being given to designing aircraft which are neutrally stable and have multiple redundant fly-by-wire control systems. Trade-offs are being made between static stability, handling qualities and performance. Reliance on stability augmentation systems which must be working in order to fly the airplane is just around the corner. With these types of factors influencing a design, how can the designer make decisions which could possibly affect a vehicle payload or performance without good simulation results to give the answers? TIFS can be used for this type of effort. The desired control system/stability augmentation system characteristics can literally be designed using TIFS. The low-frequency structural modes and turbulence can be introduced using TIFS and the effects of these on pilot control can be evaluated. Early detection of problems which can be solved by rigorous application of modern flight control technology will save costly changes should the problem turn up later.

How should an in-flight simulator be used in the design process? It certainly will not replace the ground simulator. Fixed-base ground simulators are cost effective for making preliminary assessments of trade-offs involving flying qualities during early design. However, the more realistic environment needed for final decision making can now be provided by an in-flight simulator such as TIFS at a cost which is competitive with six-degree-of-freedom moving-base ground simulation with visual attachment. Here special attention should be given to emergency conditions where total realism is necessary to obtain a good evaluation. This point is illustrated by the following comments on work done at the RAE on the flying qualities near the zero-rate-of-climb speed[6]: "Similar results were obtained in a simulator study of the same problem, reported in Ref. 4 (RAE TR 70016). This has shown the simulator to be a valuable tool for this work, so a further detailed study of V_{ZRC} recovery maneuvers could usefully be made in the same way. However, for a final validation actual flight tests are considered indispensable, for both systematic study and piloting experience." The flight tests referred to here were made in a BAC 221 slender wing research aircraft.

Although a new level of capability of in-flight simulation has been discussed here, it is important to add that in-flight simulation is not new. There have been previous variable stability aircraft which have supported the development of design criteria and specific systems. Also, in another way, existing airplanes have served as simulators for new systems under development. The B-58, for instance, was used to familiarize pilots with supersonic speed characteristics prior to the first flight of the B-70. The F-104 is used to examine the problems associated with low L/D approach and landing for re-entry vehicles. The "X" series of research aircraft have been used as simulators for developing technology which is applicable to specific classes of vehicles.

TIFS uses an approach different from the research vehicles of the past. With the variable stability system, it can change flight characteristics easily to represent many different types of vehicles. It can be used to investigate a point design of a specific vehicle under design or a parametric study for a particular class of vehicles. In addition, system hardware, as well as displays and controllers, can be installed with relative ease and tested in conjunction with the desired aircraft dynamics or a controlled variation thereof.

Capabilities

The capabilities of ground simulators are usually described in terms of the motion ranges, the characteristics of the visual attachment, and the accuracy and speed of response of the actuation devices which position the cab. For an in-flight simulator, it is also appropriate to discuss motion parameters, but the basic capability of unlimited positional freedom up to the service ceiling of a C-131H (about 20,000 ft) and of sustained linear acceleration in turns and steady sideslips does cast the discussion in a different light. The in-flight simulator matching the airspeed of the simulated aircraft (TIFS can do this up to 240 knots equivalent airspeed) has the basic capability to reproduce the motion of the cockpit exactly. There is no need for linear or angular motion washouts. A discussion of visual field is also appropriate but in terms of shape of the windshield, angle of down vision, and light transmission of the transparent material rather than whether the field is in color or in black and white and how many lines per inch are projected.

The material below covers motion, primarily, but briefly also vision, controllers, displays, audio environment, and data processing. The complete documentation of TIFS technical information is to be found in the Preliminary Design Report and the Final Report.[7,8]

Attitude and Flight Path in Unaccelerated Flight

For many simulation problems, it will be important to match attitude and/or flight path. The attitude at a given speed can be adjusted in basically two ways—a) by positioning the flaps, and b) by changing the evaluation cockpit mounting angle. The range of simulation is then given by the flap deflection allowable versus airspeed and the difference in $C_{L_\alpha}(W/S)^{-1}$ between the model and TIFS. An example of each technique is given below.

Example a

Adjust the inboard Fowler flaps and the outboard direct lift flaps to match attitude at some speed within the speed range of interest. As speed is changed during the simulation, the model following system moves the direct lift flaps from their initial position to match attitude. The speed range over which attitude can be matched is dictated by the limits of flap travel and the difference between $C_{L_\alpha}(W/S)^{-1}$ of the TIFS and the model.

