The CL-84 V/STOL Flight Simulation— A Comparison with Reality

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An assessment of the value of the CL–84 tilt wing V/STOL flight simulation to the design and flight development of the prototype aircraft is made in the light of the flight-test experience accumulated between the first flight of May 7, 1965 and the present date. The simulation comprised both a fixed base, I.F.R. simulator and a variable-stability helicopter, each with varying degrees of sophistication in simulating the particular characteristics of the aircraft and its control system. Thus, it is possible to provide some insight into the usefulness of each facility and the degree of sophistication required to produce valid results for the various phases of the programme. The effectiveness of the simulation in inducing confidence in the design and in familiarising the pilots with the aircraft, thus expediting the flight-test programme, is discussed also.

1. INTRODUCTION

Canadair, a wholly-owned subsidiary of General Dynamics Corporation, has been engaged in V/STOL research and development continuously throughout the past decade, with support from the Canadian Government. The earliest explorations in this field involved examination of the suitability of various V/STOL concepts for a typical short to medium range transport mission. The general conclusions of these studies indicated that the flapped, tilt-wing principle represented the smallest departure from orthodox design practice and contained the possibility of leading to a successful design in the shortest possible development period. The excellent short take-off and landing potential of this concept added to its attractiveness, particularly for the Canadian market. Thus, the Canadair V/STOL work has been concentrated almost exclusively on the flapped, tilt-wing concept throughout this period and has, up to the present time, materialised in the design and development of the CL–84 prototype (Fig. 1). This 6-tone, two-engined V/STOL aircraft is of such a configuration that it can be used directly in close support of ground forces and in a variety of utility roles. Detailed descriptions of the CL–84 prototype can be found in references 1, 2 or 3.

FIG. 1

It was evident at an early stage that the unique aerodynamic problems associated with the flapped, tilt-wing concept in transition flight did not lend themselves to solution by orthodox methods. Thus, considerable emphasis has been placed on the parallel development of analytical methods and experimental techniques, in order to achieve substantial progress based upon a thorough understanding of the fundamental principles involved. Methods for predicting the aerodynamic force components during symmetric flight for a flapped, tilt-wing aircraft in transition; the relationship between thrust and torque on a propeller under oblique inflow condition; and the downwash at the tail transition flight, are examples of simple, yet useful analytical developments(4). Several thousand hours of powered and unpowered model testing of flapped, tilt-wing configuration have been completed in several wind tunnels and on the Canadair mobile rig (Fig. 2). The latter facility(5) has been the only source for obtaining reasonably interference-free aerodynamic data in hover and at low transition speeds in ground effect.

As progress in the field of V/STOL aerodynamics was made, it became increasingly evident that even if all aerodynamic data for a specific configuration had been collected, for the V/STOL and transition flight regime, it was virtually impossible to assess the stability, control and handling characteristics of the aircraft by analytical means. The rapid variation of the aerodynamic data with several independent parameters, and the high degree of nonlinearity of these variations; the inherently high performance capabilities and low inherent static stability and damping; the large values of required control powers and the contribution of the controls to the dynamic stability; and the effects of piloting techniques and control system backlash and lags collectively indicated that it was essential in this type of aircraft to consider the complete closed loop system comprising the characteristics of the flight sensor system, the human operator, the control system and the uncontrolled airframe.

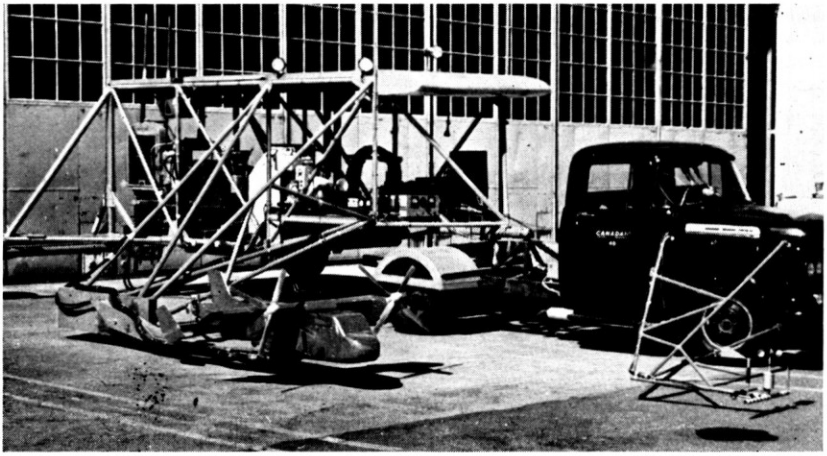

FIG. 2

Of the available methods for the solution of this problem, it appeared that simulation techniques were the most suitable, particularly in terms of speed, cost and flexibility of operation.

It is the intention of this paper to review briefly the V/STOL flight simulation at Canadair from its initiation through the design, development and flight testing of the CL–84 prototype and, in particular, to assess the value of the simulation to the programme as a whole. Because of the nature of the flight test programme so far, the comparison between flight test and simulation is mainly qualitative. Furthermore, the importance of the simulation to the success of the prototype programme is assessed subjectively by the author, since it is difficult at this stage to envisage a prototype programme without simulation.

2. FLIGHT SIMULATION DESIGN STUDIES

Our flight simulation studies for V/STOL aircraft were initiated early in 1960. Due to the costly, specialised hardware required for 'moving base, V.F.R.' simulation, in addition to the general and special purpose analogue equipment, it was decided from the outset that the simulation would be restricted to 'fixed base, I.F.R.'. However, it was considered important to represent the non-linear aerodynamic characteristics accurately, as well as to permit continuous simulation from hover to speeds beyond the transition régime. Although considerable detailed development in technique and equipment has been achieved since the initiation of the simulation, the methods used to achieve these objectives have been, in principle, the same throughout all our simulation studies and are briefly described in section 3.

2.1. *Longitudinal investigations*

The first V/STOL simulator studies at Canadair were restricted to the longitudinal degrees of freedom(6,7,8). The complete, fully non-linear, longitudinal flight characteristics in free air of an early (and smaller) version of the CL–84 aircraft were represented on the simulator for the handling qualities investigation. The problems examined were those involved during level flight accelerating and decelerating transition, and during short take-off and landing manoeuvres. Two modes of longitudinal control were explored; the first being pitch control through connection between the stick and the tail propeller, and the second, connection between the stick and a limited range of wing tilt authority, which itself varied with wing tilt angle, while the fuselage was maintained in a fixed, mean attitude by a pitch error signal to the tail propeller. In both cases, height control was obtained through a single power lever with an armrest on the pilot's left-hand side, and gross wing tilt changes by a button on top of either the power lever or the stick. Representation of the control system dynamics and aerodynamics was excluded, with the exception of simple lags in the height and wing tilt control circuits. The cockpit control damping, break-out and feel forces were in accordance with AGARD Recommendations(9).

With direct pitch control it was found that to achieve satisfactory handling qualities, corresponding to Cooper Ratings of 3·5 or better(10), the pitch damping augmentation values required were inordinately high. This situation is illustrated in Fig. 3, from which it may be seen that at least an order of magnitude higher damping than that of the natural aircraft would be required.

It was found that the introduction of synthetic attitude stiffness was beneficial in reducing the damping augmentation to more reasonable values. Figure 4 illustrates that for the case found to be of near optimum stiffness, pilot ratings of 3·5 were obtained with relatively low levels of damping augmentation.

