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BACKGROUND OF PILOTED SIMULATOR DEVELOPMENT

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ABSTRACT

In this paper a review is made of the piloted simulation facilities commonly used in the United States. An attempt is made to classify these facilities and to understand how and why these facilities are needed and came into being and how they are used. Some thoughts on the philosophy of use of simulation are offered and conclusions presented.

INTRODUCTION

In recent years the use of piloted simulators has become more and more widespread in the research and development process. In this paper a review is made of the simulation facilities in use in the aerospace industry and related organizations. An attempt is made to classify these facilities and to understand how and why these facilities are needed and came into being, and how they are used. It is hoped that this collection of information, the codifications, and the conclusions may be of benefit to those who use and are planning to use simulation facilities.

Before proceeding further, it is desirable to discuss the definition of the word simulator. As commonly used by various individuals of differing interests, it has a rather widely varying definition. Simulators can be considered in the most broad sense as facilities which will allow an analog representation of a particular control element, combination of control elements or the complete flight control - airframe - pilot system. This would include simulators to obtain data on control hardware, the human pilot and his display, the airframe with elasticity, and the complete system. This paper is particularly directed at piloted simulators, those in which a human operator performs a control task; however, it is felt that consideration of the wide spectrum of simulators under this broad definition is useful in giving a perspective view of the subject.

CATEGORIZATION AND DESCRIPTION OF SIMULATORS

There are numerous ways in which simulators can be classified or grouped. Several ways will be discussed briefly. First there is the hazy concept of computation as differentiated from simulation. Another way of looking at simulators is by the phase of research and development in which they are commonly used. It will be observed that this division does not occur very neatly. Finally, simulators can be categorized relative to the element or elements of the flight control system that they are intended to obtain information on.

First, let us look at the area of simulators versus computation, for a moment. In 1935, Mueller at Massachusetts Institute of Technology devised an electrical device for solving the longitudinal stability equations. In Reference 1.35 in addition to reporting the result of his work, he predicts the possibilities of extending his device to real time and even to use of hand controls and perhaps investigation of pilot training. During World War II and the years immediately following, rapid progress was made in development and application of differential analyzers. By 1948, electronic analog computers of significance were beginning to be available. The availability of these computers made possible the development of flight control system simulators as we know them today. All major aircraft companies in the United States have large general purpose analog computer facilities, ranging in size from 200 to 600 operational amplifiers or even larger. While simulators themselves, in a sense, these analog computers are used both for general computational purposes and also for connection with a cockpit and/or equipment to form a simulator.

While not a simulator by any stretch of the word, digital computers are making spectacular progress and have made improvement possible in scientific and engineering computations. A number of advanced operational flight simulators already use digital computers. It is undoubtedly true that the availability of these powerful tools will make possible further drastic improvements in simulation as they have done already in computation.

The phase of research and development of aerospace vehicles that you are concerned with influences considerably your choice of and use of simulators. These phases can be listed as (1) research, (2) preliminary design, (3) development, (4) flight test and (5) training and operational use. First is the research phase in which knowledge is gathered on various subjects of interest. Upon initiation of a program to design and build a vehicle, the preliminary design phase is encountered followed by detailed development of the vehicle and all of its components. The flight testing phase has its special needs for simulation. Finally, the phase is reached where the vehicles are in production and use and the operational commands are faced with training and maintaining the proficiency of their crews.

Those using research and development simulators can thank the training simulator people for providing the motivation for and the development of many of the techniques and equipments necessary for what is used. Much of the literature on simulation in past years now relates to this area. During the early years, World War II and somewhat before, various techniques and devices called trainers were developed to meet the vast training problems. Hundreds of millions of dollars were spent on trainers during World War II in the United States alone. Expert opinion is that this expenditure saved much over actual flight, in fact, that training in flight would have been impossible. With the availability of analog computers in the late forties, modern training simulators became a possibility. Also a factor was the development and availability of improved concepts and knowledge about servo systems and components developed in World War II, especially in Germany. Modern operational training simulators are large expensive devices carefully designed to simulate as nearly as possible the actual cockpit environment and the characteristics of the production vehicle. As a matter of fact, however, numerous analyses have shown that these trainers can quickly save far more than they cost in reducing expensive flight time needed to maintain pilot proficiency particularly in such areas as instrument flight and simulated emergencies.

There is no sharp line between the first four phases in the kind of simulators used as will be apparent in later discussions. The operational trainer because of the special needs and the special economic factors involved has been essentially a clearly separated category. In view of the very limited production of future vehicles and their highly specialized and complicated nature this sharp line of demarcation may not remain.

Simulators do group themselves, to a degree, with regard to the element or elements of the flight control system that they are to provide information about. To illustrate my definition of the flight control system consider Figure 1. This block diagram has a block representing the human pilot, a block representing the control equipment needed inside the vehicle, and a block representing the dynamic characteristics of the airframe. Simulators as used with respect to each of these system elements will be discussed.

Finally and most important of all to the system engineer, simulators to examine and evaluate the total flight control system consisting of all these elements will be discussed.

Assemblies of the various components of, for example, the hydraulic or electrical systems are often made. In some cases, these assemblies and the test performed tend to become complex and to verge on what could be called simulation. In general, however, the inclination is to call these bench or laboratory tests unless combined with the airframe dynamics and a pilot.

And now for a few words on the block representing the human pilot. A great variety of simulators have been and are being used to determine man's tolerance to one or more of the environmental conditions that he may encounter. There are centrifuges and various other devices to subject men to accelerations, air bearing platforms and water tanks to attempt to simulate zero g, and airplanes to actually demonstrate zero g. Chambers exist to subject men to intolerable noise and chambers to impose absolute quiet. Men have been exposed to extreme cold and roasted to high temperatures in other tests. Confinement capsules resembling cockpits and space cabins are being utilized. Simulators have been and are being used to determine the dynamic characteristics of the human pilot as a servo element.

These simulators have been of the simple fixed base type and will be discussed a little later when considering simulators to examine the complete flight control system.

To a great extent, the discussion to this point has been in the nature of giving perspective to the subject of simulation. This is important, it is believed, in understanding each other, understanding how the trend to simulation came about, and making determinations of future trends. At this point, simulators of the complete flight control system will be discussed. These, no doubt, are what many first think of when simulation is mentioned.

A bewildering variety of simulators is being used to analyze the flight control system as a whole. Figure 2 is an attempt to break these facilities down in some logical grouping. The first natural grouping is between ground based and flight.

Figure 2 divides the ground based simulators into groups as to the motions that can be imparted to the pilot; no motion, rotations, translations, and combinations of rotation and translation. In Appendix I are listed various flight control system simulators that are available. This listing is undoubtedly not complete. The class of simple cockpit - analog computer simulator that is so common in the industry and the various research organizations has been excluded.

The majority of the fixed base, and the motion simulators as well, use instrument displays, these range from simple scope or dial instrument displays to elaborate display simulators. External display simulators are becoming more common, usually for approach and landing studies, VTOL investigations, and to simulate the space environment. The complete mission of an orbital vehicle can be simulated at a number of facilities.

In a few cases, an attempt to simulate accelerations has been made by pulling on the shoulder straps or exerting pressure on the seat cushions. This is indicated by the "pseudo G" block of Figure 2. The worth of this feature in improving correlation of data with actual flight is not known.

It has become standard practice in aircraft and missile development to make use of a category of simulator that is called the "iron bird" or the "iron monster". This category is of great importance in the design and development process. The first step in the development of an "iron bird" is normally the use of a simple cockpit - analog computer simulator. Simulators such as this can be quickly built up and adapted to the problems of the particular mission and configuration by connection with the analog computer facilities that are available in all companies.

As the design of the vehicle progresses and components of the control system are designed and begin to be available, the "iron bird" simulator is built. Normally, these simulators go through a continuous refinement process all through the years of development starting with little actual equipment, then insertion of early components and then the production hardware. The cockpit also normally shows such a growth starting with simple controls and presentation and finally, in some cases, a very complete mock up. In some cases where it is felt necessary, structural elasticity effects are included to provide adequate simulation. The simulation of the aerodynamic characteristics also undergoes continuous revision as knowledge of the airplane grows with analyses and wind tunnel tests performed.

In certain cases of extremely complex systems, a second partial "iron bird" may be built to obtain reliability and qualification information on the system and the components in addition to the system performance information normally sought on the "iron bird".

In some cases a final stage of simulation would be to connect the actual airpalne system with analog computers to prove the performance.