An example is given in Fig. 3 for the Fowler flap at zero. Suppose the simulation objective is a landing approach with an initial trim speed of 190 knots equivalent airspeed (keas). Suppose the glide path is 3° and the cockpit attitude desired is $-1.2°$. The TIFS evaluation cockpit is currently mounted so that its horizontal reference line is parallel to the TIFS fuselage reference line. Therefore the TIFS angle of attack which is given by

$$\alpha_{\text{FRL}} = \theta_{\text{Model cockpit}} - \gamma_{\text{Model}} - i_c$$

where i_c is the TIFS evaluation cockpit incidence (positive for nose-up inclination) is computed to be $\alpha_{\text{FRL}} = -1.2 - (-3.0) - (0) = 1.8°$. For the TIFS at an intermediate gross weight of 52,000 lb (gross weight can vary from 48,000 to 54,600 lb) the lift coefficient at 190 keas is 0.46. Therefore, from Fig. 3 the trim direct lift deflection is about 2°. Suppose $C_{L_\alpha}(W/S)^{-1}$ for the model is 0.94×10^{-3} deg^{-1}/psf. For the TIFS at 52,000 lbs, the basic airframe value for $C_{L_\alpha}(W/S)^{-1}$ is 1.88×10^{-3}. Therefore, the effective lift curve slope must be reduced by a factor of two to maintain an attitude match at speeds other than 190 keas. A line of C_L vs α with half the slope of the basic airframe is indicated in Fig. 3 passing through the point $C_L = 0.46$ at $\alpha_{\text{FRL}} = 1.8°$. The simulation limits can then be read off as $C_{L\text{TIFS}}$ between 0.28 and 1.02 which at 52,000 lb is an airspeed range of roughly 140 to 240 keas.

Example b

The evaluation cockpit reference line is oriented with respect to the TIFS fuselage reference line to match attitude at some speed. This can be done by using an adapter ring with canted bulkheads. It can also be done by canting the cockpit floor, feel system packages and instrument panel. Changing the cockpit reference line angle would be used only if the attitude range were outside the capability of the flaps.

An example is a 240 knot approach with a 14° glide slope and a cockpit attitude of $-5°$. Here we have

$$\alpha_{\text{FRL}} = \theta_{\text{Model cockpit}} - \gamma_{\text{Model}} - i_c, = -5 - (-14) - i_c, = 9 - i_c$$

At 240 knots and 52,000 lb the TIFS is at $C_L = 0.285$. The largest angle TIFS can obtain at $C_L = 0.285$ is about 3.5° (from Fig. 3). Therefore, a value of i_c of at least 5.5° is needed, and it would be preferable to use 9° to place the required flap setting away from the buffet boundary. Under the supposition that $C_{L_\alpha}(W/S)^{-1}$ required is 0.94×10^{-3} deg^{-1}/psf, the simulation range is roughly 145 to 265 keas.

Fowler flap deflection can be used to permit matching attitude with less direct lift flap deflection in the trailing edge down direction. For this purpose use $C_{L\delta F} = 0.0063$ 1/deg and the restriction that $\delta_{F\max} = 40(206 - V_{e\text{KTS}})/66°$ for $V_{e\text{KTS}} \geqslant 140$.

The data analogous to Fig. 3 for the side force surfaces is given in Fig. 4. Given the value of $C_{Y_\beta}(W/S)^{-1}$ to be simulated, the range of sideslip angle which can be achieved can be read directly. The example shown in the figure gives a simulation range of $\pm 9°$ for a value of $C_{Y_\beta}(W/S)^{-1}$ which is one-ninth that of the basic TIFS. (Maximum sideslip angle is also governed by the rudder deflection available for trim and the vertical tail load as described in the next section.)

The flight-path angle capability of TIFS has been determined in flight at speeds up to 190 keas. In Fig. 5, the flight-path angle versus airspeed is shown for the clean airplane at sea level with maximum continuous power and for 1000 shaft horsepower per engine and gear down (gear doors removed to

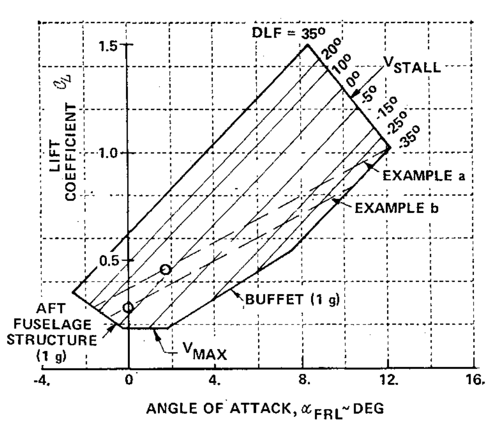

Fig. 3 Direct lift flap capability.

