service, and the arrangement is shown in Fig. 24. The U-shaped dock was to act as a loading platform and allowed the SR.N2 to dock rapidly at any state of the tide. This arrangement is, of course, very similar to the flying-boat dock, once a more familiar scene than it is now.

7. Conclusions

We hope that the operational results discussed in this paper have helped to show that the hovercraft (i.e., air-cushion vehicle) is already a very safe and comfortable vehicle which has been developed to the point where it is a suitable and competitive form of transport for relatively short, sheltered-water routes.

There also appears to be a significant place for the smaller, high-performance utility hovercraft for rescue, exploration, and out-back transport roles in the more undeveloped and barren areas of the world. For the first time we have a nonflying craft that can traverse grassland, ploughed fields, mud, sand, snow, and water with almost equal ease, providing the discontinuities are not too great.

For the opening up of an area we think we may well see vehicles operating over bulldozed tracks, these tracks possibly being slightly concave in section and devoid of trees, shrubs, and boulders. This will allow a simpler, cheaper craft to operate at quite nominal clearances (and if twin guide tracks or "single line" working is used, the risk of collision is avoided).

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Application of Flight Simulators to the Development of the A-5A Vigilante

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The development and use of flight simulators as an aid to solving many of the critical design problems encountered during the design and development of the A-5A Vigilante are briefly traced in this paper. Flight simulator studies, piloted and nonpiloted, played an important role in the development of the airplane. The early determination of roll coupling problems due to high spoiler-slot-deflector yawing and pitching moments and the subsequent correction of the problems through the incorporation of the inverted spoiler-slot-deflector system can be attributed to the use of flight simulation. In addition, it is shown that the criteria for determining satisfactory lateral-directional and longitudinal handling qualities established by piloted flight simulator studies are in good agreement with pilot opinion from flight test.

Nomenclature

b = wing span, ft
$C_{1/2}$ = cycles to damp to half amplitude, cycles
C_l = rolling moment coefficient
C_n = yawing moment coefficient
f_n = natural frequency, cps
Fs = stick force, lb
g = acceleration due to gravity, ft/sec²
I_x = roll inertia, slug-ft²
K = function of the period of an oscillation
L = roll acceleration, $qSbC_l/I_x$, deg/sec²
n = load factor, g
P = period of oscillation, sec
$|p_1|$ = amplitude of roll rate oscillation at first overshoot, deg/sec
$|p_{ss}|$ = absolute value of steady-state roll rate, deg/sec
PR = pilot rating
q = dynamic pressure, psf
S = wing area, ft²
$T_{1/2}$ = time for oscillation to damp to half amplitude, sec
$|v_e|$ = amplitude of lateral equivalent velocity oscillation, fps
β = sideslip angle, deg
δ = appropriate cockpit control deflection, deg or in.
ζ = damping ratio of oscillatory mode
$|\phi|$ = amplitude of bank angle oscillation, deg
τ_p = roll mode time constant, sec

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Introduction

HANDLING-QUALITIES requirements for military aircraft provide invaluable guides in tailoring the design of piloted vehicles to meet the pilots' needs. However, with each advancement in vehicle design and each change in mission requirement there has been a corresponding new set of

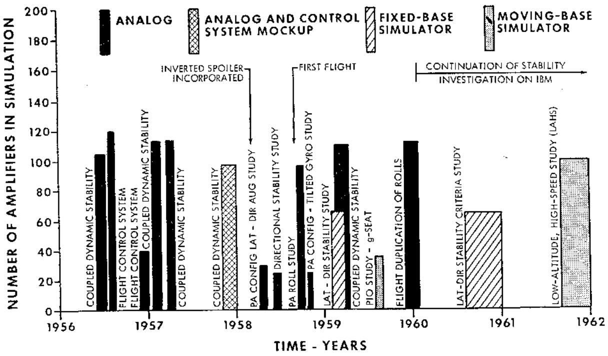

Fig. 1 Summary of simulation studies.

handling-qualities problems unique to that particular vehicle for which a solution must be found. These problem areas, in past years, have remained undefined until the actual flight-testing phase of development. This has been costly both in loss of time and in additional expenses incurred in making necessary modifications late in the development cycle.

Realizing the shortcomings of this approach, flight simulators were introduced early in the development of the Vigilante as a means of defining the stability and control problems and obtaining their solutions in the least possible time. Fourteen extensive simulation programs were conducted specifically in support of the Vigilante development. Two of these programs included the pilot in the loop, one with a fixed base simulator, the other with a moving base simulator. In addition, the results from two piloted flight simulation research programs, sponsored by the Stability and Control Branch of the Bureau of Naval Weapons, were of considerable help in defining the flight characteristics considered to be satisfactory by the pilots.