These results were attributed to the large, positive moment speed stability of the configuration at low speeds in the neighbourhood of hover, as discussed in detail in ref. 11. It should be noted that in this simulation the speed

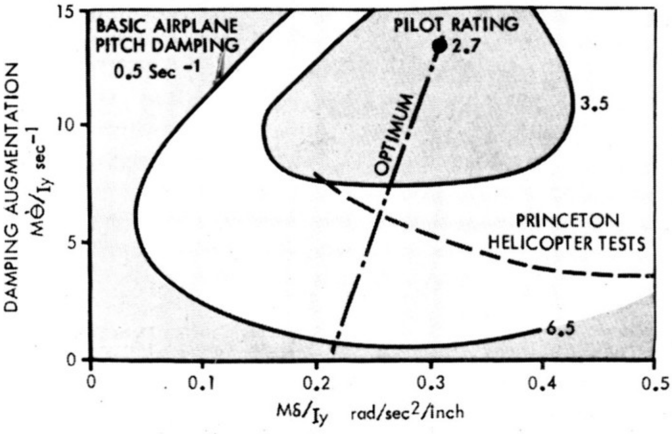

FIG. 3 — Flying qualities rating for damping augmentation only

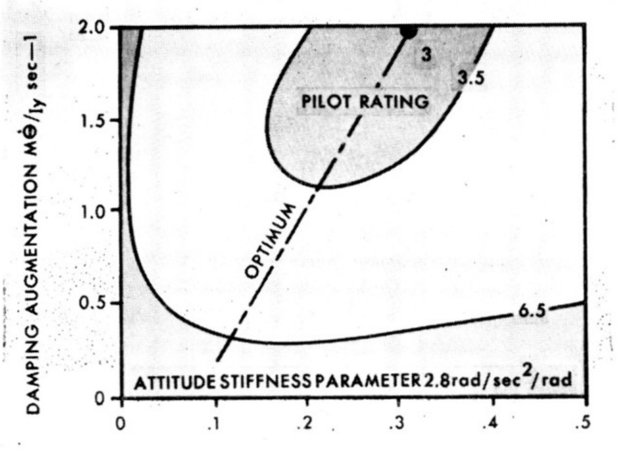

FIG. 4 — Control sensitivity $M\partial/ly$ rad/sec^2/in.

stability term was considerably larger than that representative of the CL–84 prototype, since the effects of flap and tailplane programming with wing tilt were not considered at wing angles above 20 degrees.

Results for the case of wing tilt control from the longitudinal stick, demonstrated that a somewhat larger value of attitude stiffness would be required to achieve satisfactory ratings with the same level of damping augmentation. From the handling point of view, there did not appear to be any distinct advantage to the wing tilt control method when compared with the direct pitch control. However, from the STOL performance point of view, the wing tilt control offered a marked improvement over the direct pitch control, due to the higher accelerations achieved during ground run. With the conventional type of pitch control, larger wing tilt angles were required during the ground run to avoid tail contact with the ground and negative tail loads at the unstick point.

The investigation indicated that the single power lever represented the optimum for thrust control throughout the flight regime.

A control sensitivity of about $\frac{1}{3}$ *g* normal acceleration per inch of displacement was found ideal in hovering flight. Constant rates of wing tilt, corresponding to the maximum acceleration–deceleration characteristics of the simulated aircraft, proved satisfactory for the wing tilt trim system. Thus, use of a simple spring-loaded, two-way switch classified the wing tilt operation as a trim task rather than a primary control. It was found advantageous to locate the thumb-operated wing tilt button on the power lever while maintaining the conventional longitudinal trim on the stick.

In addition to the handling qualities investigation, these longitudinal simulation studies also examined piloting techniques during the hover, transition, short take-off and landing phases and recovery following an engine failure in the hover and low speed flight regimes. Simulation of a medium range, 4-propeller, tilt-wing transport aircraft, in which the effects of ground proximity were fully represented, was included in this investigation as well as the simulation of the smaller aircraft described above.

2.2. *Lateral-directional investigations*

2.2.1. *Canadair fixed-base simulator.* Following the ‘go-ahead’ on the CL–84 prototype programme in 1963, the Canadair V/STOL simulator was expanded to include the lateral-directional degrees of freedom. Due mainly to equipment limitations, the pitch degree of freedom was restricted to a second order linear differential equation with constant coefficients selected to be representative of the CL–84 characteristics as obtained from the previous simulation. In the remaining five degrees of freedom, the dynamic and aerodynamic representation was non-linear, but with several simplifications, namely the control system dynamics were excluded, the control aerodynamics were linearised and the lateral-directional sideslip characteristics were assumed proportional to the sine of the sideslip angle. A detailed description of this phase of the simulation is presented in refs. 12 and 13.

The lateral-directional control sensitivity and damping requirements for acceptable handling qualities were evaluated using a standard I.F.R. approach pattern in the transition configuration by means of conventional I.L.S. instrumentation. The approach task was initiated by a down-wind 'fly-over' at 80 knots at an altitude of 500 feet and terminated in hover at about 20 feet altitude within a pre-described area over the runway. Following the successful approach, a rapid accelerating climb-out was made. The investigation included the determination of the effects of various levels of simulated atmospheric turbulence on the handling qualities of the configuration.

Figure 5 shows typical 'calm air' pilot rating boundary obtained from this study with the optimum combination of lateral-directional control sensitivities and dampings indicated by the symbol ⊕. However, bearing in mind that the simulation was a fixed-base, I.F.R. exercise, it appeared that lower values of both damping and control sensitivity would be acceptable, particularly in the roll degree of freedom. The importance of control harmony, as well as proper matching of the control sensitivity with the damping, was quite evident in these results.

The introduction of simulated atmospheric turbulence indicated that the deterioration in handling qualities was sensitive to the representation of the turbulence. With the most severe (and in Canadair's opinion, the most realistic) representation of the turbulence input, the handling qualities

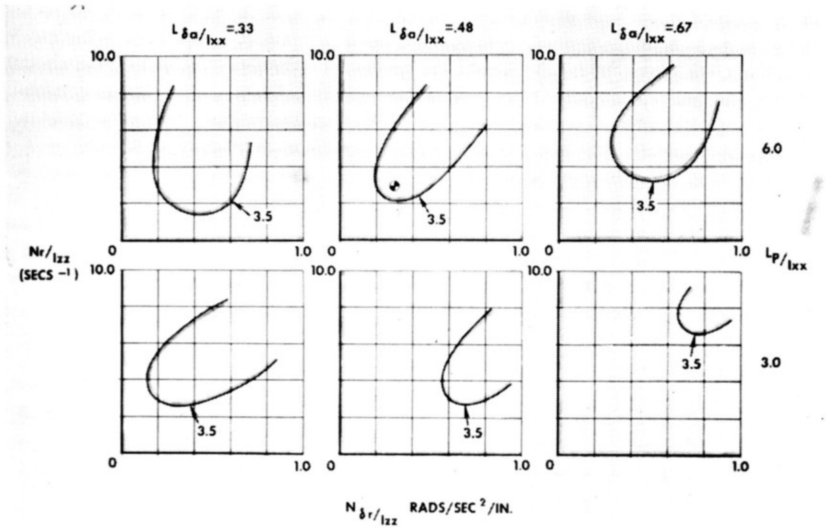

FIG. 5

deteriorated considerably and consistent pilot ratings below 4 were not obtained in any of the cases investigated. One of the prime reasons for this appeared to be the difficulty in maintaining turn co-ordination.