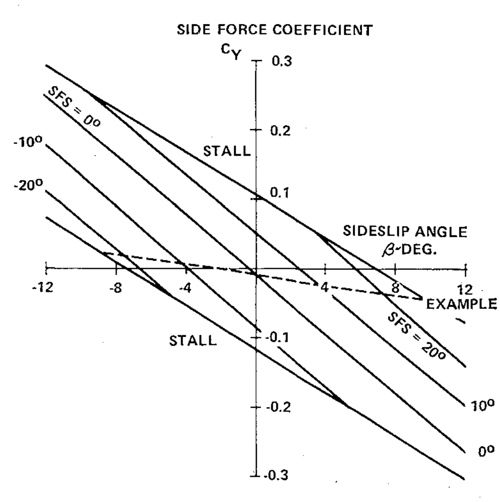

Fig. 4 Side force surface capability.

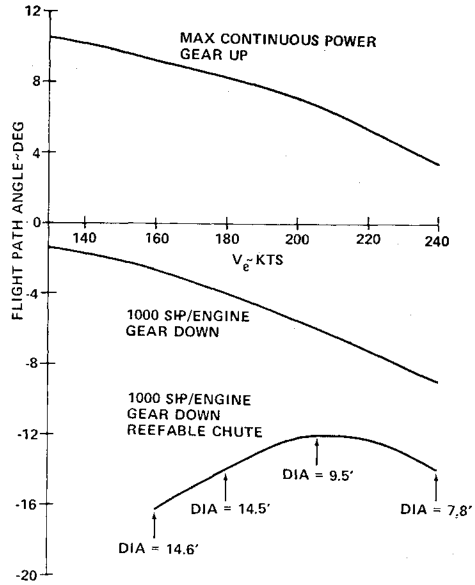

Fig. 5 Flight-path angle capability.

allow speeds up to 240 keas). The figure of 1000 hp/engine is based on retaining enough margin for transients.

The second curve was derived from this one by assuming a reefable ribbon chute deployment, maximum Fowler deflection and direct lift flap deflection as in Example b adjusted to account for Fowler usage. TIFS currently does not have such a chute installed but this way of adding variable drag to the aircraft is feasible. Engine power is again constant at 1000 SHP/engine. The derivation of the chute diameter indicated was based on achieving $\gamma = -14°$ at 178 keas and at 240 keas.

Dynamic Motion

There are constraints which arise naturally because of the inherent limitations of the C-131. The aircraft is a 2.5 g vehicle with -1.0 design g in a pushover. Roll rate capability is given in deg/sec by $p_{max} = .11 V_{FPS}$. Maximum angular accelerations are governed by the C-131's standard elevator, rudder, and aileron moment producing capability. These numbers work out to give roughly 60, 20, and 120 deg/sec^2 respectively at speeds above 170 keas. However, these limits are not restrictive when simulating large aircraft.

The maximum sideslip angle is governed by vertical tail load due to sideslip angle at the tail and due to rudder deflection. Each component of vertical tail load is important since torsional conditions can also be critical. The limit can be expressed as

$$(\beta^2 - 0.521\beta\delta_r + 0.586\delta_r^2)(\bar{q}/1010.)^2 = 1$$

where β and δ_r are in degrees, and $\bar{q}$ in psf.

For trim sideslips, $\delta_r \approx .87\beta$, so the limit for these maneuvers is

$$\beta_{DEG} \approx (546/V_{e_{KTS}})^2$$

with $\beta_{MAX} = 12.4°$ below 155 keas.