Referring back to Figure 2, let us pass on to a brief discussion of the various motion simulators in use. Very few, if any, simulators are now available with only one rotational degree of freedom. Depending on the intended function of the simulator, two or three rotational degrees of freedom will normally be incorporated. An example of two rotations is the pitch roll chair used in past years at NASA. A number of three rotational degree of freedom simulators have recently come into being, motivated basicially by interest in space vehicles, VTOL configurations, and reaction controls. Many of these devices utilize air bearings and in some cases they are quite elaborate. NASA - Lewis has a four gimbal type simulator in which high spin rates are possible.

The rotation simulators of the Link trainer type have limitations on the rotational travel. By incorporating initial motion into the simulator and then "washing out" the motion in actuality but continuing it on the instruments, what is said to be a very effective simulation of continuous motion is obtained. This capability is incorporated in the Air Force general purpose simulator and is referred to in Figure 2 as "pseudo motion".

Centrifuges, as is known, have been used to produce steady g forces on pilots to determine their tolerance and capabilities while enduring these forces. At the Naval Air Development Center at Johnsville, Pennsylvania, a facility is available which combines a centrifuge with a piloted capsule with two rotational degrees of freedom. Much interesting work was done on this facility with respect to the X-15 program.

An interesting facility to simulate zero g was investigated by Lockheed, Marietta, Georgia. This facility simulates zero g by spinning a man submerged in water about his longitudinal axis.

The only simulator that the author knows of that has just one translational degree of freedom and no rotational freedom is the g seat at G/D, designed to study turbulence at low altitudes. Normally if translational degrees of freedom are included some rotational degrees are also included such as on the pitch - heaving g seats available at NASA - Langley and North American, Columbus.

Grumman has a unique facility which incorporates pitch, roll, and heave. It has both external and internal display and incorporates "wash out" to simulate large motions. It is especially useful for VTOL, low altitude flight, and approach and landing studies.

A large simulator is available at Bell-Dallas to study VTOL problems. This simulator has a three degree of freedom cabin mounted on a strut. This strut can be moved up and down to provide heaving to the cabin and also can be moved in the other two directions to provide a corrected vertical acceleration as the cabin is rotated.

NASA - Ames has a six degree of freedom simulator which has a three rotation cabin able to translate to a limited degree in all three axes. This would be intended for V/STOL and approach and landing studies.

Another impressive facility is the NASA - Ames facility having a three rotational degree of freedom cabin able to translate vertically, mounted on a centrifuge.

A number of very elaborate and expensive simulators have been built or are in construction to simulate various space missions, rendezvous, docking, lunar approach, and lunar landing. Expecially worthy of mention are the several simulators at NASA - Langley, LOLA and the Lunar Landing Facility.

To provide the various motions to the simulators as discussed, results in additional complexity and cost so that, in general, as we move from left to right on Figure 2 the problems of constructing and operating the simulators are increased.

The purpose in adding these motions to the simulators, of course, is to add fidelity to the simulation, improving the correlation with actual flight. Unfortunately, this correlation is in a very imperfect stage and the answer to what is the minimum motion to provide acceptable fidelity of simulation is not available.

It is quite possible for motion of one sort or another introduced into a simulator, while being impressive to see, to do more harm than good as far as giving results comparable to the flight situation.

About fifteen years ago as a result of the newly developed knowledge and ability in artificial stability and computation, an idea was born of a flight research facility which has been called the variable stability airplane. At the present stage of advanced concepts, a better name might be in-flight simulation. The latest versions do much more than vary the stability. In Appendix II of this paper are listed all of the variable stability aircraft of which the author has knowledge, in more or less chronological order. The development of the concept and the increasing complexity and also capability of these aircraft can be followed by reading through this listing and the descriptions. The listing starts with the Cornell-Navy F4U-5 and has reached its high point with the Air Force-Cornell T-33. The Air Force-Cornell T-33 has the features of variable stability, control, feel, display and L/D. It has the capability to vary stability and control characteristics with time such as occurs in a re-entry. It does not as yet have the ability to vary C_{L_α} without varying other derivatives. This would be a desirable addition. The T-33 can also be used as a fixed base ground simulator by connecting it to an analog computer in its hanger.

In the area of V/STOL variable stability aircraft, NASA - Ames has a limited variable stability installation in an X-14 aircraft and NASA - Langley has an installation in a helicopter. Coming in the future is a new aircraft, the X-22, which is designed from the beginning as a variable stability machine.

Being such a realistic simulator when properly done, the variable stability aircraft is a most valuable research tool. It is also valuable in evaluation of preliminary design concepts and in training and indoctrinating flight test pilots. The concept has been proposed for use in operational trainers. Enthusiasts have even proposed a universal trainer using variable stability ideas. Such thinking does not recognize the practical limitations and difficulties that exist. There may be certain possibilities in this idea for the future, however.

Experience has shown that, in common with most flight tests, use of these airplanes for research and development is expensive and time consuming for each data point obtained. In the opinion of the author the most suitable usage of these airplanes is to make final checks and correlations of data points that have been explored as well as possible in ground simulators. See Appendix III for extensive references to variable stability aircraft.

TYPICAL USE OF SIMULATION IN RESEARCH AND DEVELOPMENT

At this point it may be interesting to indicate what would be typical use of simulators during the research and development cycle.

Figure 3 shows the various phases of this cycee. Relatively simple fixed base simulators are widely used in research programs involving the human pilot. For research purposes, this simplicity is not necessarily a handicap. It is more important to carefully control the experiment and specify the controlled element precisely than to come to as exact similitude as possible.

There are many basic studies yet to be performed on the pilot-vehicle combination for which extremely simple simulation is entirely adequate. For example, use is still being made of Dr. Elkind's data, obtained at MIT many years ago, following a target on a scope with an electronic pointer. These basic studies and the associated simple simulators are particularly suitable for the university environment. One university, Princeton, has a variable stability aircraft, a Navion. It has a simple installation, however, it is a very effective tool for demonstrations and research studies either by thesis students or the faculty. Government facilities, as has been shown, have and operate many elaborate simulators for research purposes. There is tendency for these studies to become oriented to some system under study or development such as Apollo, SST, CX-HLS, C-142, etc. These studies then tend to be related to one later phase of the research and development process.

The three phases of primary importance to an aircraft company are shown in the center of Figure 3. During the preliminary design extensive use of the simple cockpit simulator would be made to firm up design requirements and to give information on specific problem areas not sufficiently covered by general research programs. Considerable variation in the extent of these programs would be caused by the mission and configuration. For instance, at the present time this phase of simulation would be considerably higher if a VTOL fighter were under consideration than if a more conventional fighter were in design. As is no doubt obvious both the kinds of simulators used and the types of programs conducted are very similar to those in the research phase.

Variable stability aircraft can and have been of use in examining particular problem areas of specific designs not sufficiently understood.

In the detailed development phase, heavy emphasis is laid on the "iron bird" simulator. In a not too sophisticated system most of the effort may be placed on the equipment development and proof testing. Preliminary exposure of the flight test group to the characteristics of the system will be provided in order to allow proper planning of the flight test program.

In view of the elaborateness of the "iron bird" simulator, considerable expense is involved in both constructing and operating it. However, its use is universally endorsed by the industry, with no exceptions to the knowledge of the author, as a time and money saver. Basically its use is a function of the complexity of the design, the degree to which the design is pushing the state of the art, and, related to the first two, the dollar cost of the system. With the tremendous cost of bringing a design to the flight test stage, the fantastic cost of flight test time, and the horrendous economic waste caused by mistakes, miscalculations, and redesign, the "iron bird" is felt by all to be an essential.

As the aircraft progresses into the flight test stage, increased emphasis may again be placed on the cockpit simulator. The dust may be brushed off the simple simulator and it may be improved to demonstrate dangerous conditions to the pilots and to guide the test program. The "iron bird" is utilized in evaluating the final equipment to be used in the production aircraft.

If the particular design is conventional both in aerodynamic configuration and its control system and is of relatively low performance, simulators may not be used. A judgment that they are not needed would be based on the economic factors referred to previously and to what could be called a "confidence factor". This "confidence factor" is a function of how sure the engineers are of their knowledge and theoretical calculations. Such cases with a high "confidence factor" will be very few in the future.

On the other extreme are the designs which push the state of the art to the extreme such as Dyna Soar, and certainly Apollo. In these cases research type information is needed and will be gathered through all the phases indicated. Extremely complex simulation can be easily justified on the basis of the high cost of the total system. Much of the equipment is necessarily of high performance or of new design and consequently needs much simulator evaluation. Pilot training needs are much greater than normal. In view of the research nature of many such vehicles, the operational use phase merges into the normal flight test phase with resulting readjustments in the consideration of flight test and operational training simulators.