The study also examined the effects of variations in the sideslip stability parameters and the 'cross-damping' derivatives from the estimated values for the prototype, as well as the effects of lateral-directional control cross-coupling. Although these effects perhaps were suppressed by the severe turbulence and the large values of control sensitivity and damping used in this investigation, the results indicated that the handling qualities were not seriously affected by quite large variations in these parameters.

2.2.2. *N.A.E. variable stability helicopter.* In addition to the V/STOL simulation at Canadair, the Flight Research Section of the National Aeronautical Establishment, a Division of the National Research Council, completed several lateral-directional investigations on their airborne V/STOL simulator during the period of the CL–84 prototype programme, with Canadair personnel assistance. This variable stability helicopter used the 'model-controlled' method and has been described in detail(14). Although these programmes were in general in nature and the analogue capacity of the helicopter was inadequate to simulate the specific aerodynamic characteristics of a tilt-wing V/STOL aircraft, the overall trends obtained were believed to be applicable to the CL–84 aircraft. The first of these studies(15) examined the effects of lateral-directional control cross-coupling on handling qualities. Figure 6, which is taken from ref. 15, shows the relationship between Cooper-rating boundaries and the degree of cross-coupling in a V.F.R. hovering and low-speed flight circuit task. The fixed aerodynamic parameters used in the exercise were believed to be typical for the CL–84 at mid-transition speeds. The plot demonstrates clearly the limited amount of cross-coupling tolerated by the pilot for normal operation, but more significantly, it shows the large amount of coupling (cross-coupling approximately equal to prime effect) permissible under emergency conditions.

Two other studies by the N.A.E.(16,17) investigated the effects of weathercock stability and dihedral effect on the directional handling qualities. The visual flight task performed by the pilots included hovering turns, in the presence of simulated wind and turbulence, and a complete circuit terminated by a steep, low speed approach to landing. It was found that as the values of weathercock stability or dihedral effect were raised, large increases in both damping and control sensitivity were required to maintain acceptable handling qualities. However, for values of weathercock stability and dihedral effect representative of those used in the Canadair simulation, the requirements were less severe than those obtained by Canadair. This was considered an expected result due to differences both in the type of simulation and in the generation of the effects of turbulence.

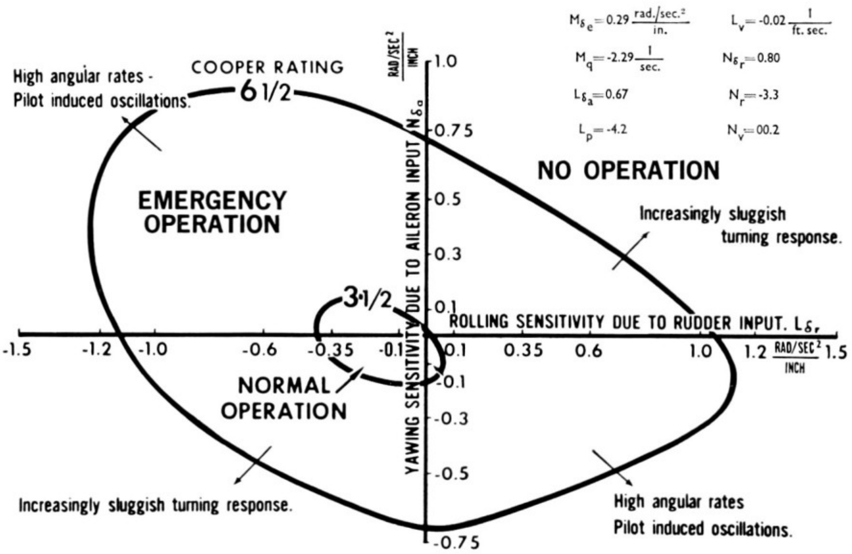

FIG. 6 — Lateral-directional control cross-coupling handling qualities boundaries

2.3. *Prototype system design as influenced by the simulation*

The design specification for the flight control system and the stability augmentation system (S.A.S.) for the CL–84 prototype relied in large measure on the results of the flight simulation design studies.

Because of the dubious advantages of the wing tilt control from the longitudinal stick in relation to the resultant system complexity, it was decided to retain the direct pitch control mode of longitudinal control for the prototype. However, a separately selected, high rate, limited 'wing-up' range was incorporated, in addition to the normal wing tilt rates available from the tilt button, in order to obtain optimum STOL performance capability.

To minimise the effects of pitch trim changes and the moment speed stability term in transition, the angles of the wing trailing edge flaps, the horizontal tailplane and the tail propeller blades were programmed as a function of wing tilt angle. The conventional elevator was connected directly to the longitudinal stick and the pitch control power was kept essentially constant throughout the wing tilt range by programming the tail propeller control authority from the longitudinal stick with wing tilt angle. Independent programming of the lateral stick and the rudder pedal inputs to the differential angles of the main propeller blades and the flap-ailerons, by use of four cams, permitted changes in control authority without affecting the control cross-coupling and vice versa.

The S.A.S. specification called for dualised pitch rate channels in combination with pitch attitude stiffening to ensure acceptable I.F.R. handling qualities in the event of a single failure. In the roll and yaw axes, only single channel rate damping was specified, even though the Canadair simulator was virtually unflyable in hover without roll damping augmentation. This was a result of the less severe requirements obtained by the airborne N.A.E. simulator. However, provisions for 'lagged rate' (equivalent to short term stiffening) were included in both the roll and pitch channels. The S.A.S. actuator outputs were summed with the pilot's inputs upstream of the control programming units, such that the authority of the S.A.S. would be 'faded out' with decreasing wing tilt. The pilot's controls were isolated from the control system and S.A.S. actuator feedback forces by irreversible actuators under the cockpit floor.

For the thrust control system, a blade angle scheduler was added to the otherwise conventional turboprop governing system, such that immediate thrust response would be obtained during hovering and low-speed flight. The scheduled blade angle input was attenuated with blade angle itself, such that only a small input was obtained in cruise.

The cockpit layout of the controls and flight instruments was also strongly influenced by the simulator investigations. In fact, the CL–84 prototype cockpit simulator, derived from the design studies, served as an excellent mock-up of the prototype cockpit.

3. THE CL–84 PROTOTYPE SIMULATION

During the design, construction and flight testing of the CL–84 prototype, the Canadair fixed-base simulator was expanded to a reasonably complete prototype representation of the six degrees of rigid body freedom and the five control degrees of freedom, including the three S.A.S. feedback loops, within a speed range from -20 knots to $+200$ knots EAS. The acquisition of an improved variable stability helicopter by the N.A.E. also permitted a four degree of freedom airborne simulation of the prototype in the hover and low speed flight regime.

3.1. *The Canadair simulation*

It is beyond the scope of this paper to describe the various aspects of the CL–84 prototype simulation in detail. Such an account is given in ref. 18. However, there are some basic concepts involved in the representation that may warrant comment.

The principal expansion of the Canadair simulator from that used in the lateral-directional investigation described above, involved the introduction of a 'multi-point suspension' concept and the inclusion of the vehicle's control system dynamics. A block schematic diagram of the CL–84 prototype simulation is shown in Fig. 7.