The results of other research programs, which were conducted both by government agencies and industry, were utilized extensively as guides in orienting the in-house efforts. These programs included ground-based flight simulation, variable stability aircraft, and the servo-analysis techniques as applied to the closed-loop, pilot-vehicle-control system combination. In particular, the results presented in Refs. 1–3 concerned with the longitudinal stability and control characteristics were used in the analysis of the A-5A flying qualities. Although a discussion and comparison of actual flight-test results with the results of all these research programs would be highly desirable, it is beyond the scope of this paper. However, comparisons of flight evaluations with simulation results are presented for those programs that were intimately related to the Vigilante development.

History of the Use of Simulation in Development of the A-5A

The major investigations of the Vigilante's handling qualities have been conducted through the use of piloted and non-piloted simulation. The initial studies were all made using maximum rate control inputs through the simulated control systems to study the basic airplane response characteristics. Piloted simulators were used where pilot opinion was considered the major input to design direction, and existing design criteria were not considered adequate.

A summary of the major simulator studies conducted in support of the design and development of the A-5A airplane by the Flying Qualities Group is presented in Table 1, indicating the type of study and the significant results. A bar chart showing the relative size of the simulator studies and

Table 1 Simulator studies

Study	Date	Type study	Significant results
Coupled dynamic stability, project cyclone	May 1956	Analog	Investigation of augmentation schemes. Determined that spoiler-horizontal and spoiler-vertical interconnects were required to stabilize roll maneuvers
Flight control system, electronic associates computer center	June 1956	Analog	Design study of the pitch augmentation system
Flight control system, RADAC	Dec. 1956	Analog	Pitch augmentation system gain schedule determination
Coupled dynamic stability, Downey, Calif., first phase	Jan.–Feb. 1957	Analog	Maneuvers were evaluated with pitch augmentation and yaw augmentation and interconnect systems incorporated
Coupled dynamic stability, Downey, Calif., second phase	March–April 1957	Analog	Parametric study indicated that the interconnect could be eliminated by reducing $c_{n_{\delta_{sp}}}$
Coupled dynamic stability, servo lab	Nov.–Dec. 1957	Analog and mockup	Evaluation of spoiler-vertical interconnect and proved inverted spoiler eliminated need for spoiler-vertical interconnect
Lateral-directional augmentation study power approach configuration (PA) RADAC	April 1958	Analog	Investigation of roll damper, yaw damper, and stability augmentors plus a parametric study to improve lateral-directional qualities in PA
Directional stability study RADAC	May 1958	Analog	Minimum level of $Cn_\beta = 0.0005$ established
PA roll study, RADAC	Aug. 1958	Analog	Determined PA rolls satisfactory to meet specification requirements. Determined magnitude of pitch-down caused by spoilers
PA tilted gyro study, RADAC	Oct. 1958	Analog	Improved lateral-directional characteristics in PA with tilted gyro
Lateral-directional simulator study, RADAC	Feb. 1959	Fixed base simulator	Results led to navy contract and later to lateral-directional criterion
Coupled dynamic stability, servo lab	Feb.–March 1959	Analog	Further evaluation of inverted spoiler-slot-deflector configuration, recommended reduced spoiler deflection for supersonic roll maneuvers
Longitudinal control sensitivity study dynamic simulator, g seat	Sept. 1959	Dynamic simulator, g seat	Duplicated the airplane flight characteristics and investigated the stabilizing effects of increased stick to stabilizer gearing, viscous stick damper, and bob weights
Coupled dynamic stability flight-test support, RADAC	Dec. 1959–Jan. 1960	Analog	Duplicated flight-test rolls and predicted roll characteristics at other conditions. Determined the variation of spoiler-slot-deflector yawing and pitching moment with sideslip angle
Lateral-directional stability requirements, flight simulator study, servo lab	Aug.–Dec. 1960	Fixed base simulator	Evaluation of the lateral-directional design criteria $1/T_{1/2}$ and $\|p_1\|/\|p_{ss}\|$
Low-altitude, high-speed dynamic simulator study, servo lab	March–June 1962	Dynamic simulator, g seat	Investigation of the dynamic longitudinal characteristics during low-altitude, high-speed flight

significant events during the airplane development is presented in Fig. 1. It should be noted that following the development phase of the airplane the nonpiloted simulation studies were transferred to IBM. This made it possible to continue brief investigation of the airplane response characteristics without having to set up or maintain an analog simulation.