Users of aircraft, the operational commands of the services and the airlines, are most concerned with the operational use phase. As has been discussed, very elaborate operational trainers have become very common. The accent has been on procedural training. Exact matching of the dynamic behavior has not been an essential objective and only recently have any motion cues been considered worthy of providing. There is now interest in the Air Force in providing motion cues to simulate various maneuvers and emergency conditions. Even the airlines have become interested as a result of the recent series of incidents and accidents of jet transports caused by turbulence initiated maneuvers. There has been considerable interest by the airlines and FAA in use of a variable stability aircraft as a final operational trainer for SST operation.

NEED FOR AND PHILOSOPHY OF USE OF SIMULATION

In the main, the discussion to this point has been concerned with "what" simulators are available and in use. Some of the discussion has been concerned with "where" these simulators are used. Some comments have been made as to "how" this trend became possible, basically the availability of computation equipment and servo system knowledge and capability. It may be interesting to examine briefly some of the underlying reasons "why" this trend has become established and is expanding.

Fundamentally, simulators are used where basic knowledge is weak, complex interrelationships are not fully understood and calculations, estimates, or judgments are not trusted. In other words the confidence factor, referred to previously, is low. Also involved are the economic factors. With a modern complex weapon system, the costs of carrying a design through the flight test phase may be a billion dollars or more. Shown on Figure 4 are some facts on system costs. If we were to include systems such as Apollo, or beyond, on the chart the costs would really go to an asymptote. When we examine the configuration, the speed regimes to be traversed, and the complexity of the vehicle to perform its mission, the reasons for differences in cost between the Wright Flyer and the F-111 become apparent. These economic "facts of life" underlie any discussion of the trend to simulation.

Another factor to be considered is the fact that for modern systems there may be no extensive production, as such, to eliminate "bugs". Under such conditions major errors or deficiencies in the design are intolerable.

The use of simulation is affected by the philosophy of development of new aircraft in a country. Rapid exploitation of the state of the art invites the "cut and try" approach. Such a philosophy has been followed in the United States, exemplified by the research series of aircraft. If the development of new types of aircraft proceeded at a slow steady pace, research would normally be properly accomplished prior to initiation of the design and a designer would not have the compulsion to use such extensive simulation. This rapid pace of development application of knowledge, however, has become a way of life and it is not believed that it will change under present conditions.

From the above factors a continual and increasing trend toward complex simulation can be predicted. There is a very real danger involved, however. Simulators are not only costly in dollars to build and operate but more importantly they are costly in technical talent to operate. Technical talent of high grade is not plentiful and if too much is tied up in work related to simulation, to the detriment of analytical studies and planning, the consequences can be serious. Most serious of all is the type of attitude that sometimes develops, to simulate without thinking. This is deadly. It results in blind repetitive programs of little real worth.

This is not to imply opposition to simulation, to the contrary. Rather it is a plea for their intelligent use.

Another thought related to the above is with regard to the organization of simulator groups. It is the author's feeling that simulator groups many times tend to look on the simulator facility as their goal and try to continually develop and improve it whether it is needed or not. It appears much preferable for an organization to be problem oriented, having and using simulators as necessary to solve their problems.

CONCLUSIONS

In the preceding discussion an attempt has been made to give some perspective to the subject by classification of simulators in various ways, a review of various facilities available in the United States and some historical background given. Discussed in more detail were flight control system simulators, particularly the "iron bird" type used extensively in development. An indication of the typical use of simulators in research and development was made. Finally some notes on the need for any philosophy of use of simulators were made.

In closing, it can be stated that simulation is a tool, use it as such and do not let it use you.

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BLOCK DIAGRAM - FLIGHT CONTROL SYSTEM

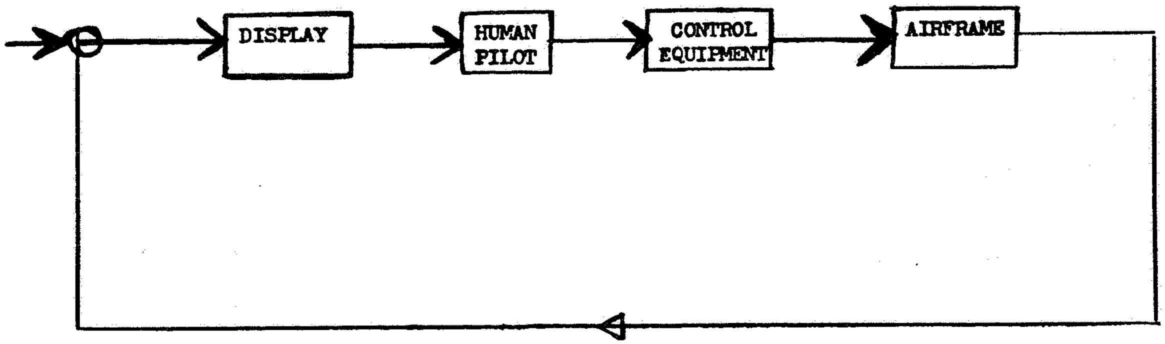

Figure 1

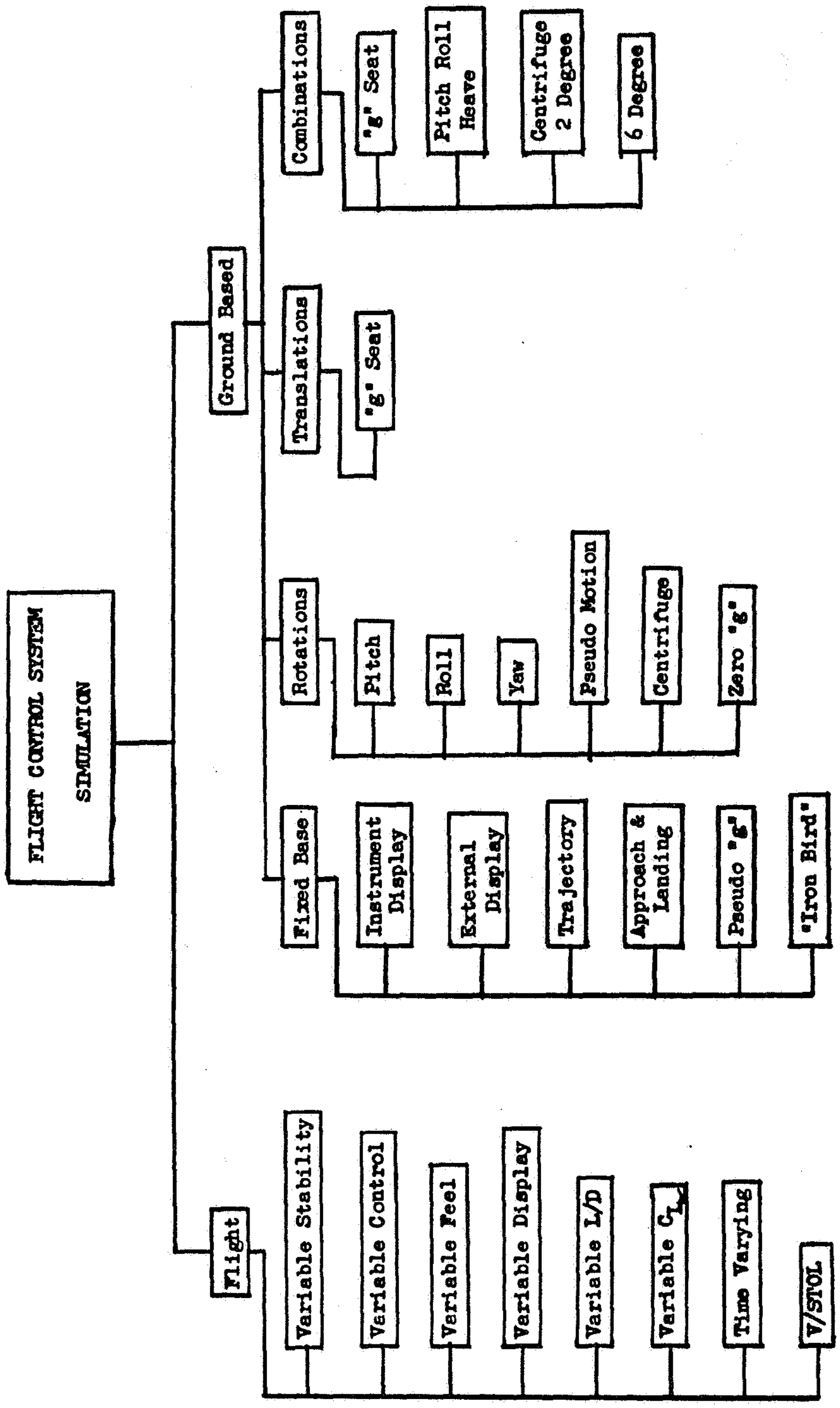
FLIGHT CONTROL SYSTEM SIMULATION
Flight
Variable Stability
Variable Control
Variable Feel
Variable Display
Variable L/D
Variable C_L
Time Varying
V/STOL
Ground Based
Fixed Base
Instrument Display
External Display
Trajectory
Approach & Landing
Pseudo "g"
"Iron Bird"
Rotations
Pitch
Roll
Yaw
Pseudo Motion
Centrifuge
Zero "g"
Translations
"g" Seat
Combinations
"g" Seat
Pitch Roll Heave
Centrifuge 2 Degree
6 Degree