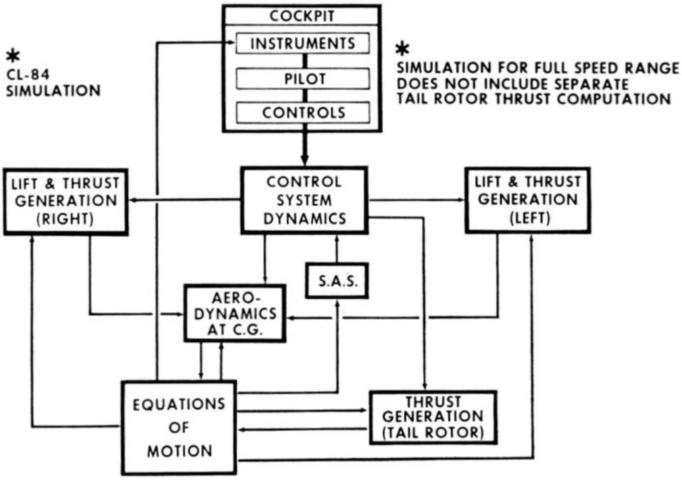

FIG. 7 — Block schematic of CL–84 simulator

In the multi-point suspension concept, part of the aerodynamic reactions were derived separately for the right and the left halves of the aircraft. Due to certain difficulties which would be encountered in the simulation near hover if a conventional free-stream wind axes system were used, the aerodynamic reactions were referred to a slipstream co-ordinate system derived by the method described in refs. 4 and 19. This method also demonstrated that non-dimensional force coefficients based on the slipstream mean dynamic pressure could be expressed as functions of two variables for a given fuselage angle of attack to the free stream. Since the effect of the fuselage angle of attack on the lift and longitudinal forces (at a given free-stream wing angle of attack), were shown to be small by model test data, they were neglected in the generation of these force components.

The force coefficients normal ($C''_{L_{ss}}$) and along ($C''_{X_{ss}}$) the slipstream axis, including the main propeller thrust components, were generated as a function of the slipstream angle of attack (α''_{ss}) and the freestream-to-slipstream velocity ratio (V/V_{ss}) for each half of the aircraft. This generation was effected by an updating of the familiar conducting sheet technique with the aid of modern materials and has been described in detail(12). Each sheet contained three sets of contours, of $C_{L_{ss}}$, for example (Fig. 8), corresponding to three flap-aileron angles, and was adapted to a standard X–Y computer type plotter. The plotter was fed with α_{ss} and V/V_{ss} so that these two para-

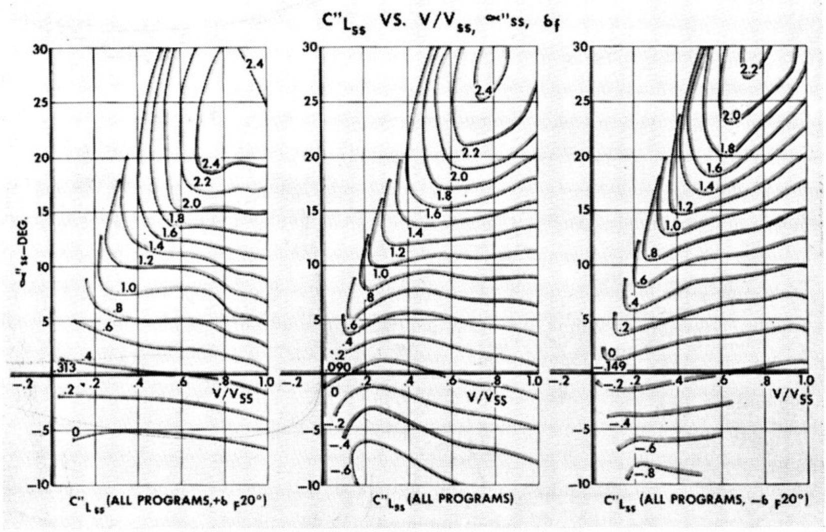

FIG. 8

meters controlled the position of a three probe arm replacing the normal pen carriage (Fig. 9). Linear interpolation between flap angles was achieved by feeding the three signals to taps on a multiple servo positioned with flap-aileron angle as demanded by the cockpit controls and S.A.S. inputs. The effects of the programmed flaps, tailplane and tail propeller (as a function of wing tilt angle), were included in the basic contours under the assumption that the fuselage angle of attack remained close to zero. The components were resolved on to the fuselage body axes and the appropriate contributions from the two halves of the aircraft were summed to obtain the normal force and the longitudinal force components, respectively. Differences between the two halves, scaled appropriately for moment arms and 'carry over' factors, gave the rolling and yawing moments due to differential thrust and flap-aileron angle. The velocity components and slipstream angles of attack were computed relative to the centre of pressure of each half, such that the changes in these quantities due to the rotational velocities about the aircraft centre of gravity were included. Thus, this simulation yielded not only the lift, longitudinal force, rolling and yawing moments of the wing-propeller combination as influenced by the lateral-directional control inputs, but also the first order effects of the lateral-directional damping and cross damping terms. The effects of the empennage were added separately.

The independent and explicit generation of all the contributions to pitching moment in transition flight proved to represent an impossibly complicated simulation. However, by assuming that all the objectives in the programming

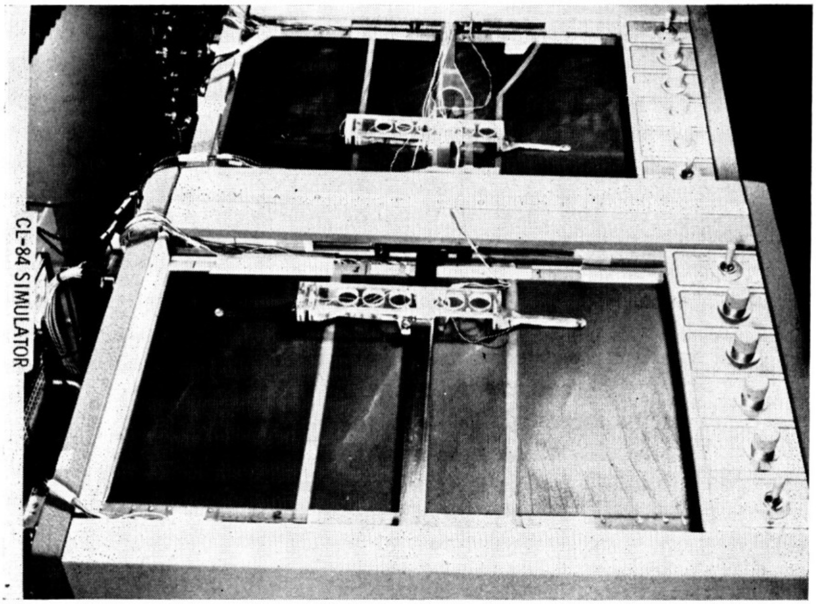

FIG. 9 — C''_{Lss} and C_{Lss} Function generators (for one wing/propeller system)

of flaps, tailplane and tail propeller blade angles, as functions of wing tilt were achieved, the complete 'tail-on' pitching moment with controls neutral for the complete aircraft could be generated for various fuselage angles of attack in a similar manner to the generation of the force components described above. This approach appeared justified from the results on powered, 'tail-on' model test data.

The sideslip terms were assumed to be linear functions of the sine of the 'slipstream sideslip angle' and were generated for the complete aircraft continuously throughout the speed range as functions of wing tilt angle and freestream to slipstream velocity ratio.

The control dynamics simulation was reasonably conventional. However, it should be noted that the lateral-directional cam profiles in the aircraft 'control system mixing box' and the collective main propeller scheduler profile and gain were represented individually on diode function generators. Thus, these functions could be readily altered to represent changes in cam profiles, enabling assessment in the simulator of the effects of such changes on control sensitivity, cross-coupling, S.A.S. damping, etc.