Early wind-tunnel data were used to study the longitudinal, lateral, and lateral-directional characteristics of the airplane throughout the flight envelope. The first study was a five-week program conducted on the Reeve's Instrument Corporation analog equipment at Project Cyclone in New York City. Maneuvers investigated were the conventional airplane longitudinal, lateral, and lateral-directional response characteristics to control surface deflections. In conjunction with the basic airplane response characteristics, various stability augmentation schemes were evaluated to improve the longitudinal and lateral-directional damping characteristics.

It was determined during this initial study that the basic airplane was unstable in roll maneuvers because of the large yawing and pitching moment input of the lateral control system which was a spoiler-slot-deflector system. Attempts were made at this time to introduce longitudinal and directional interconnects between the spoilers and the horizontal and vertical stabilizers to counteract the magnitude of the pitching and yawing moment inputs of the spoiler-slot-deflectors. As a result of this simulator study, the initial design requirements for the A-5A control systems included interconnects. The results of the study were used to establish the magnitude of the vertical stabilizer and horizontal stabilizer inputs required to stabilize the airplane throughout the flight envelope during roll maneuvers of up to 720° of bank angle change with full lateral control applied.

Wind-tunnel testing was being continued throughout the early stages of the Vigilante development, and each refinement to the aerodynamic characteristics was incorporated in the data used to simulate the airplane. Concurrent with the development of the aerodynamic configuration was the design and development of the control system. Because of the wide range of longitudinal parameters it was realized that a system providing relatively constant longitudinal response throughout the flight envelope would be required. The pitch augmentation system that grew out of these requirements provided the airplane with constant stick force and displacement per g as a function of pitch rate and normal acceleration.

The interconnects required to stabilize the airplane during roll maneuvers, determined during the first simulation study, were incompatible with the pitch augmentation system design philosophy. The second five-degree-of-freedom roll investigation was initiated to study further the airplane with the pitch augmentation system included. A parametric study conducted during this investigation indicated that a reduction in the yawing moment input of the lateral control would

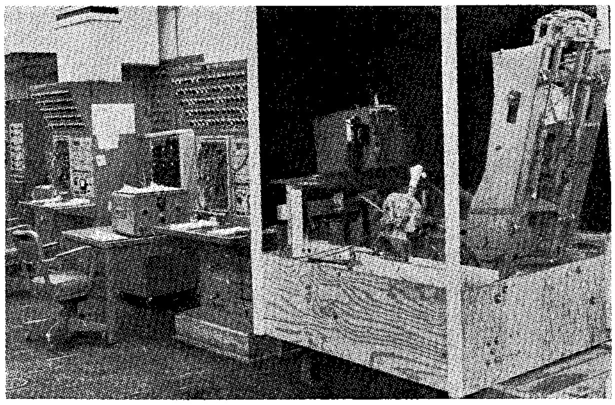

Fig. 3 Stationary simulator.

eliminate the roll instability and the requirement for control interconnects. Based on this finding the development of the inverted spoiler-slot-deflector system was initiated.

Wind-tunnel data of the two-section conventional spoiler-slot-deflectors (inboard and mid) and single section inverted spoiler-slot-deflector (outboard on the opposite wing) indicated an appreciable reduction in both the lateral control induced yawing and pitching moments, as indicated in Fig. 2, while maintaining essentially the same high level of lateral control effectiveness. The elimination of the roll instability was subsequently verified by the third, five-degree-of-freedom roll investigation, which utilized the control system mockup.

Following the development of a satisfactory high-speed configuration, a series of simulator studies were made to investigate the airplane handling qualities in the power approach configuration. It was determined during these studies that the airplane handling characteristics were satisfactory, although some improvement could be gained through the use of augmentation schemes such as a roll damper or tilted yaw damper gyro.

Wind-tunnel data corrected for aeroelastic effects indicated a low level of directional stability at high speeds. Although the estimated data indicated that the requirements of Ref. 5 regarding the Dutch roll mode ($1/C_{1/2}$ vs $|\phi|/|v_e|$) would be satisfied, the analog traces indicated that an abrupt lateral control input resulted in a rolling motion that had a marked oscillatory characteristic, rather than the typically smooth, first-order response. This was traced to the combined effects of low directional stability and high dihedral effect causing a high level of Dutch roll coupling, which was being excited by the lateral control yawing moment. In order to establish whether or not the pilots would find this type of rolling motion objectionable, a fixed-base piloted flight simulation study of the high-speed flight regime was conducted. The simulator, shown in Figs. 3 and 4, was equipped with a stick,