Figure 2

FLIGHT CONTROL SIMULATOR USE

IN DESIGN CYCLE

	Design Requirements Data on Specific Problems	Final Design Requirements Proof of Design Acceptability Equipment Development Pilot Training	Pilot Training Pilot proficiency Dangerous Regimes Resolution of Problems	Crew Training Procedural Training Navigation All Weather Operation
RESEARCH	PRELIMINARY DESIGN	DETAILED DEVELOPMENT	FLIGHT TEST	OPERATIONAL USE

TIME →

Figure 3

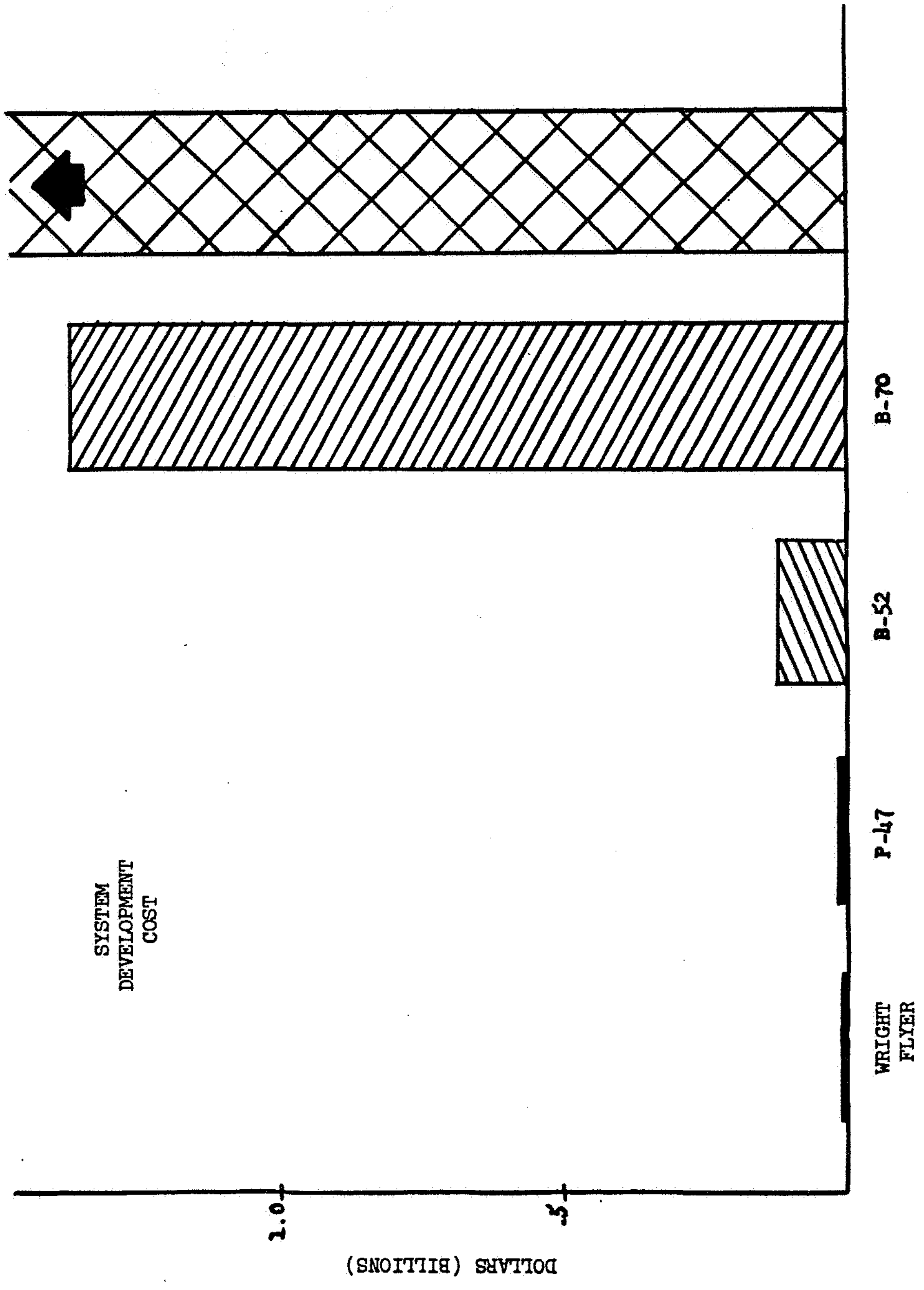
SYSTEM
DEVELOPMENT
COST
1.0
.5
DOLLARS (BILLIONS)
WRIGHT FLYER
P-47
B-52
B-70

Figure 4

Appendix I

F/C SYSTEM GROUND SIMULATORS

TITLE	LOCATION	DESCRIPTION	REFERENCE OR REPORTS	COMMENTS
General Purpose Hypersonic Simulator	Air Force WPAFB Ohio	Fixed base simulator to evaluate new display and instrument concepts in the hypersonic flight regime. Primarily used in re-entry studies.		
T-37 General Purpose F/C Simulator	Air Force WPAFB Ohio	Modified T-37 moving base simulator used for instrument and flight control-display concept research. Has force wheel steering split axis auto-pilot, and electronically generated visual runway presentation.		
Night Sky Simulator	Air Force WPAFB Ohio	A small fixed base simulator enclosed in a dynamic star field to study the interrelationship between the external visual motion cues and the symbolic cockpit displays.		
Flight Control Integrated Systems Facility	Air Force WPAFB Ohio	Hybrid, 6 degree (plus) of freedom simulation facility for use in design and evaluation of all aspects of flight control systems. Can tie in airborne electronics and fixed base fully instrumented cockpits		This facility is essentially composed of analog and digital computers plus the X-20 Guidance and Control Dynamics Model.
Six mode Simulator	Air Force WPAFB Ohio	6-Degree of freedom simulator. Hydraulic shakers will actuate pushrods and universal joints to vibrate a magnesium test platform. Will accommodate 2,000 lb. load and induce vibrations up to 30 cps and g-loads as high as 20.		To be built by MB Electronics

TITLE	LOCATION	DESCRIPTION	REFERENCE OR REPORTS	COMMENTS
Dynamic Escape Simulator	Air Force WPAFB, Ohio	450 ton simulator to study performance of pilots under stresses of simultaneous tumbling, spinning, oscillation, vibration and rapid acceleration during launch, flight and re-entry phases.		Being built by Franklin Institute
Aerospace Simulator	AFMTC Cape Canaveral, Fla.	Aerospace profile simulator for pilot training and integration of pilot with ground crew.		
Rotation Simulator	AF School of Aviation Medicine	3 degrees of freedom, roll, pitch, yaw. 10 ft sphere on air bearing. Pilot can operate jets or reaction wheels. Pilot display, perturbations, can be introduced. Pressure can be simulated 50 rpm in one axis, 70 rpm resultant.		
Spin Chair	AF School of Aviation Medicine Brooks AFB, Tex.	Rotatable chair electronically controlled for study of pilot reactions and disorientation.		
Ballistic Control Simulator	Edwards AFB (Air Force)	Simulator floated on air bearing and driven by reaction jets powered by high pressure nitrogen in spheres.		Used by AF in training future space pilots.
Flight Acceleration Simulator	Naval Air Development Center Johnsville, Pa.	Centrifuge combined with piloted capsule with two degrees of freedom.		
Photo-reconnaisance Plane Simulator	Navy	Free to move in 4 directions, gives pilot-student realistic over-the-ground moving image of his camera targets. Supplements existing Chance Vought F8U-1P Crusader photo-plane cockpit and camera trainers.		To be delivered by Chance Vought

TITLE	LOCATION	DESCRIPTION	REFERENCE OR REPORTS	COMMENTS
SST Cruise Simulator	NASA-Ames	Cruising flight stability and control qualities simulated dynamically. 4 degrees-of-freedom-pitch, roll, yaw, and lateral acceleration.		
SST Approach and Landing Simulator	NASA-Ames	Stationary cockpit with flight simulated by servo-driven instruments and a closed-circuit television display projected onto a screen.		
3 Degree of Freedom	NASA-Ames	Gas bearing, 360 rotation possible in 3 axes provided with cockpit and controls.		
V/STOL Landing Simulator	NASA-Ames	Landing Approach Simulator having 120 ft of vertical travel, constructed on outside of 40 x 80' wind tunnel.		
Visual Projection Facility	NASA-Ames	Projection facility to simulate horizon stars or landing approach situation. Can be used with other simulators		
5 Degree Simulator	NASA-Ames	Roll-pitch-yaw carriage free to heave, installed on a centrifuge.		
Apollo Mid Course	NASA-Ames	Air supported table for investigation of space control systems.		
6 Degree Simulator	NASA-Ames	6 degree of freedom simulator having limited travel for V/STOL and transport landing studies.		
Lunar Landing Test Vehicle	NASA-FRC	Manned jet lift vehicle for investigating lunar landing.		