As a result of the decision that the first flights of the CL–84 should be in the hover mode, the initial phase of the prototype simulation was restricted to a transitional speed range of about 20 knots in any direction. This restriction resulted in several simplifications in the set up and permitted a separate and reasonably complete representation of the tail propeller aerodynamic and control system characteristics.

3.1.1. *Results of the hover simulation.* The prime objectives of the hover simulation before the first flight were:

(*a*) To establish optimum S.A.S. and control systems parameters.

(*b*) To determine the effect on handling qualities of various degrees of backlash, lag and flexibility in the control system.

(*c*) To assess the effect of various types of S.A.S. and control system malfunctions.

(*a*) As a result of pilot's comments, small modifications to both the pitch and roll parameters were required. Analysis of the records of the pilot's control movements indicated that a more heavily damped response with a longer rise time would be beneficial as a result of the 'over-shoot and check' type of control inputs used in hover. Thus, the pitch and roll rate damping values were increased, and the pitch stiffness decreased. It was also found beneficial to reduce the roll control sensitivity to $\frac{2}{3}$ of the original design value.

With these modified parameters, the Cooper Ratings of the simulator varied between $1\frac{3}{4}$ and $2\frac{1}{2}$ ('Pleasant to fly', 'Good').

(*b*) The effects of backlash in the four primary control systems were evaluated first separately and then in combination. (The effect of backlash in the wing tilt system was not evaluated). As ground tests on the aircraft proceeded and more information became available on the actual characteristics of the aircraft systems, the fixed-base simulator was supported by similar investigations on the N.A.E. variable stability helicopter. In the cases involving both large backlashes and S.A.S. failures, the fixed-base simulator was found to be of no value in that it was virtually unflyable with roll or pitch S.A.S. out, even without backlash.

The backlash in the height (thrust) control system involved both backlash between the pilot's power lever and the engine N_1 governors, and between the propeller governor/scheduler assembly and the propeller blade servos. It was found that propeller blade servo backlash had a relatively minor effect, while anything more than 1° ($\frac{1}{8}$ inch at the pilot's hand) in the power lever circuit caused serious deterioration of the height control. Figure 10 shows the pilot rating boundaries for combinations of the two backlashes, both from the fixed base simulator and the N.A.E. tests. The results are similar, but the pilots were clearly less sensitive to power lever backlash in the V.F.R. airborne simulator.

The original values of backlash in the pitch and roll circuits, as measured in system tests on the aircraft, produced Cooper Ratings of 6 to 7 ('barely acceptable' to 'unacceptable' for emergency operation). It was eventually found possible to reduce the roll and pitch control lost motions to a small

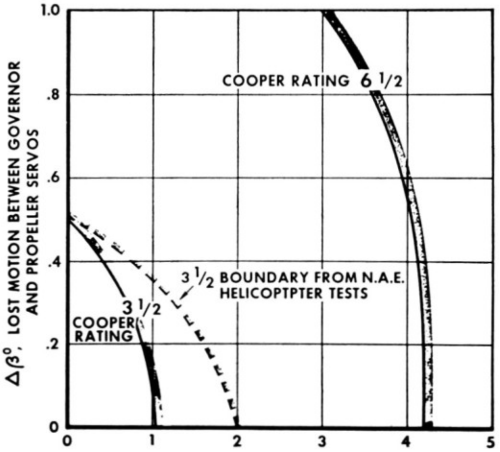

FIG. 10 — CL–84 hover simulation. Effect of lost motion in engine/prop control system on height control

fraction of the above values before flight (*see* section 4), and the resulting ratings were close to those for zero backlash.

The yaw control circuit proved to be the least critical of the three angular controls and at the same time, the one with which the least difficulty was experienced on the actual aircraft. The effects of the measured backlash were evaluated on the simulator and found to be insignificant.

Failure of either the roll or the complete pitch S.A.S. rendered the fixed-base simulator virtually unflyable, even without backlash. However, a single failure in the pitch S.A.S. system only degraded the pilot rating by $1\frac{1}{2}$ in the worst case (without backlash).

As in the case of the backlash, the yaw axis proved the least critical with S.A.S. failure.

During the last phase of the hover simulation, the effect of ground proximity on lift, as obtained from model tests, was included in the representation. The staple ground cushion proved quite detrimental to height control, particularly in combination with appreciable backlash in the height control system.

3.1.2. *The complete speed range simulation.* The period during which the final full six degree of freedom simulation has been available (since October 1965 up to the present time), has coincided with an intensive Flight Test programme on the CL–84. Thus the type of detailed, systematic programme which was carried out in the previous studies has been considered neither practical nor appropriate. The full simulation indicated from the outset that all the main handling qualities problems had been solved throughout the hover, transition and low speed conventional flight regimes, at least as far as the simulation was concerned. The overall pilot ratings of the simulator has ranged between $2\frac{1}{2}$ and 4, depending on the details of the task and pilot familiarity with the simulator.

Thus, it was necessary to await problems in flight and as had been envisaged at the outset, the main function of the simulator in this phase of the aircraft development has been in support of the Flight Test programme. In this capacity, the simulator has been used to give the pilots an indication of the effect of such changes as removal of the tail-rotor (for 'conventional-flight' investigations). Certain Stability Augmentation System gains which had been optimised for hover before the first (hovering) flights, were re-assessed in transition and conventional flight, and two of these gains were changed on this basis. Also, since both rolling and vertical take-offs are provided for, the pilots were able to familiarise themselves with the trim changes to be expected throughout the flight regime from 0 to 200 knots, before actual transition flights and STOL take-offs and landings were attempted.

In addition to serving as a useful pre-flight training aid for new CL–84 pilots, the simulator, as presently developed, is capable of reproducing, with reasonable accuracy, the effects on handling qualities of the following:

Changes in stability augmentation system gains
Changes in control mixing-unit programmes
Changes in propeller governor and scheduler characteristics
Backlash and lost motion in any control system (including engine/propeller controls)
Flight with tail rotor removed, or stopped and stowed
Failure of one engine
Failure of various components of the stability augmentation system separately or together
Partial hydraulic system failures
Trim changes during take-off and landing (VTOL and STOL), including ground restraints and ground proximity effects.

The simulator has also proved valuable for performance prediction, particularly for short take-off performance for various weights under varying temperature and altitude conditions.