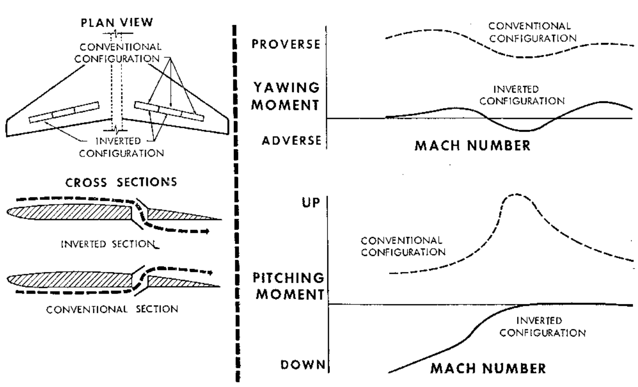

Fig. 2 Conventional and inverted spoiler-slot-deflector yawing and pitching moment.

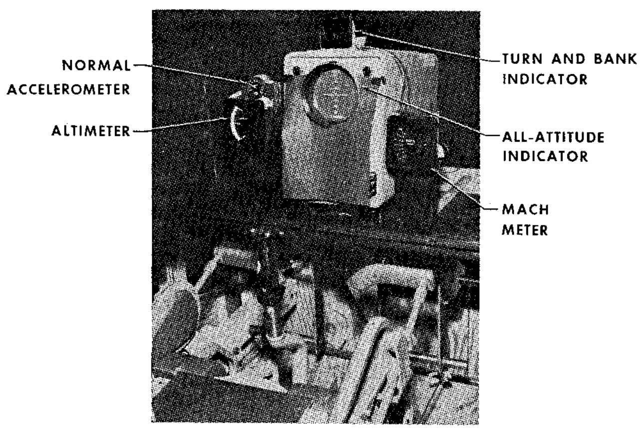

Fig. 4 Cockpit controls and instrumentation for stationary simulator.

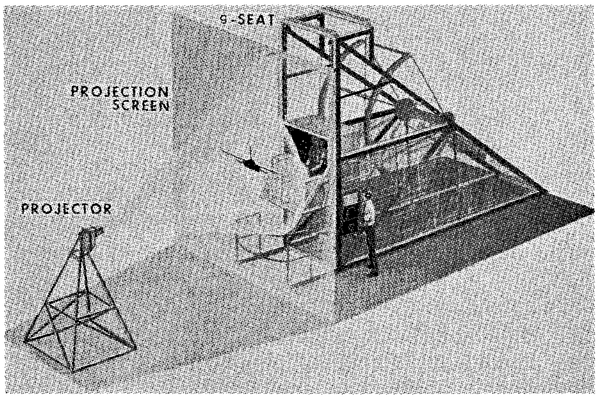

Fig. 5 Dynamic simulator.

rudder pedals, and a throttle. A two-component display was provided on a cathode ray tube providing the pilot with an indication of the primary control parameters, pitch, yaw, and bank angle. In addition, a Mach meter, altimeter, normal accelerometer, and turn and bank indicator were provided to augment the attitude parameters. The North American test pilots and former Air Force and Navy pilots employed at North American flew this simulator through a series of maneuvers and evaluated the airplane handling characteristics that were systematically varied through the ranges of interest. This study was later increased in scope, and the results were used to establish a lateral-directional criterion suitable for establishing tentative requirements for satisfactory lateral-directional flying qualities. A comparison of flight-test results with the criterion is presented later in this paper. Furthermore, it was found that a better balance of spoiler yawing moment was required to provide the airplane with improved handling characteristics at high supersonic speeds. The results of this program were an appreciable aid in establishing the proper balance between the static and dynamic directional stability level and the lateral control yawing moment and side force characteristics which the pilots considered desirable. The results of this study, which were considered generally applicable to other high-speed attack or fighter-type aircraft, were presented in Ref. 6. It is of interest to note that the Vigilante flight results have generally verified the simulator results as indicated later in this paper. The final spoiler-slot-deflector yaw balance was achieved by differential deflection of the inverted and convention sections and was checked during a subsequent coupled dynamic stability study.

Longitudinal characteristics at high subsonic speeds indicated the possibility of a control sensitivity problem. Investigation of the longitudinal control sensitivity led to the construction of a moving-base dynamic simulator. The dynamic simulator or g seat has been used to investigate the longitudinal stick force and displacement per g and the use of the stick damping in the improvement of high-speed handling qualities. The results of the g seat investigation provided guidance in determining the longitudinal sensitivity for satisfactory flight characteristics.

The dynamic simulator, shown in Fig. 5, consisted of a vertically moving cockpit capable of accelerations of $\pm 6\ g$ from trim flight. The pilot's task was to track an airplane silhouette projected on a screen in front of the pilot. The projected display was capable of simulating motions in pitch, yaw, and roll which were tracked by the simulator pilot.