TITLE	LOCATION	DESCRIPTION	REFERENCE OR REPORTS	COMMENTS
"Iron" Cross Control Simulator	NASA, HSFS Edwards, AFB, Cal.	Three degrees of freedom, roll pitch and yaw. Used to investigate pilot control with jet reaction devices.		
General Purpose Simulator	NASA Edwards AFB	Fixed Base, cockpit simulator, contact analog display in color.		
LOLA Lunar Orbit & Landing Approach Simulator	NASA Langley	Four maps of moon will be photographed by television and projected inside a dome. Display will simulate view from 200 miles to 0.75 miles.		
Lunar Landing Research Facility	NASA Langley	Steel Framework 400 ft long by 250 high and 50' wide. 11,000 # lunar landing vehicle suspended so that 5/6 of weight is carried by cables		
Visual Docking Simulator	NASA Langley	Fixed base with television display projected from moveable mirror 20' diameter spherical projection screen.	AIAA 64-334	
Planetarium Simulator	NASA Langley	Fixed base simulator using 55' inflated radome as planetarium		
Lunar Gravity Simulator	NASA Langley	200 ft. long oval track on its side with cable suspension. Cable supports to pilots head, body, and legs.		
Rotating Space Station Simulator	NASA Langley	Similar to above, except that a totating drum is incorporated instead of a stationary wall.		To be built
"g" Seat	NASA Langley	Vertical translation and pitching degrees of freedom. For evaluation of low altitude flight characteristics.	NASA TM X-420	

TITLE	LOCATION	DESCRIPTION	REFERENCE OR REPORTS	COMMENTS
SST Simulator	NASA Langley	Fixed base, cockpit display-Simulated air traffic control		
Space Rendezvous Docking Simulator	NASA Langley	Large 6 degree-of-freedom simulator installed in a hangar on overhead truck and dolly	AIAA 64-334	
MASTIF Multiple Axis Test Inertia Facility	NASA-Lewis	Four gimbals to simulate yaw, roll and pitch angles. Installed in altitude wind tunnel--altitude and temperature factors of space flight can be simulated. High spin rates possible.		Used for reaction control and Mercury Capsule studies.
Apollo Mission Simulator	NASA-Lewis	Simulator will duplicate what crew will see and hear during prelaunch, launch, parking and earth orbit, escape injection, coast, circumlunar pass, circular lunar orbit, lunar excursion module separation and rendezvous, injection into trans-earth trajectory, coast, re-entry and landing.		Being built by Fink Div. of GPI.
Lunar Landing Module Simulator	NASA	Simulator to practice rendezvous and docking for Apollo. Can move 25° around each axes.		Being built by Martin
Control Simulator	Bell Helicopter Dallas, Texas	6 degrees of freedom simulator - load capacity of 1000 lbs. 5 cycles/second in pitch, roll and yaw.		Particularly useful for helicopter and V/STOL studies.
STOL Control Simulator	Boeing Witchita, Kansas	A six degree of freedom STOL flight simulator to examine handling qualities, flight control and display.		

TITLE	LOCATION	DESCRIPTION	REFERENCE OR REPORTS	COMMENTS
Vibration Study Effects	Boeing Wichita	Vibrations between 1-30 cps with amplitude of 20 inches at lowest frequency up to 1/64 inches at highest frequency are produced by a hydraulic cylinder actuating a platform holding in aircraft seat. Checks pilot's ability to read instruments and actuate controls under vibration.		
Multiple Stress Chamber	Boeing Seattle	Pilot subjected to vibrations and enviromental conditions of boost. Pilot performs tracking task.		
Space Flight Simulator	Boeing Seattle	Rendezvous Docking simulator-fixed base with large circular screen-6 degree of freedom space display also includes a full scale moving cockpit docking simulator.		
VTOL and Terrain Simulator	Boeing Seattle	Fixed base-6 degree of freedom point legal source display projected on quarter flight sphere-allows flight over terrain 15 by 1.1 inches		
Control Systems Simulator	Vought Dallas, Texas	Structure supported by air bearing. Reaction controls inertia wheels - will accommodate a pilot.		
Fixed Base Orbital Flight Simulator	Vought Dallas, Texas	Fixed base, elaborate cockpit with 560 amplifier analog computer puls digital computer to simulate six degree of freedom flight mechanics and equations for orbital and space navigation.	Vought Report ADB 1-4	Particularly useful for orbital flight, rendezvous and re-entry studies.
V/STOL Simulator	Vought Dallas, Texas	Fixed base - hydraulic stick & rudder feel-extensive display.	IAS Paper 6-60	

TITLE	LOCATION	DESCRIPTION	REFERENCE OR REPORTS	COMMENTS
Space Flight Simulator	Vought Dallas, Texas	3 axis motion compartment. External display on 20 ft sphere surrounding cockpit, enclosed in space environmental conditions simulator, heat, noise, vibrations, pressure, temperatures, radiation & meteoritic impact. Digital computer used to simulate flight mechanics equations.	Vought Report ADB 1-4	
T-33 Ground Simulator	Cornell Aero Lab., Buffalo New York	T-33 Variable Stability Airplane used as fixed base ground simulator by use of computer to simulate dynamic equations.		
Carrier Landing Simulator	Douglas	Fixed base simulating mirror landing approach system.		
ANIP Simulator	Douglas, EL Segundo, Calif.	Fixed base - investigation of advanced display concepts.		
General Purpose Flight Simulator	G/D Ft. Worth,	Fixed base, instrument display plus projection, external viewing.		Particularly useful for low altitude flight simulation
"g" Seat	G/D Ft Worth Texas	Simple simulator used to simulate jolting ride at low altitude, scope display.		Low altitude flight studies
Air Bearing Simulator	GD/Astronautics Point Loma	For testing and product improvement of contour stage control system during coast phase. Consists of pedestal, 30" sphere and two 25' boom and relate response of control jets to autopilots commands.		

TITLE	LOCATION	DESCRIPTION	REFERENCE OR REPORTS	COMMENTS
Space Vehicle Pilot Simulator	General Electric Missile & Space Vehicle Dept.	9' x 12' room accoustically insulated bordered by large computer-programmer observation area. Vehicle characteristics simulated. Simple seat-control-display setup used.	WADD TR 60-695 Part I and Part II	
Motion Simulator	GE/Missile & Space Vehicle Division	Air bearing supported simulator for testing Numbus control system-360° in pitch, 160° yaw, 120° roll.		
Docking Simulator	GE M&SVD	Cold gas altitude and translation controls in 5 degrees of freedom. Target assembly moves for 6th degree motion on 2 axis.		
Motion Simulator	Grumman Aircraft Eng. Co.	Free in roll, pitch and heave-3 "g" acceleration limit, instrument display and also provided with external display for VTOL and approach and landing simulation.	Grumman Reports	Particularly useful for approach and low altitude studies.
Lunar Landing Simulator	Grumman	Simulator utilized for control system parameter studies and for evaluation of lunar landing techniques. Controlled by analog computers. Comprises 2 degree-of freedom motion seat and a 4 degree-of-freedom visual display.		
Mark IV Space Cabin Simulator	Lear Grand Rapids, Michigan	Fixed base, elaborate display, space cabin simulator.		
Null Gravity Simulator	Lockheed Marietta	Simulates zero g's by placing in center of spinning tank of fluid.		Not completed
"Humming Bird" VTOL Simulator	Lockheed Marietta, Ga.	VTOL tethered rig using jet engines to evaluate VTOL handling qualities and flight control.		Other tethered rigs have been used (X-13, Avro machine, etc.) to check specific designs