3.2. *Results of the N.A.E. simulation*

The simulation of the prototype using the N.A.E. airborne simulator, shown in Fig. 11, was restricted to the hover and low speed flight regimes. The programme was undertaken to assess in flight, under V.F.R. conditions, the influence on the handling qualities of backlash and flexibility in various

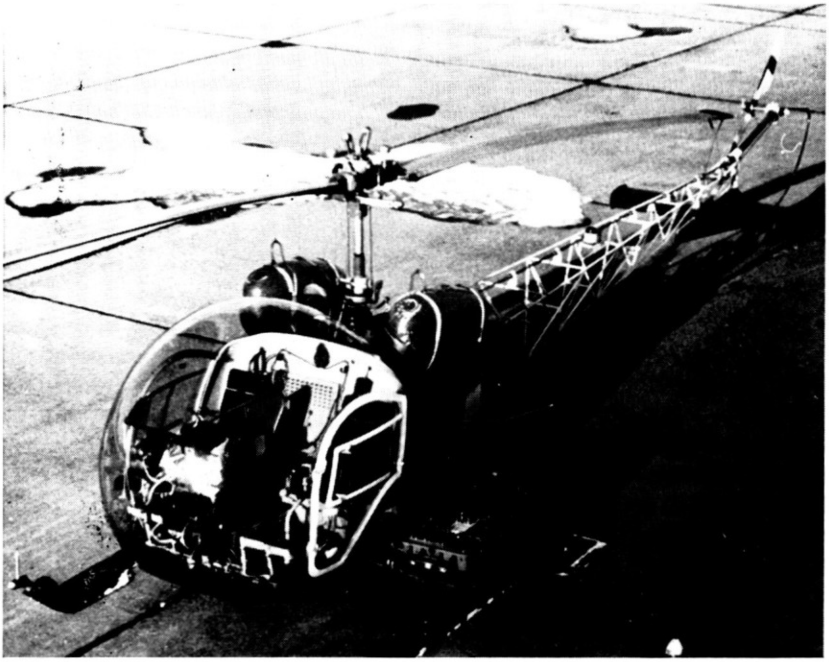

FIG. 11

locations in the control system, and of various stability augmentation failures in the presence of these backlashes. Thus, this investigation supplemented the Canadair fixed-base hover simulation under conditions more similar to those of the first flight of the aircraft. Results were obtained while changing the various parameters in the three rotational degrees of freedom, as well as in the vertical mode of motion and are presented in detail in ref. 20.

The investigation confirmed that the change in the height control lever, from a helicopter collective type to a power lever type, presented no difficulty to the pilots after the first trip. The basic aeroplane, without backlash and with the S.A.S. fully operative, was rated 2 on the Cooper Rating scale.

It was found that the handling qualities detiorated with the introduction of backlash, as in the fixed-base simulation; however, the deterioration was not as rapid. With the worst cases of backlash investigated, the airborne simulator rated no worse than 5·5 while the fixed-base simulator was virtually unflyable. Similar comparisons were obtained with respect to S.A.S. failures in pitch and roll. With all S.A.S. channels failed simultaneously, the airborne simulator rated 5 to $5\frac{1}{2}$, without backlash in the control system. Thus, it was possible to obtain meaningful ratings with combinations of backlash and S.A.S. failures. It was found that only the lowest set of values of backlash and first order lags investigated fell within the 6½ pilot rating boundary with all S.A.S. channels failed.

It is believed that the testing performed in this airborne simulator was invaluable in preparing the Canadair pilots for the subsequent flights in the prototype aircraft. The investigation also helped in interpretation of the results from the fixed-base simulator.

4. PROTOTYPE GROUND AND FLIGHT TESTING

Ground testing of the prototype aircraft began in January, 1965. The testing was done with the aircraft tied down at the landing gear struts by strain-gauged arms to a heavy steel rig. Following the attainment of satisfactory operation of the propulsion system, the control system functioning for hovering flight was tested in detail. Cost and schedule considerations had prevented any testing of the system before installation and, as a result, numerous minor deficiencies were revealed during the early testing. Since, both simulators had indicated the importance of reducing backlash and lag, considerable time and effort was expended in improving the control system by a series of small modifications, consisting of pre-load springs, local stiffness increases, elimination of fouling and undue friction and additional actuators in the main propeller pitch control circuits.

The first hover flight of the CL–84 took place on May 7, 1965, with Canadair's Chief Test Pilot at the controls. During the four short lift-offs, some difficulty in height and pitch control was experienced by the pilot in his effort to keep the aircraft within the first five feet of altitude (*see* section 5). However, on the following flights within this period, the pilot's handling of the aircraft was quite impressive. Although the flight envelope explored was very small with respect to speed and height (– 10 to 25 knots, zero to 25 feet), the manoeuvre envelope established was quite large with regard to linear and angular accelerations and angular rates and displacements.

The six months following the first hover flights were devoted to systems development and endurance ground testing, with the exception of another short period of flights in August. Considerable progress was made during these flights; demonstration of (*i*) acceptable handling qualities in hover with the S.A.S. completely de-activated and (*ii*) adequate control in winds gusting to 25 knots; sustained flight with hands of the controls; forward flight from hover to 33 knots and return to hover; flight at the targeted VTOL gross weight; and check-out of the assistant project pilot.

After replacement of ground test hardware and various modifications generated by ground testing, the aircraft was ready for flight in mid-November, albeit without the tail propeller. As a result of extensive testing, it had been decided to redesign and strengthen parts of the tail propeller.

The first flight as a 'conventional' aeroplane took place on December 6 with the wing fixed at 15° tilt angle. During the seven subsequent flights, the wing was lowered to 0° and the fixed gear limited airspeed of 175 knots E.A.S. was reached. No serious problems were encountered in these flights, although caution in the use of power for take-off had to be exercised (*see* section 5).

The aircraft was ready for flight with the modified tail propeller by late December. Following a few check-out flights, the bridging of the gap between hover and wing tilt 15° was accomplished in two flights on January 16.

The first of these involved two passes down the runway at about 30 ft height from hover to wing tilt 30° and 20°, respectively, and back to hover. On the subsequent flight, transition from hover to wing tilt 15° was made over the runway, followed by a climb-out, a partial circuit and a decelerating, descending, turning inbound transition approach to hover over the runway. A full transition was made on the following day and, during the subsequent ten days, twenty full transition flights were made and some experience was obtained in short take-off and landing and in slow, steep descents.

Progress of the aircraft was steady in the following four months; the landing gear was retracted in flight in February, $2g$ at 200 knots was reached in March, as well as hover in winds gusting to 35 knots, sustained level turns at 50 knots with a turn radius of less than 200 feet were accomplished in April, and stopping and starting of the tail propeller in flight was accomplished in May.

On June 9, the aircraft was making a routine inbound transition after test flight No. 110 when a malfunction of the propeller governing system resulted in large r.p.m. and thrust variations. The attendant lift and pitching moment changes resulted in a partial loss of control, and the aircraft sustained damage in the subsequent heavy landing on the runway. No injuries to the crew of two occurred. During the repair, the opportunity was taken to equip the prototype with dual controls, dual ejection seats and modified nacelles as previously planned for this summer. This work was completed in August and the aircraft is expected to be ready for flight in mid-September 1966.

5. Comparison of Results from Flight Tests and Simulation

Up to the present time, little systematic stability and control data have been obtained from the CL-84 flight tests. One of the many reasons for this is perhaps that few significant problems have been encountered in flying qualities. The many thousands of feet of oscillograph flight test records have received only cursory examination in most cases since proper analysis is both difficult and time-consuming when too many parameters vary simultaneously.

Some typical pitch control data obtained from steady state flight testing are compared with estimates in Fig. 12. Since the fixed-base simulator total control power is based on the assumption that the estimates of the combined control powers of the tail propeller and the elevator are correct, elevator and tail propeller angles do not appear explicitly in the simulation and a direct comparison with the flight test data is not possible. However, if it is assumed *a priori* that the simulator computes correctly, the resultant control power in the simulator corresponds to that represented by the estimated angles of the tail propeller and the elevator. The good agreement shown in both steady level and descending flight indicates that both the control power and the 'tail on, tail propeller on, fully programmed' pitching moments used in the simulator, correspond well with the actual values of the aircraft.