A third simulator that proved invaluable in checking out the control system of the A-5A airplane was the fixed-base control system mockup shown in Fig. 6. The mockup was provided with a cockpit so that all control system characteristics could be evaluated by the pilots. The mockup in turn was connected to an analog computer on which the aerodynamics parameters were simulated at various flight conditions. Air loads on the control surfaces were simulated through hydraulically controlled actuators. With this setup the flight control and stability augmentation systems could be evaluated with the hardware mockup providing the most realistic representation possible for ground simulation.

In addition to the various simulator studies just discussed, numerous specialized investigations have been conducted throughout the A-5A development. These studies included the investigation of landing approach characteristics, the effect of transient acceleration during linear bomb ejection, the incorporation of the auto pilot, and the jettisoning of external stores. Studies were also conducted to support the flight-test program. Some results of a roll duplication and prediction investigation are presented below.

Roll Duplication and Prediction

The primary index of validity for a simulator study is the comparison of the study results with flight-test data. Although the majority of the studies performed prior to the first flight were to provide design direction, tests were conducted to provide guidance to the pilots in expanding the flight envelope. Early flight-test data were used to correct estimated data. These corrected data were then used to investigate flight characteristics to the maximum speed of the aircraft.

The duplication and prediction of airplane response characteristics from flight-test data were particularly helpful in providing the pilots with guidance during developmental flight testing. During the roll duplication study, two aerodynamic characteristics that had been considered negligible were found to have a significant effect on the roll characteristics. The parameters were the variation of spoiler-slot-deflector yawing moment and pitching moment with sideslip angle. The incorporation of these parameters into the analog simulation made it possible to duplicate the flight-test rolls. An example of a roll duplication time history is

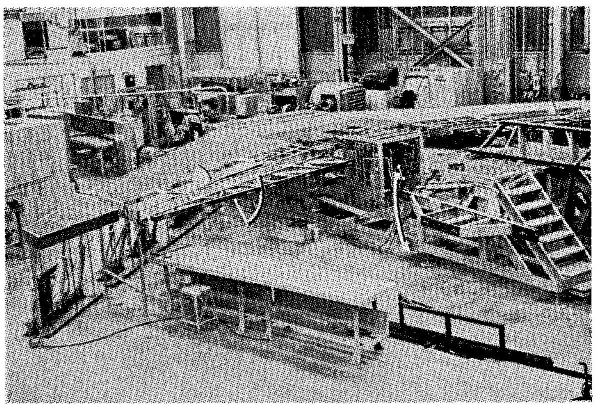

Fig. 6 A-5A control system mockup.

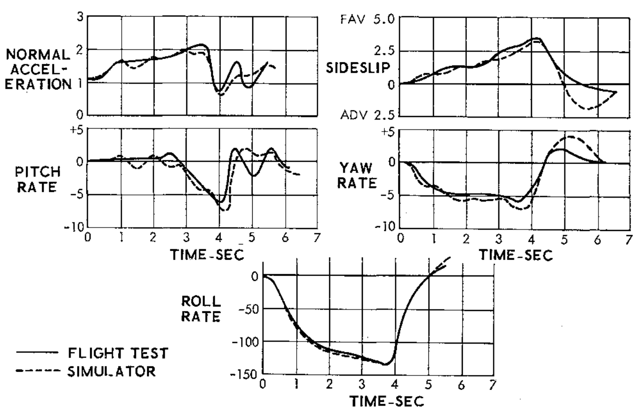

Fig. 7 Duplication of a 360° roll.

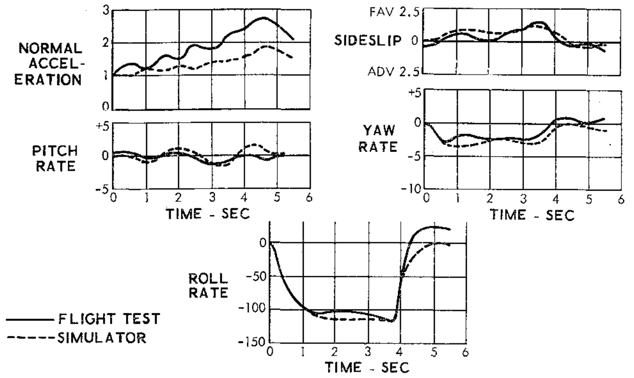

Fig. 8 Comparison of a predicted and flight-test roll.