TITLE	LOCATION	DESCRIPTION	REFERENCE OR REPORTS	COMMENTS
Lifting Body Simulator	Martin/ Baltimore	Will simulate entire flight of orbital lifting, body vehicle—100,000' to touchdown, 6 degree-of-freedom projection of approach area displayed on 16' x 20' wall.		
Gemini Simulator	McDonnell	Will be used to simulate last 100' of flight and docking with Lockheed Agena stage. Crew station located on Gimbal and translation structure. Agena is on target structure.		
Simulator	Norair	6 degrees of freedom, moving base. Peak vertical g of 15. Cockpit instrument display		
Visual Flight Simulator	North American Aviation Columbus, Ohio	Fixed base, V/STOL Simulator with television presentation free in 6 degrees of freedom projecting terrain picture.	IAS Crone & O'Harrah	Used for V/STOL studies
"g" Seat	North American Aviation Columbus, Ohio	Subjects pilot to variable vertical acceleration similar to ride through turbulence. Vertical translation and pitching degrees of freedom. Similar to NASA-Langley "g" seat.		
SST Simulator	North American Aviation Los Angeles Boeing, Seattle	Boeing 707 cockpit-pitch and vertical translation analog computation with digital time varying input. Display derived from moving belt projected on screen.		
Flight Simulator	Ryan	Realistic visual-display for optimization of aircraft systems designs-moving terrain type-stationary cockpit located near projected center of wrap-around screen. Controls in 2 place simulator are for pilot only and include collective for lift control, stick for pitch and roll, rudder for yaw, and throttle for forward speed control.		

TITLE	LOCATION	DESCRIPTION	REFERENCE OR REPORTS	COMMENTS
Rotating Station Simulator	North American	Will study effects of prolonged artificial-g on four-man orbital lab modules at each end of 150" center beam.		Being built
V/STOL Flight Simulator	UAC/Sikorsky	Capable of representing helicopters, compound helicopters, tilt wing, fan-in-wing and lift-engine or deflected exhaust VTOL aircraft.		

NOTE: The above listing does not include the class of fixed base simple cockpit-computer simulator. There are literally scores of these simulators of varying degrees of simplicity in government and industry. Also not included is the class of fixed base simulators used in the development of the flight control system of a given vehicle, the "iron bird" simulators. It is quite probable that there are simulators in existence or planned that should be added.

Appendix II

IN FLIGHT SIMULATORS

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
F4U-5 (Navy-Cornell)	1948-49	Servomechanism system of the autopilot, fed with electrical signals from sideslip and yawing velocity pickups, deflected auxiliary rudder. Simulated changes in directional stability & damping in yaw. Periods from 1.5 to 5.5 sec. Ref. 2.2 and 2.4	Obtain pilots comments on a large range of aircraft dutch roll frequencies and damping in order to justify or revise many handling qualities requirements.	A proposal for Navy handling qualities requirements as a result of these tests was "The Lateral-Directional Oscillation shall always lose at least 40% of its amplitude during each cycle following a disturbance."
PT-26 (Air Force Cornell)	1949-50	Stabilizer incidence adjustable in flight to large negative values. Airplane would maintain steady state glides at angles of attack as high as 28 degrees. Angle of attack at the peak of the lift curve peak 15 deg. Manual means used to prevent wing roll off. In later tests an autopilot used. Ref. 2.3 & 2.11	Project purpose was to obtain both static and dynamic data pertaining to the longitudinal motions of an airplane at angles of attack covering both stalled and unstalled flight.	Static data obtained in trimmed power-off glides Qualities determined were pitch angle, angle of attack, normal acceleration, longitudinal acceleration.
B-17 (Air Force)	1951-52	Conventional autopilot was connected to a force wheel. This wheel fed in a signal to the autopilot through strain gages on the spokes of the wheel, and on the pedals. Final arrangement was such that a small force commanded bank angle while a force over 3 pounds commanded aileron displacement (or roll rate). Ref. 2.8	Purpose of this work was to investigate the possibility of the pilot controlling the autopilot rather than the aircraft direct. Provided better stability characteristics and smoother control without adding additional force.	Use of force wheel control, in conjunction with inboard stabilization of airframe dynamics, made simultaneous flight path stability and control realizable.

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
C-45F (Air Force Cornell)	1951-53	Provided continuously variable artificial inputs proportional to yaw velocity sideslip, rate of change of sideslip and yaw acceleration to the rudders; yaw velocity and roll acceleration to the ailerons; and rate of change of airspeed to the elevator. Artificial force feel on all three controls is provided with continuously variable force gradients. Ref. 2.5, 2.7, and 2.9	Purpose was to make all the nature modes of the airplane's motion non-oscillatory and convergent. Automatic turn coordination within a practical degree of accuracy was to be provided.	Essentially dead beat Dutch roll and phugoid were accomplished. (Limited pilot evaluation)
B-26B (Air Force Cornell)	1951-present	An Artificial longitudinal stability & control system was installed to provide extreme variations in the following parameters; short period mode frequency and damping, phugoid mode period and damping, and control force and position needed to trim and maneuver. Short period f = .2 to .6 CPS I = .15 to 1.2 Phugoid I = .15 to +.60 f = .01 to 0.5 CPS In 1962, a second B-26 was given similar variable stability capabilities in both longitudinal and lateral directional modes. This second aircraft is used primarily for demonstration flights Ref. 2.13, 2.14, 2.15 and 2.22	Purpose of this program was to determine in flight the optimum & minimum flyable characteristics of bomber type aircraft. The program was later extended to investigate handling quality characteristics of other large aircraft and to train test pilots at locations such as the USAF & Navy Test Pilot Schools	Consistent pilot ratings of various values of short period frequency & damping ratios were obtained. Accomplishments include: 1) Investigation of the effects of various short period & phugoid dynamics, elevator force gradients & types of force feel on handling quality characteristics of bomber type aircraft. 2) A study of SST longitudinal stability & control characteristics during the approach & landing maneuver. 3) Approach to over 230 Air Force, Navy, FAA, and manufacturers' pilots in stability and control evaluation techniques.

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
Navy T-33 (NASA-Langley)	1952-53	Variable damping in yaw was obtained by a flap-type control surface fitted to a fixed fin called a nose fin located on the forward part of the airplane. Ref. 2.27	Flight investigation of the effects of varied lateral damping on the effectiveness of a typical high speed fighter airplane as a gun platform.	Results of simulated strafing runs indicate that the gun-line dispersion could be expected to be decreased about 7% by increased lateral damping and to be increased about 85% by decreased damping.
F86A (NASA-Ames)	1952-54	This variable-stability servomechanism operated in essentially the same manner as the F6F-3 equipment except the rudder & rudder tab were driven automatically & the primary power used was hydraulic rather than electric. Range of the stability derivatives were: C_{n_β} .50 to 0 C_{n_r} .38 to -1.6 C_{n_p} .34 to -1.0 C_{l_β} .074 (normal) C_{l_p} .385 (normal) $C_{n_{\delta a}}$ -.016 to .104 $C_{l_{\delta r}}$ .0155 (normal) Ref. 2.20	Same as F6F-3 but higher speed range.	Simulation of higher performance prototype aircraft. Periods appear to have run from 1.0 to 1.6

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
F6F-3 (NASA-Ames)	1952-56	Variation of the stability derivatives through servo actuation of the ailerons and rudder were obtained. The stability derivatives ranges were as follows: C_{n_β} .079 to -.002 C_{n_r} .143 to -.306 C_{n_p} .250 to -.151 C_{l_p} .125 to -1.02 C_{l_β} .048 to -.350 $C_{l_{\delta_r}}$ .118 to 0 $C_{n_{\delta_a}}$ .007 (normal) Ref. 2.10 & 2.20	Simulation of prototype aircraft in order to define the ranges of acceptable characteristics which could be used as design criteria. Pilot opinion of lateral oscillatory characteristics relative to current flying qualities were considered.	Flight experience was obtained which in most cases directly applied to particular flying qualities problems associated with individual prototype development programs. Aircraft also used in simulating tracking in rough air.
F94A (Air Force Cornell)	1952-58	Artificial longitudinal stability & control systems were installed to provide extreme variations in 1. Short period mode frequency and damping. 2. Phugoid mode period & damping. 3. Control forces & position needed to maneuver & to trim. 4. Control breakout forces. Short period f = .7 to 1.15 CPS I = .25 to 1.75 Ref. 2.13, 2.26, & 2.28	Purpose of this program was to determine in flight the optimum and minimum acceptable characteristics of a fighter aircraft. (Associated with B-26 work	Similar to B-26