The abrupt transient linear acceleration capability of the direct lift flaps and the side force surfaces are given in Fig. 6. The initial position of these controls is assumed to be zero and the initial flight condition is 1g level flight at $\beta = 0$. The motion is rapid and the limits are position limits for the flaps, stall limits for the side force surfaces, and power limits for the engines. When the direct lift flaps are moved more slowly and there is time for the angle of attack to change, the

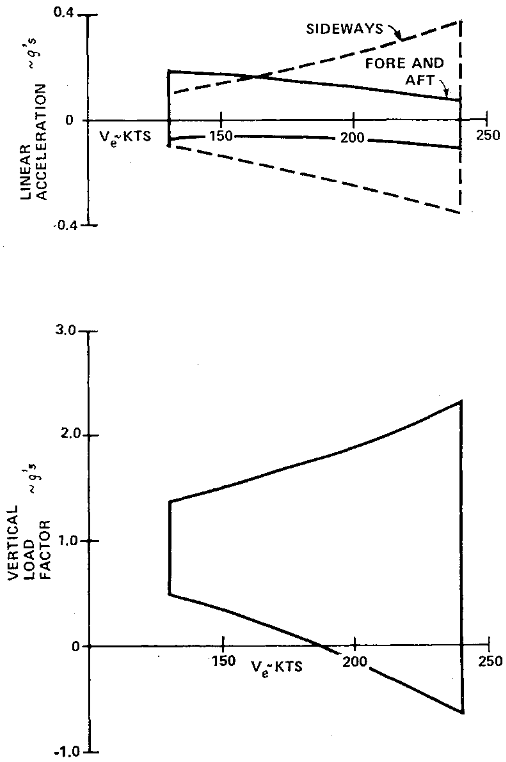

Fig. 6 Linear acceleration capability for step control inputs.

normal acceleration limits are governed by structural loads in the aft fuselage. These limits are shown in Fig. 7. The aft fuselage loads are currently limited during simulation to 75% of calculated allowable load.

The control surface actuators have bandwidths in the range 3 to 6 Hz with rate limits varying from 40 to 70 deg/sec. Thus, it is possible to simulate the predominant structural bending motion of very large aircraft, and produce the response to rough air.

For many simulation tasks it is not important to match trim airspeed. These tasks involve primary control of attitude, acceleration, and speed perturbations about a steady flight condition. Examples are station-keeping, in-flight refueling, control following engine failure, control following SAS failure, etc. When trim speeds are not matched but attitude and accelerations are matched, the increments in model flight path angle in the horizontal and vertical planes

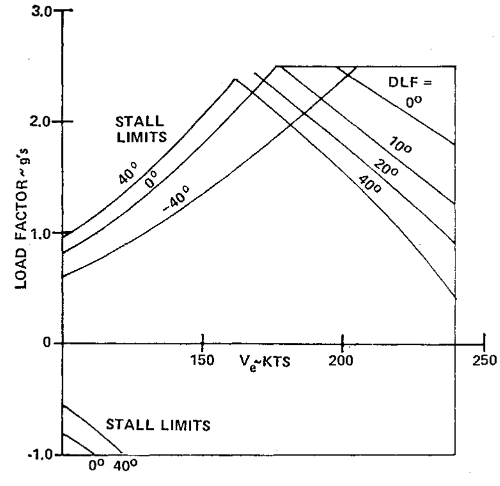

Fig. 7 Linear acceleration capability at fixed DLF settings.

are limited by the simulator direct lift and side force capability.[1] Simplified expressions for the limits are derived in the preliminary report on capabilities.[9] These are as follows:

$$\Delta\gamma_{M_{\mathrm{Ext}}} = \frac{C_{L_{\mathrm{Trim}}}}{C_{L_\alpha}}\left[\frac{V_M}{V}-1\right]^{-1}\left[\frac{\Delta C_L(\Delta\delta_z)_{\mathrm{Ext}}}{C_{L_\alpha}} - \left(\frac{C_{L_\alpha}/C_{L_{\mathrm{Trim}}}}{C_{L_{\alpha M}}/C_{L_{\mathrm{Trim}}}}-1\right)\Delta n_{z_M}\right]$$

$$\Delta\chi_{M_{\mathrm{Ext}}} = \frac{C_{L_{\mathrm{Trim}}}}{-C_{Y_\beta}}\left[\frac{V_M}{V}-1\right]^{-1}\left[\frac{\Delta C_Y(\delta_y,\beta)_{\mathrm{Ext}}}{C_{L_{\mathrm{Trim}}}} + \left(\frac{C_{Y_\beta}/C\bar{q}_{\mathrm{Trim}}}{C_{Y_{\beta_M}}/C_{Y_{\mathrm{Trim}}}}-1\right)n_{y_M}\right]$$