C.G. AT 30% MAC

AIRSPEED K.	TILT ANGLE	DESCENT ANGLE-DEG.	ELEVATOR ANGLE-DEG.		TAIL ROTOR β-DEG.	
			ESTIMATED	FLT. TEST	ESTIMATED	FLT.TEST
45	40	0	-3.8	-3.6	+5.5	+5.5
36	50	0	-2.6	-2.0	+7.6	+7.5
28	60	0	+1.4	-0.3	+9.5	+11.0
18	70	0	+3.6	+3.2	+12.0	+11.9
90	16	15	-5.7	-6.5	-1.6	-1.5
70	26.5	11.5	-5.4	-4.5	+0.5	+1.0
57	31	12.1	-5.2	-4.5	+3.1	+2.8

FIG. 12 — Canadair CL–84 comparison of flight test and estimated pitch control data

A comparison of power required versus speed through transition, cannot be made at this time due to insufficient flight test data. A few reliable points obtained at about 40 knots agree well with values obtained in the simulator. It should be noted here that the accurate computing of this quantity in the simulator requires precise adjustment of all the function generation and servo equipment, a characteristic that tends to slow up STOL performance work.

From the various hover flights and ground tests, it has been possible to derive the control sensitivities and the damping values of the aircraft. Figure 13 shows a comparison between the aircraft and the fixed-base simulator† of total control power, control sensitivity, natural damping, artificial damping, artificial stiffness and S.A.S. authority, in hover. The total control power has been derived by extrapolation, in that full control has never

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† The values used in the N.A.E. airborne simulator were essentially the same as those of the fixed-base simulator.

been used in any one axis as the aircraft went through zero rate. The natural damping values in roll and pitch are somewhat uncertain, while that in yaw is considered to be fairly accurate. The variations of control power with forward speed for the aircraft, as indicated in the footnotes, have been established to be within ±10% of the simulator values.

PARAMETER	ROLL		PITCH		YAW	
	A/C	SIM.	A/C	SIM.	A/C	SIM.
CONTROL POWER-RAD/SEC^2	1.8 (1)	1.8	±1.35 (2,3)	$^{+1.12}_{-1.87}$	0.45 (4)	0.40
CONTROL SENSITIVITY-RAD/SEC^2/IN (HOVER ONLY)	0.36	0.36	0.41	0.375	0.21 (5)	0.135
NATURAL DAMPING-PER SEC (HOVER ONLY)	0.6	0.6	0.4	0.5	0.4	0.4
ARTIFICIAL DAMPING-PER SEC	2.4	3.6	3.6	3.6	1.8	2.15
ARTIFICIAL STIFFNESS-PER SEC^2	-	-	1.8	1.8	-	-
S.A.S. AUTHORITY - %	32	42	51	50	41	37

1 ROLL CONTROL POWER DECREASES TO ABOUT 70% AT 50 KNOTS, THEN INCREASES WITH SPEED IN BOTH CASES.

2 PITCH CONTROL POWER IS CONSTANT WITH SPEED IN SIMULATOR, INCREASES SLIGHTLY IN AIRCRAFT.

3 CONTROL SENSITIVITY IN AIRCRAFT IS NON-LINEAR DUE TO CHARACTERISTICS OF TAIL PROPELLER.

4 YAW CONTROL POWER INCREASES TO ABOUT 0.8 AT 80KNOTS IN BOTH CASES.

5 "UP" AILERON HITS STOP AT 70% RUDDER PEDAL TRAVEL.

FIG. 13 — Comparison of control powers, sensitivity and damping for hover (and transition)

It will be noted that the aircraft has somewhat less artificial roll damping than that represented in the simulator. This reduction was not by intent, but since it has not influenced the handling qualities noticeably, the mistake has been left uncorrected. The considerably higher yaw control sensitivity in the aircraft is partly due to a larger value of control power and partly due to intentional 'over-travel' of the controls. The artificial yaw damping saturates at 5 degrees per second yaw rate so that for any rates above this value, the total control power in the direction of the yaw would be reduced by 41% if full pedal travel corresponded to full aileron. By use of the over-travel, the available control power is reduced by only 20% with the S.A.S. saturated. This has proved of value in turning out of strong winds in hover.

The height control sensitivity in the aircraft (not shown in Fig. 13) has been demonstrated to be $0{\cdot}2\,g$ per inch, the same value as that used in the simulation.

In general, the dynamic behaviour of the aircraft throughout the flight regime appears very similar to that of the fixed-base simulator. In particular, the roll and pitch oscillations in hover with the S.A.S. failed are almost identical to those obtained in both the fixed-base and the airborne simulators.

The best overall comparison between the aircraft and the simulators is perhaps obtained by comparing the pilot ratings. Figure 14 shows the pilot ratings of the CL–84 in hover, including landing. With all systems operative, the overall rating of the aircraft is 2·5 as compared with the 'no backlash' values of 2·0 for the airborne simulator and $2\frac{1}{4}$ for the fixed-base simulator.

RATING REFERENCE	CASE- S.A.S. AND HYD. SYSTEMS OPERATIVE	S.A.S. 'FAILED'	PRIMARY HYD. SYST. 'FAILED'	SECONDARY HYD. SYST. 'FAILED'
PITCH	2.5	2.5 (1)	2.5	6 (2)
ROLL	2.5	4	2.5	3.5
YAW	2	2	3.5	2
HEIGHT	2	2	5.5	2
OVERALL	2.5	4	5.5	6 (2)

NOTES: (1) ON BASIS SINGLE FAILURE IN PITCH CHANNEL, WHICH IS DUPLICATED. WITH S.A.S. COMPLETELY INOPERATIVE COOPER RATING IS 5.5

(2) DUE TO EXCESSIVE FRICTION IN CONTROL SYSTEM. CAN PROBABLY BE REDUCED TO RATING 4 OR BETTER

FIG. 14 — Canadair CL–84 preliminary pilot ratings in hovering and vertical landing. Ref. Cooper rating scale

In 'single failure' of the S.A.S., the aircraft rates 4; the most comparable rating without backlash (roll failed only) on the airborne simulator was about 4 to $4\frac{1}{2}$ and the fixed-base simulator was essentially unflyable (7–8). With the S.A.S. completely inoperative, the aircraft rates 5·5 and the N.A.E. simulator rating was 5 without backlash.

Hydraulic system failures were investigated on the fixed-base simulator by introducing heavy cockpit control loads and cockpit servo valve backlash. In the simulation of the primary system failure, sufficient roll damping was retained to yield the same rating, with the hydraulics on, as the airborne simulator with the roll S.A.S. failed. This was done since no meaningful result could be expected from the fixed-base simulator with the roll S.A.S. damping completely removed. Failure of either hydraulic system rendered the simulator marginally flyable with Cooper ratings of 6 to $6\frac{1}{2}$. These ratings are only slightly worse than the overall ratings obtained for the aircraft. However, it must be admitted that the friction load in the longitudinal circuit of the aircraft was considerably larger than that expected (and used in the simulation), as indicated in Fig. 14.

The pilot ratings for the CL–84 in transition and STOL flight are shown in Fig. 15. It will be observed that these ratings fall within the $2\frac{1}{2}$ to 4 ratings obtained in the fixed-base simulator. The flight evaluation of the S.A.S. failure has not been completed in this flight regime.