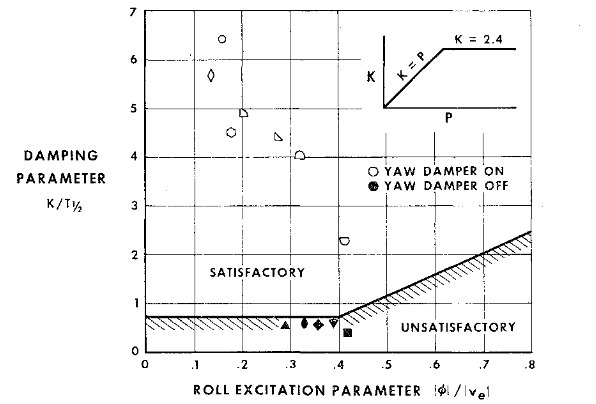

Fig. 10 Dutch roll characteristics.

shown in Fig. 7. These data show that by studying the flight-test data on the simulator it was possible to duplicate accurately the flight-test maneuver. Having established the trend of the aerodynamic characteristics at subcritical flight conditions, it was possible to predict the roll characteristics at other flight conditions with reasonable accuracy. A time history of a predicted roll maneuver from the simulation study and a flight-test roll maneuver obtained at a later date are compared in Fig. 8. These data show good agreement in rate response and sideslip angle. The roll duplication and prediction study provided the pilot with guidance during the flight investigation. In addition to predicting the characteristics in a 1 g roll maneuver, the study was expanded to investigate the effect of various pilot inputs, such as a push-over or a pull-up during the roll. This information was used to brief the pilots on airplane characteristics prior to expanding the flight envelope to the maximum speed.

Comparison of Flight and Piloted Simulator Results

The flight-test evaluation results of the A-5A have been compared, wherever possible, with the tentative flying qualities criteria of Refs. 6 and 7. These criteria were proposed as being generally applicable for the lateral-directional mode and longitudinal mode, respectively. The flight-test data used in the comparison were selected to cover a major portion of the A-5A flight envelope and include a considerable assortment of basic airplane response characteristics with augmentation "off." This was done to insure the widest coverage possible in terms of the fundamental dynamic parameters used in expressing the flying qualities criteria.

Lateral-Directional Data

It was shown in Ref. 6 that, although the lateral-directional response characteristics complied with the conventional Dutch roll criterion of Ref. 5, and with the pure roll response criterion of Ref. 8, satisfactory lateral-directional handling qualities would be better insured if the maximum overshoot (or undershoot) of the oscillatory component of the roll rate is less than 4.5% of the commanded steady-state roll rate. For comparison twelve A-5A flight evaluation points were chosen which would cover the desired range of characteristics. The pilot ratings were obtained from company engineering test pilots evaluating the lateral-directional characteristics while performing 360° rolls.

The flight evaluation points are presented in Figs. 9 and 10 to indicate the basic lateral-directional characteristics in terms of the maximum obtainable roll acceleration ($L_\delta\ \delta_{\max}$), roll time constant τ_p, Dutch roll damping ($K/T_{1/2}$), and the Dutch roll excitation parameter ($|\phi|/|v_e|$). The pure roll response characteristics, shown in Fig. 9, fall within the satisfactory boundary of Ref. 8. The corresponding Dutch roll characteristics are shown in Fig. 10. The seven yaw damper "on" points are shown to lie well within the satisfactory boundary (expressed here in terms of $K/T_{1/2}$ which, as discussed in Ref. 6, is identical to the conventional $1/C_{1/2}$ criterion for periods less than 2.4 sec but is more stringent for the longer periods), whereas the yaw damper "off" data fall slightly below the satisfactory boundary.

The pilot evaluations of the 360° roll maneuvers are presented in Fig. 11 in terms of the pilot assigned Copper rating and the ratio of maximum oscillatory component of roll rate to the commanded steady-state roll rate ($|p_1|/|p_{ss}|$). These flight results, in general, show good agreement with the simulator results for both yaw damper "on" and "off."

The results of a NASA simulator study reported in Ref. 9 verified the $|p_1|/|p_{ss}| < 4.5\%$ criterion for both adverse and proverse yawing moment, but indicate a less severe degradation in pilot rating for larger values of $|p_1|/|p_{ss}|$ caused by adverse lateral control yawing moments than for the larger values of $|p_1|/|p_{ss}|$ caused by the proverse moments. In order to obtain flight data for comparison to the NASA results, flight conditions were purposely chosen to include both

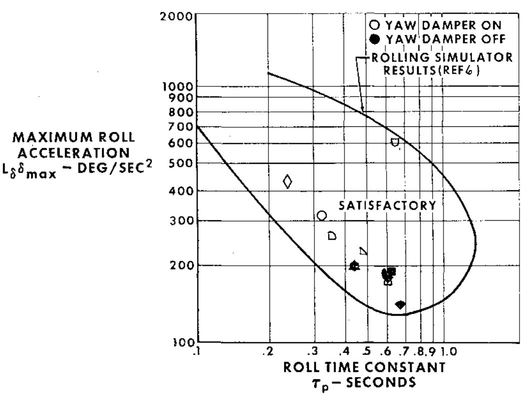

Fig. 9 Roll response characteristics.