Model Following

The equations of motion describing the dynamic and static variations of the simulated aircraft are mechanized on the onboard analog computer. The computer capacity was sized to accommodate the conventional set of six-degree-of-freedom equations of motion with the usual nonlinear kinematic terms. The total number of amplifiers is 332 with 128 amplifiers used in nonlinear function generation. Some aerodynamic nonlinearities can be accommodated. Table 1 is a list of the model computer components. The committed amplifiers listed in the table cannot be used for other purposes. The uncommitted amplifiers can be used as summers or special-purpose amplifiers but are necessary to the nonlinear equipment when it is used. The multipliers perform $x \cdot y$. Dual multipliers perform $x_1 \cdot y$ and $x_2 \cdot y$. Quad multipliers perform $x_1 \cdot y, x_2 \cdot y, x_3 \cdot y$, and $x_4 \cdot y$. Special circuits are single amplifiers with the summing junctions accessible on the patch panel. They are typically used for wiring single amplifier second-order systems such as might be used for bending mode simulation.

This model capability is planned to be expanded through the installation of a digital computer to form a hybrid arrangement. The digital computer is particularly attractive for generating nonlinear aerodynamic functions of several variables.

The model-following capability of the system has been explored in the speed range 140 to 180 keas. Although refinement of the techniques is continuing, a quite impressive capability has been demonstrated in flight. Figure 8 illustrates this.

Vision

If vision outside the cockpit is part of the simulation task, then the obstruction to vision must be defined. Of particular concern is the down-vision angle over the nose for a landing approach.

Table 1 Model computer

	Committed amplifiers	Uncommitted amplifiers
60 Inverters		60
40 Summers		40
20 Integrators		20
8 Resolvers	8	32
10 Dual multipliers	20	20
8 Quad multipliers	16	32
10 Balance-hold circuits	10	
10 Special circuits	10	
30 Multipliers	30	
10 Function generators	30	
1 Servo pot control system	4	
Total	128	204

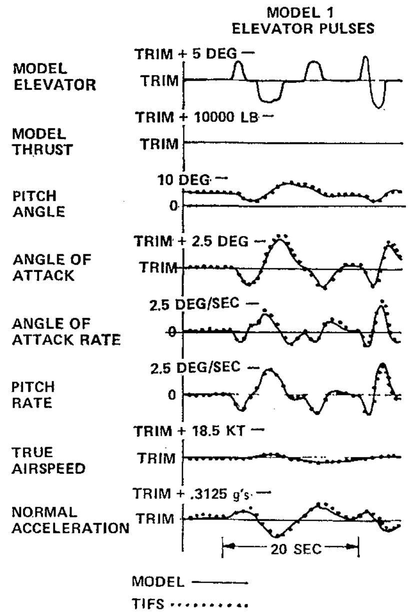

Fig. 8 Longitudinal model following flight test record.

The TIFS general purpose cockpit was designed with as large an area of unobstructed vision as possible with the intent of masking out specific windshield configurations. The down-vision angle from the nominal eye point is 14°. The eye point can be raised about two inches giving a maximum down-vision angle of 16°.

Unusual vision problems such as might be encountered with a windshield designed for high aerodynamic heating could be reproduced by replacing the present canopy with another with the proper material thickness and light transmission properties. The present canopy is built to be easily removable.

Cockpit Controllers

The feel systems in a simulator of any type form an important link in a pilot evaluation. As mentioned earlier, TIFS is presently equipped with two conventional wheel and column controllers and two rudder pedal units. The TIFS feel system provides force versus position characteristics at the controls of each test pilot through electrohydraulic servos. The principle used is to measure the applied control forces and to command the control position of the hydraulic actuators. The voltages from a force measuring system that represent the forces applied by the pilot and co-pilot are summed to form a total force command. These voltages are used as position commands to the actuators connected to each pilot's control wheel and rudder pedals. The pilot and co-pilot units are not mechanically connected. Inputs to one column, however, cause the other column to move as if they were.

The resultant feel system provides the following characteristics at the elevator, aileron or rudder controls of each test pilot: a) linear adjustable force vs position gradient; b) adjustable breakout force; c) adjustable hysteresis; d) adjustable split hysteresis (combination of breakout force and hysteresis); e) adjustable deadband; f) bobweight effects such as those due to normal acceleration and pitching acceleration; g) variation of the force gradient as a nonlinear function of some arbitrary variable.

The breakout force, hysteresis, and nonlinear functions can be inserted in the force channel. Control deadband is inserted in each of the position feedback loops. The control force gradient can be present to a constant value or varied as a function of another variable such as dynamic pressure.