RATING REFERENCE	CASE- TRANSITION	STOL (1)
PITCH	2.5	2.5
ROLL	2	2.5
YAW	3	2.5
THRUST	3	3
OVERALL	3	3

NOTE: (1) S.A.S. OPERATIVE; INOPERATIVE CASE NOT YET ASSESSED

FIG. 15 — Canadair CL–84 preliminary pilot ratings in transition and STOL flight. Ref. Cooper rating scale

Figure 16 shows the pilot ratings of the prototype in conventional flight Again the overall ratings fall within the band obtained in the fixed-base simulator. The ratings in yaw with S.A.S. in and out deserve comment. The flight test records have shown that small yaw disturbances occur immediately following either power lever or propeller governor actuator motions and it would appear that the changes in blade angles on the two propellers are slightly out of phase. In an effort to reduce these effects, the control system mixing box was re-rigged so that a small authority of differential blade angle from rudder pedals and yaw S.A.S. actuator remained with the wing locked down. It is evident from the ratings that the pilot is quite sensitive to these yaw disturbances.

Both the values and the hazards of fixed-base simulation have been demonstrated several times during the prototype flight test programme. The positive ground effect on lift in hover was included in the fixed-base simulation about one week before first flight. Although favourable on performance,

RATING REFERENCE	CASE- S.A.S. OPERATIVE	S.A.S. INOPERATIVE
PITCH	— (1)	2
ROLL	2	2.5
YAW	2.5	3.5
THRUST	3	3
OVERALL	3	3.5

NOTE: (1) NOT EVALUATED

FIG. 16 — Canadair CL–84 preliminary pilot ratings in conventional flight. Ref. Cooper rating scale

the ground cushion rendered the aircraft prone to pilot-induced oscillations in height near the ground, particularly with appreciable backlash in the height control circuit. Unfortunately, only the assistant project pilot had experienced the effect of the ground cushion in the simulator before first flight. Subsequent to encountering this difficulty during the first four lift-offs in the aircraft, the chief pilot practised on the simulator and demonstrated steady hover at all heights within the ground cushion during the following hover flights in the aircraft. Since that time, the height control of the aircraft has been improved considerably and it is not expected that any competent pilot would experience similar difficulties at this time, provided he was properly briefed in advance.

In the simulation before first 'conventional' flight, without the tail propeller, the fixed-base simulator indicated two possible problem areas. The first one involved take-off at near-maximum available power. Following such a take-off with a wing tilt angle of 15 degrees, the simulator would end up in a low speed, steep climb with the longitudinal stick hard against the forward stop. (It should be noted here that the tail propeller normally produces a considerable upload, even with the control neutral under these conditions.) Thus, the maximum power to be used for such take-offs in the aircraft was restricted by decree. On one occasion, the pilot exceeded this power by a substantial margin, ran out of pitch control and aborted the take-off by a rapid reduction in power.

The second problem area defined by the simulator was caused by the effect of ground proximity on the pitching moment in landing. This strong nose-down pitching moment change made it almost impossible to touch down consistently at low sinking speeds. It was realised by the engineering staff that this problem would be significantly alleviated under actual V.F.R. flight conditions, but both project pilots expressed considerable concern. Following the first conventional flight in the aircraft, the chief pilot reported that he was unaware of any adverse effects during touchdown. However, the flight test records showed that the longitudinal stick moved from about one inch aft to almost full aft during the flare, without any appreciable change in aircraft altitude.

During the first attempts at STOL approaches, great difficulty was experienced by the pilot with height control in the final flare-out. These tests were done at relatively light weights in very cold weather and it was suspected that the cause of the difficulty was the 'off-design' operation relative to the main propeller blade angle scheduler. The simulator was set up with the scheduler biased to give the same type of R.P.M. response that had been obtained from the flight records. However, the pilots found the control of the flare-out little affected, and analysis of the simulator records showed that the thrust transients due to the poor governing were of too short a duration to affect the type of height control required. A re-examination of the flight test records indicated that the engine compression bleed-valves were open during the approach, but closed when power was applied for the flare. This resulted in a sudden surge of power, considerably in excess of that anticipated by the pilot. Due to the hysteresis characteristics of the bleed-valve operation, a large aft movement of the power lever was required to re-open the valves. With the characteristics of the bleed-valve operation included in the simulation, the height control on final approach was of the same order of difficulty in the fixed-base simulator as in the aircraft. Subsequently, the bleed-valve settings in the aircraft were adjusted to prevent their operation in the critical regime.

During Flights 51 to 54, a marked deterioration in lateral-directional control was reported by the pilot. Analysis of the flight records showed that while all the controls appeared to be functioning properly, the aircraft 'hands-off' roll behaviour in hover matched that of the simulators with the S.A.S. failed and, in attempts to perform steady sideslips in transition, only 8° of sideslip was produced for almost fully crossed controls. It was deduced that the appropriate differential blade angle signals were not reaching the propellers, in spite of the indications from the control system instrumentation. Accordingly, the simulator was set up with ±1° of backlash in the differential blade angle circuit. Behaviour of the simulator almost exactly matched that of the aircraft in the steady sideslips in transition. Subsequent checks of the aircraft revealed that, due to changes in the Propeller Pitch Control Units, a backlash of about ±1° had indeed developed downstream of the control instrumentation. Rectification of this fault restored the lateral-directional control to normal.

Attempts to simulate the events before the hard landing in June have not been fruitful. However, since no flight test records are available, the simulation must rely upon speculative inputs and emotional memories. Under these conditions, proper simulation is probably impossible.

6. CONCLUSIONS ON THE VALUE OF SIMULATION

Flight simulation has been an integral part of the CL–84 prototype design, development and flight test programme. As judged from the experience gained so far, the following conclusions can be drawn of the value of the simulation to the various phases of the programme:

1. The I.F.R., fixed-base simulation design studies, which were completed before the detailed design of the aircraft, defined the control and stability requirements for the vehicle sufficiently well throughout the flight envelope to yield final design specifications for the flight control and the stability augmentation systems. In addition, these investigations illuminated certain characteristics of the configuration, such as the dominant effect of the speed

stability terms and the requirements for the cockpit control and instrumentation layout. The results from the N.A.E., airborne simulator increased the confidence in the fixed-base simulator findings.

2. The six degrees of freedom, fixed-base simulation of the prototype served to finalise the control and stability augmentation system gains before flight in all regimes. While this simulation proved useful in defining the acceptable levels of backlash and lag in the control system, the simulation grossly exaggerated the effects of S.A.S., failures in hover.

3. The airborne simulator predicted accurately the handling qualities of the prototype in and near hover, both with the S.A.S. operative and 'failed'. However, the airborne simulation was restricted to hover due to the limited capacity of the helicopter computer.

4. The combined use of a fixed-base, I.F.R. simulator, with a sophisticated representation of the complete flight characteristics of the aircraft, and the airborne simulator, representative of the aircraft only in a restricted flight regime, has proved most valuable in that comparison of the results from the two facilities in hover have assisted in interpretation of the fixed-base simulator results in the other flight regimes.

5. The simulation has, without doubt, been of great value to pilots. In an aircraft with as novel characteristics as the CL–84, pilot familiarisation with the characteristics of the aircraft before flight must be considered essential. The pilot's confidence in both the aircraft and the simulator is perhaps best evidenced by the rapidity with which the transition from hover to conventional flight was accomplished.

6. The fixed-base simulator has been of considerable use in analysing certain phenomena which have been uncovered in the flight test programme, and should continue to serve a useful purpose in support of future flight test work.

7. Certain performance and handling characteristics, such as STOL performance and the recovery from engine failure, have been defined with reasonable confidence on the simulator. These results should reduce both the time and the risk involved in investigating such characteristics in the aircraft.

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