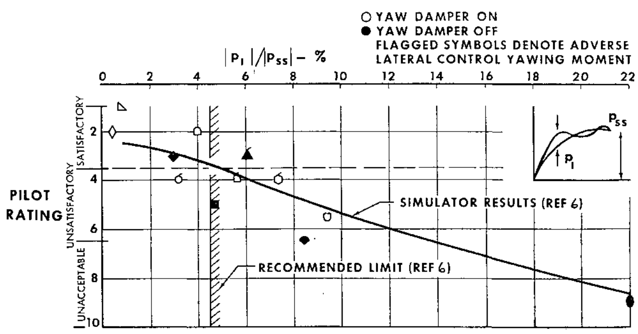

Fig. 11 Comparison of flight and simulator results for oscillatory roll characteristics.

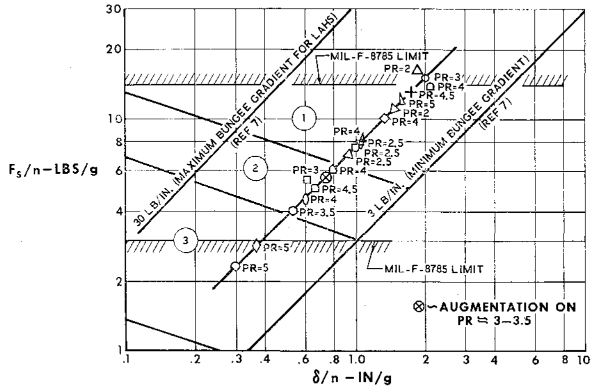

Fig. 12 Longitudinal control characteristics.

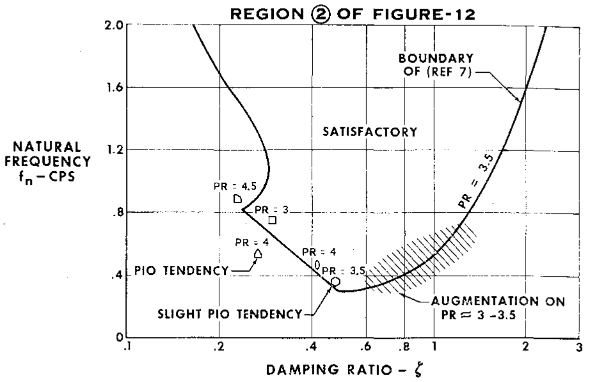

Fig. 14 Satisfactory longitudinal dynamics for moderate force gradients.

adverse and proverse lateral control yawing moments. Unfortunately, only a relatively narrow range of adverse yawing moment data (denoted by the flagged symbols) were available and the results are inconclusive. The $|p_1|/|p_{ss}|$ parameter is strictly an open-loop parameter that requires a step input of lateral control for numerical evaluation but is used to establish the acceptability of closed-loop maneuvering characteristics not requiring step inputs. Since there is not presently a prescribed flight-test maneuver from which the value of $|p_1|/|p_{ss}|$ can be obtained directly from the flight data, the values presented on Fig. 11 were obtained by the following procedure. Flight-test roll maneuvers were duplicated by using the actual flight control inputs and modifying the estimated aerodynamic data as required during the roll duplication study. Using the corrected aerodynamic derivatives, the complete three-degrees-of-freedom lateral response transfer function was obtained. By evaluating the oscillatory component of the inverse transform at the time of the first overshoot and the steady-state component, the values of $|p_1|/|p_{ss}|$ were obtained. The approximate equation suggested in Ref. 6 was found to be inadequate for the A-5A, as has been the case in several other attempted applications, and is, therefore, not recommended for use unless it is proved acceptable for the characteristics of the particular aircraft being evaluated.

Longitudinal Data

The recent results of the longitudinal study conducted on a dynamic simulator and reported in Ref. 7 indicated a generally more liberal "satisfactory" region of the longitudinal dynamic characteristics than had been obtained in previous research programs, viz., Ref. 10. Also, the influence of the basic control system characteristics on the shape of the "satisfactory" longitudinal dynamic region was established, based on pilot-induced oscillation (PIO) considerations.