Table 2 Feel system characteristics

	Elevator	Aileron	Rudder
Breakout force	±10 lb	±10 lb	±20 lb
Hysteresis	±10 lb	±10 lb	±20 lb
Split hysteresis	±20 lb	±20 lb	±40 lb
Deadband	±1 in.	±10°	±0.5 in.
Maximum force	100 lb	100 lb	200 lb
Minimum gradient	2.5 lb/in.	0.1 lb/deg	10 lb/in.

Table 2 is a list of the maximum ranges for the characteristics.

In addition to providing the above static characteristics, controls are available in the TIFS feel system electronics to vary the dynamic relationship between applied force and control position. As presently mechanized, the dynamic relationship between force and position is a second-order system with natural frequency variable from 0 to 50 rad/sec and damping ratio variable from 0 to 2.0. Stability requirements limit the range of static gains which can be used with a given set of dynamic parameters.

Cockpit Equipment and Audio Environment

Displays are an important aspect of the TIFS concept. The type of information and how it is displayed play a role of ever increasing influence on the ability of a pilot to fly the future large jets. Various display concepts can have an actual flight evaluation with TIFS before hardware is tested in an operational aircraft. In addition, the interrelationship of handling qualities and displays may be investigated, varying both displays and the stability and control characteristics of the airplane in a controlled manner.

The display panel now installed in TIFS has the major flight grouping of instruments developed under the PIFAX program (Pilot Factors Program sponsored by the FAA and performed under Air Force direction). The instruments include an attitude indicator presenting pitch and roll angles, turn rate, horizontal and vertical steering commands, and flight-path angle, and a sandwich indicator displaying radar altitude and vertical velocity.

Special displays such as CRT type attitude instruments or special approach aids can be installed. The volume forward of the instrument panel and above the rudder pedal feel units is currently empty. Structurally, that area can accommodate 200 lb of additional equipment.

The aircraft is equipped with dual VOR and dual ILS. Dual VHF and standard UHF communications are provided. The evaluation pilots can communicate through the basic aircraft's radios to the tower and approach control. The radios are controlled from the safety pilot's cockpit. A versatile intercom system is provided to allow all stations including the observers in the aft cabin to communicate. A private line is available for voice recording of evaluation pilot comments.

The evaluation cockpit, being well forward of the engine, is noticeably quiet. The TIFS turboprop engines operate at constant rpm so power changes do not cause noise frequency changes which would be disconcerting to the evaluation pilot, nor are engine sound level changes apparent. Normal boundary-layer noise is present and this, of course, increases in level with airspeed.

Should the sound of jet engines winding up and down with throttle motion be judged important to the simulation, this can be added by wiring a commercially available jet engine noise generator to cockpit speakers. The natural aerodynamic noise can also be augmented in this manner.

Data Acquisition and Processing

A digital tape recording system provides 58 channels of recorded information that is compatible with the IBM 370 system. The signals must be d.c. to 17 Hz in the range ±10v. The system can record at speeds of 50 or 100 samples of each channel per sec. The system records a 10-bit binary number plus a sign bit. The over-all recording system accuracy is approximately 0.2% or better. Each channel is filtered to avoid aliasing errors. The filter cutoff frequency changes from 7.0 to 17.5 Hz automatically with the system record speed so that the best possible recording bandwidth is utilized. The tape recorder is an Ampex CTM-14593 9-track, 800-byte-per-in. unit.

A complete ground playback system comprised of an Ampex TM-7293 tape transport provides quick-look functions. Any 8 of the 58 channels can be selected and played back on a strip chart recorder in analog form. A four-channel Brush strip chart is mounted in the aircraft for in-flight monitoring. Forty different channels of information can be selected rapidly by selector switches.

Any signal in the system that is compatible with the digital recorder can be readily patched into that unit. These include all motion variables, model inputs, feel system forces, and measured air turbulence.

The digital tape can be processed automatically. Computer programs are available to do aircraft equation parameter identification, power spectral density analysis, and frequency response computation by Fourier analysis.

Conclusions

The utility of various methods of simulation must ultimately be judged on the basis of aircraft development cost, considering simulation cost and the cost of system or airframe rework. The actual cost trade-off in using more realistic simulation is very difficult to determine. However, TIFS is another powerful design tool at the engineer's disposal and like the wind tunnel it should prove to be quite useful from a general research viewpoint as well as cost effective in the design of a specific aircraft.

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