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
H-5 Helicopter (NASA-Langley)	1952-58	A single rotor helicopter was outfitted so that the damping in roll, yaw & pitch could be varied by means of electrical components. The components were actuated by the rear cyclic stick or rudder pedals as well as by signals proportional to rate of roll, yaw or pitch (signals proportional to helicopter attitude were also available but were not used in the tests.) Ref. 2.19 and 2.32	An investigation of helicopter damping as it effects flying qualities.	Variations of flying qualities with increased damping in roll yaw, roll and pitch. Results indicate that increased damping can improve the accuracy of maneuvers and reduce the effort required of the pilot.
Navion (Air Force Princeton)	1952-present	Bob weights and springs, etc. to vary longitudinal dynamics. Ref. 2.47 Variable stability equipment has been subsequently added.	Investigate effects of these devices on longitudinal dynamics.	Demonstrated flight characteristics involving degeneration of short period & phugoid into other dynamic modes.
XF88A (Air Force McDonnell)	1954	The variable-stability system basically consisted of aileron & rudder servos actuated by sideslip, yaw and roll rate inputs. Dutch roll oscillations were induced by rudder kicks in straight and level flight. Ref. 2.12	To fulfill the need of improved specifications on rolling motion. Examples - amplitude ratio of roll angles to yaw angle or roll angle to sideslip etc. Establish a tolerable intolerable boundary surface, for flight with auxiliary equipment inoperative.	Periods from 1.00 to 2.555 were accomplished.

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
F86E (Air Force Cornell)	1954-55	A non-linear yaw damper was added to the rudder with the servo driving the rudder direct. An artificial rudder feel system using dynamic pressure and a spring was used to simulate the normal airplane feel. The yaw damper was set so that sensitivity was left high for small sideslip angles around zero. Ref. 2.17	To make the rudder motion not only proportional to yaw rate but also to yaw rate as it varies with sideslip. With this equipment it was hoped that in a dutch roll oscillation, the aircraft would return to center swiftly but be damped well near center.	Tracking aim errors with this system were reduced to about two-thirds the value experienced with the normal airplane with damping of the dutch roll to around 70% of critical (I = .7).
F9F-2 (NASA)	1954-55	Two types of automatic pilots were used; one of these was of the attitude type and the other was of the rate type. With the attitude automatic pilot control system, two-types of stick force feel were used, spring feel and damper feel. Motion of the stick generated an electrical signal proportional to its deflection. Ref. 2.18, 2.44, 2.45 & 2.46	A flight investigation to obtain experimental information on the handling qualities of a fighter airplane controlled through an automatic pilot control system.	The pilot liked the characteristics provided by the damper force feel system much better than those provided by the spring feel system. The flying qualities of the airplane with the rate sutomatic pilot control system was very good.
T-33 (Air Force Cornell)	1954-present	Irreversible hydraulic power controls are used to drive the control surfaces. This system is also designed for research in the field of design of cockpit controls. The basic system which was limited to steady state or quasi-steady state flight conditions has	This aircraft was initiated in order to increase the effectiveness of research work on the problems that are continually arising in the field of airplane stability & control (handling qualities).	Continual development and revision over a period of several years of this aircraft has brought about a flying simulator which can duplicate the characteristics of almost any aircraft under any conditions. Accomplishments include:

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
T-33 Cont'd		been supplemented by a device which permits changing of stability derivatives as a function of time for a predetermined flight path. Installation of drag petals has added a variable L/D capability which permits simulation of low L/D lifting bodies and of vehicles operating on the back side of the thrust required curve. Also, it is possible to link the airplane to a computer to convert it to a ground simulator. ω_{n_d} = (less than 0) to 1.5 cps I_{n_ϕ} = (less than 0) to 0.6 $\omega_{n_{s.p.}}$ = (less than 0) to 1.5 cps $I_{n_{s.p.}}$ = -0.1 I 1.5 Phugoid period 25-200 sec I_p = -0.20 to 0.60 (Refs. 2.16, 2.21, 2.23, 2.35, 2.36, 2.37 and 2.38).	One of the revised purposes of this aircraft is for carrying out a systematic investigation of the re-entry task & handling qualities problems associated with advanced vehicles.	1. Pilot training for the X-15 program. 2. Investigation of lateral-directional handling quality parameters to assist in the development of the TSR-2. 3. Investigation of the effects of L and true speed on longitudinal handling qualities. 4. A study of longitudinal and lateral-directional handling qualities for piloted reentry vehicles. 5. Determination of the significance of certain longitudinal and lateral-directional flight parameters in limiting minimum approach & landing speeds. 6. Determination of handling quality characteristics of advanced vehicles possessing unusual dynamics such as a coupled roll-spiral mode. 7. Accumulation of a large amount of handling qualities data for conventional aircraft upon which to base improvements of present design requirements. 8. Verification and evaluation of the importance of new handling quality parameters such as M_u, X_u, $1/T_{h1}$, $[(\frac{\omega\phi}{\omega d})^2 - \|]/\| \phi/\beta \|$ associated with advanced vehicles.

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
YF86D (NASA-Ames)	1956-58	By use of a control system stabilizer, position was commanded thru a servo system by stick force. The breakout force, system time constant, and system gain (i.e. stabilizer angle per unit stick force) could be varied over a wide range. Aircraft dynamics were varied over a wide range. tude and speed. short period $f = .63$ & $.57$ CPS $I = .21$ & $.36$ breakout force 0 to 25 lb time constant 0 to 4 sec static force gain 1 deg/lb to .04 deg per pound. Ref. 2.29	Obtain pilots comments on: 1. Breakout forces large enough to be objectionable & to make small precise control application difficult 2. sensitivity which makes it difficult to avoid persistent amplitude oscillations. 3. Pilot-induced oscillations of a divergent nature.	In an examination of the over-all system response in the two test flight conditions, the dynamic normal acceleration response of the airplane to stick force appeared to be the critical factor in the pilot's choice of control system dynamics.
F86E (NASA-Ames)	1957-59	Servo actuation of the ailerons & the rudder provided artificial variation of some of the lateral and directional aerodynamic stability parameters. Three modes of aileron & stabilizer system operation were available to the pilot: 1. normal control, 2. position servo (fly by wire), 3. variable stability. Stability derivatives ranges were as follows:	Basically this aircraft was used to determine the acceptable lateral oscillatory damping in the landing approach with emphasis on the emergency condition of damper failure	Three regions of lateral oscillation characteristics were defined and investigated: 1. long period $3.11 \leq P \leq 4.32$ sec and moderate-roll-yaw coupling $0.49 \leq \lvert \phi/v_e \rvert \leq 0.70$ 2. long period $2.75 \leq P \leq 6.9$ sec and high roll-yaw coupling $0.93 \leq \lvert \phi/v_e \rvert \leq 1.65$ 3. short period $1.54 \leq P \leq 2.38$ sec and moderate roll-yaw coupling $0.45 \leq \lvert \phi/v_e \rvert \leq 0.63$.

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
F86E Cont'd		C_{n_β} .510 to -.305 C_{n_r} 1.15 to -1.53 C_{n_p} .121 to -.200 $C_{n_{\delta_a}}$ .180 to -.142 C_{l_β} .430 to -.625 C_{l_p} .22 to -1.10 $C_{l_{\delta r}}$ .176 to -.152 Ref. 2.30		
F10.A (NASA-Langley Air Force)	1957-60	This vehicle was to provide the test engineer with the flexible features of a general purpose computer, coupled with those of a variable stability airplane. The airborne analog computing equipment was to be used in flight research programs to solve in real time certain sets of differential equations to provide control information to the aircraft. Inputs to the computer system as a whole were to come from the airplane motion and flight sensors, from the problem input equipment and from the pilot.	Some of the planned uses for this aircraft were roll requirements for blast escape and tracking, artificial stability for roll coupling, roll limiting & "G" limiting schemes, control stick steering, adaptive servo and other new techniques, study of negative stability augmenters, problems of unconventional bombing techniques and studying problems of advanced vehicles along portions of their trajectories.	Not flown