The comparison of the A-5A data with the simulator boundaries is presented in Figs. 12–15. Since the A-5A augmentation system limits the short-period dynamics to a narrow band and a fixed value for the control system characteristics regardless of flight condition, as indicated in Figs. 12 and 14, the data used for comparison are for the augmentation "off." Figure 12 presents the control system characteristics for the flight evaluation conditions. These data are shown to fall into the three areas of 1) high, 2) moderate, and 3) low force gradients which were established in Ref. 7 to have different regions of short-period dynamics considered to be satisfactory by the pilots. Specifically, from the simulator work, the longitudinal stability characteristics which are considered satisfactory are defined by the boundary of Fig. 13 for control system characteristics falling in region 1 of Fig. 12. Likewise, Fig. 14 presents the satisfactory dynamic characteristics for control characteristics falling in region 2, and Fig. 15 presents the satisfactory dynamic characteristics falling in region 3. As indicated by these figures, the proposed acceptance boundaries separate the flight data considered to be satisfactory in a reasonably consistent fashion. Also, the shrinkage of the satisfactory dynamics region because of lightening of the stick-force load-factor gradient would appear to be approximately right, based on the few combinations of characteristics considered to have PIO tendencies in Figs. 14 and 15 which would be coincident with points considered satisfactory in Fig. 13.

Conclusions

The use of flight simulators, piloted and nonpiloted, has been traced through the design and development of the A-5A Vigilante. Flight simulator studies were shown to have played an important role in the development of the airplane. The early determination of roll coupling problems due to high spoiler-slot-deflector yawing and pitching moments and the

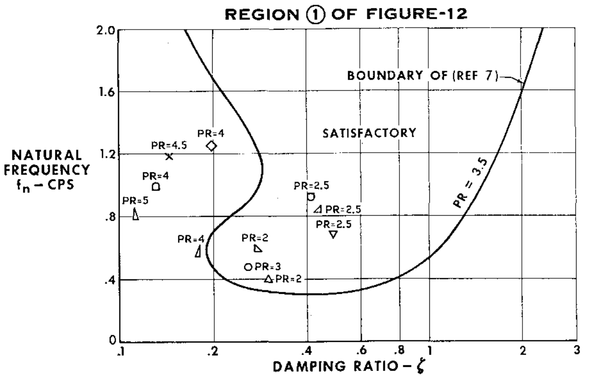

Fig. 13 Satisfactory longitudinal dynamics for high force gradients.

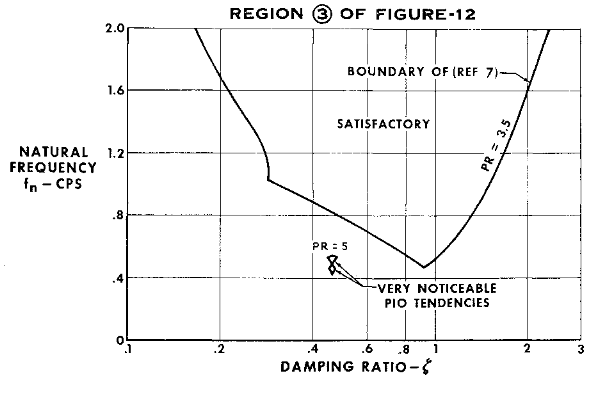

Fig. 15 Satisfactory longitudinal dynamics for low force gradients.

subsequent correction of the problem through the incorporation of the inverted spoiler-slot-deflector system can be attributed to the use of flight simulation. In addition, it has been shown that the criteria for determining satisfactory lateral-directional and longitudinal handling qualities established by piloted flight simulator studies are in good agreement with pilot opinion from flight test. It should be noted, however, that caution should be exercised in the use of the approximate equation suggested in Ref. 6 for determining the values of $|p_1|/|p_{ss}|$.

Experience gained during the design and development of the A-5A Vigilante lead to the following conclusions:

1) Airplane-control-system simulation should be employed during the early stages of preliminary design and continued throughout the entire airframe design and development as a tool for the early detection and solution of design problems.

2) Inclusion of the pilot in the airframe-control loop should be accomplished at the earliest possible time in order to benefit from pilot experience in design direction and to investigate closed-loop stability characteristics in critical flight regimes.

3) Piloted simulators should also be used to evaluate control-system functions, e.g., control harmony and trim transients, and to determine acceptable handling characteristics in design areas where existing design criteria are not considered adequate.

4) Finally, continued use should be made of piloted simulators as research tools to establish design criteria to aid in the design of future aircraft and spacecraft.

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