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
F7U-3 (Navy-Cornell)	1958-59	A large vertical canard control surface was used to generate the required yawing moment to prevent the uncontrolled motions experienced at high angles of attack in the region of reduced stability, a $\dot{\beta}$ feedback loop was used to control this surface. Ref. 2.31	Determine a means of preventing large uncontrolled motions using automatic control.	In symmetrical stalls the motions were very mild; when large aileron and rudder deflections were applied at the stall, the airplane did little more than roll.
HUP-1 (Princeton)	1958-60	A standard Minneapolis-Honeywell E-12 autopilot was installed in this helicopter to provide for variation of dihedral effect, static directional stability, roll damping and yaw damping. The rolling convergence root held approximately constant at a value $\lambda_2 = -6.68$ Spiral mode damping varied from +.15 to -.85 and the Dutch roll damping (1/C 1/2) varied from .5 to 7.8. Ref. 2.33	Conduct a pilot evaluation of carefully selected stability configurations to provide pertinent commentary and numerical ratings which could be related to known dynamic characteristics.	Analysis of test results indicated a number of areas of importance in helicopter lateral handling qualities. Specifically it was found that the Dutch roll oscillation should be well damped; positive spiral damping is desirable, and, in fact, is light; steady state control deflections should not be required to make turns after completion of the entering transients.
F-100C (NASA-Ames)	1958-present	The following derivatives can be varied: Longitudinal-Directional-Lateral C_{m_α} C_{n_β} C_{l_β} C_{m_q} C_{n_r} C_{l_r} $C_{m_{\delta_s}}$ C_{n_p} C_{l_p} $\delta Fs/\delta f_s$ $C_{n_{\delta a}}$ $C_{l_{\delta a}}$ $C_{n_{\delta_r}}$ $C_{l_{\delta_r}}$	Used as a backup for ground simulators to pick up points where it is felt that motion cues are important. Has recently been transferred from FRC to Ames	Has been used to investigate X-15 controllability problems with roll damper off and to study SST handling quality characteristics.

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
F-100C Cont'd		Estimates based on perfect servos indicate the following characteristics will be available at 15,000 ft.		

Mode	Char	Max	Norm	Min	Mach
Lateral	ω_d	.95CPS	.59CPS	0CPS	.9
	I_d	1.0	0.13	-.80	.65
	$\lvert\phi/\beta\rvert$	24.0	2.00	.40	.80
Longitudinal	ω_{sp}	2.5CPS	1.5CPS	0CPS	1.1
	$I_{s.p.}$	.85	.30	-2.0	1.1

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
D-18 (NASA)	1959-60	The control surface modifications consisted of a main trailing-edge flap which was connected to the aileron for maximum lift-changing capability, a short auxiliary portion of the elevator to counteract the wing pitching moment caused by deflection of the main wing flap.	To provide an automatic control system capable of varying static longitudinal stability and lift curve slope. An investigation of positive and negative static longitudinal stability coupled with various effective lift-curve slopes.	Pilot opinions and flight results of an investigation at relatively low values of normal acceleration per degree change in angle of attack indicate that the upper tolerance limit of unstable static stability of the airplane (C_{m_α}) is between 0.10 and 0.16.
F11F-1-F (NASA)	1960-61	An adjustable feel system connected to the longitudinal control system of a transonic fighter airplane. Variable control feel including response feel is provided from the following five sources: control position, control rate, normal acceleration, pitching velocity, and pitching acceleration. Ref. 2.39	Provide a means whereby a through study could be made of the effects of large amounts of response feel and the stability of airplane and control system response modes.	Flight tests indicate that: (1) at the frequency of the short period mode, large amounts of normal-acceleration feel cause the control system to oscillate and excite the airplane short period mode at the same frequency.(2) The pitching acceleration component of feel is almost equivalent to viscous damping on the stick. A large

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
F11F-1-F Cont'd				pitching acceleration component excites an oscillation of the control system.
X-14 (NASA-Ames)	Sept 60-present	The Bell X-14 aircraft has been modified with the addition of a more powerful engine and a secondary automatically controlled jet control arrangement to permit its use as a variable stability airplane. The following moments can be obtained:	The purpose of this aircraft is to investigate hovering and transition, etc. for VTOL work.	Determination of the attitude control power and damping requirements for a visual hovering task.

ESTIMATED MAXIMUM EFFECTIVENESS

	Axis		Manual		Augmented
Roll	L_δ	$\frac{\text{rad.}}{\text{sec.}}$	1.9	+	1.72
Pitch	M_δ	$\frac{\text{rad}}{\text{sec.}}$	.95	±	.86
Yaw	N_δ	$\frac{\text{rad}}{\text{sec.}}$	.54	+	.48

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
Bell 47G (NRC of Canada	1961 present	The vehicle has been modified so that stability and gust sensitivity can be varied about all three axes. Another similar vehicle that will be able to vary stability in the vertical plane as well, is presently entering service.	Obtain VTOL handling qualities under motion stimulus.	Have carried out investigations on the effects of lateral-directional cross-coupling on flying qualities and on the effect of weathercock stability on the amount of directional control sensitivity and damping required.
YHC-1A (NASA)	1961	This new type helicopter which has sufficient space for an adequate payload is being fitted with improved variable stability equipment which will permit simulation not only of control power and angular velocity damping but also variations of static stability. During initial use additional equipment will be installed when feasible. This could include items such as methods of providing time lag in controls. Ref. 2.41	Stability and control and handling qualities tests of VTOL aircraft	
NC-130B (NASA-Ames)	1961 present	The aircraft has been equipped with blowing-type boundary layer control trailing edge flaps and a stability augmentation system which operates on signals associated with side force characteristics of the aircraft.	To investigate problem areas associated with the operation of large STOL aircraft at low forward speeds.	Speeds down to 68 knots have been achieved and investigations of low speed lateral-directional control problems have been conducted.

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
X-22A (BuWeps Bell-	1962 present	Designed from the beginning to incorporate a variable stability & control system, the vehicle will be able to investigate the following parameters: 1) control power 2) control feel, 3) angular rate damping, 4) weight damping, 5) thrust response, 6) attitude stabilization, 7) stability derivatives The vehicle will be able to vary its characteristics continuously throughout transition.	To provide a versatile research vehicle for VTOL handling qualities research. Will investigate the vertical take-off and transition flight regimes in order to define future V/STOL design and specification criteria	None - System under development.
JETSTAR (NASA-FRC)	1963 present	Based on the model following principle, this aircraft will possess variable stability about all three axes. Forces along the longitudinal axis will be modified by thrust control.	To provide the capability of simulating the stability, control and certain performance characteristics of a variety of advanced airplanes (such as the SST) and aerospacecraft.	None - System under development.
367-80 (Boeing-NASA-Langley	Future	The aircraft has been equipped with boundary layer control high-lift flaps and is to be given a variable stability capability. Moments will be varied by servo actuation of the elevator, ailerons and rudder, lift will be varied by servo actuation of the speed brakes, and drag will be varied by thrust modulation.	To be used for in-flight simulation of supersonic transport configurations in the approach and landing phase and for slow speed flight research	Has demonstrated lift coefficients of 3.0 and speeds as slow as 65 knots. Variable stability modifications not yet incorporated.

TYPE AIRCRAFT	DATE	SYSTEM DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
C-131	Future	This aircraft, which employs the concept of total in-flight simulation (TIFS), will be able to vary forces along and moments about all axes. TIFS will provide: 1) actual flight simulation, 2) fully representative test cockpit, 3) correct external visibility, 4) servo-driven displays to properly present simulated flight variables to the pilot, 5) cockpit controls with correct feel characteristics, 6) control of the test cockpit's linear and angular accelerations and motions to duplicate those of the simulated vehicle.	To provide a facility to assist in the development of advanced manned vehicles. The probable great size and weight of some of these vehicles combined with their tremendous range of performance create handling quality questions which at present are beyond our ability to answer. By defining and solving anticipated flight control problems associated with these vehicles, TIFS should supply the answers which at present can be obtained in no other way.	None - TIFS under development.
Dynamic Lunar Landing Simulator (NASA - FRC)	Future	18' high, four truss-type legs with shock struts attached. Pilot will ride in an encapsulated cockpit in a zero-altitude, zero-velocity ejection seat facing a display panel. GE CF-700 turbofan engine provides thrust equal to 83% of vehicle weight-simulating moons gravity (12% of earths).	Typical moon landings will be simulated by starting a descent from 5000' altitude. Thrust of engine will cause descent velocity to approximate that which would be experienced on moon. Pilot will control simulator's attitude through control system linked with 4 hydrogen peroxide attitude control jets on each of 4 landing legs. Deceleration rockets will be used to brake rate of descent at proper time.	None as yet.

TYPE AIRCRAFT	DATE	SYSTEMS DESCRIPTION	PROJECT-PURPOSE	ACCOMPLISHMENTS
VTOL Test Rig - (Lockheed)	1964	Free flight piloted vehicle powered by six jet engines.	To develop techniques for multiple jet lift engines, obtain control criteria and handling qualities data and demonstrate multiple engine jet lift capability.	None