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Impact of Advanced Control Concepts on Aircraft Design

by

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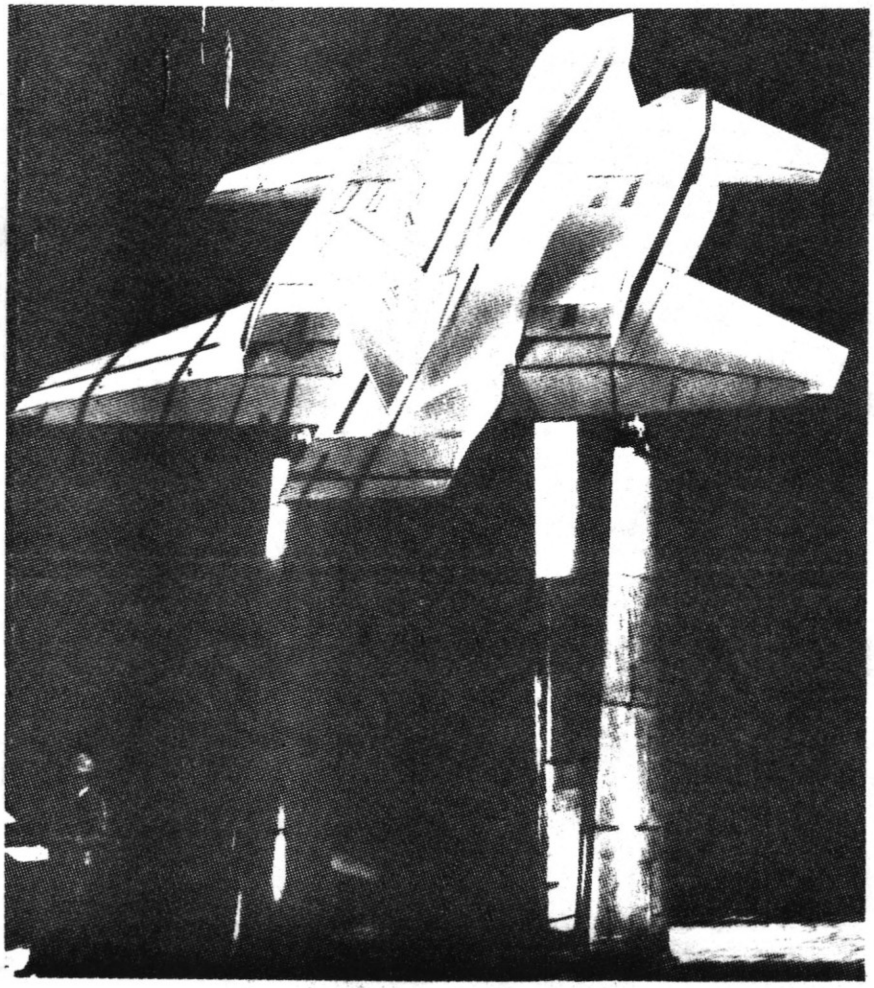

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IMPACT OF ADVANCED CONTROL CONCEPTS ON AIRCRAFT DESIGN

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Abstract

Applications of automatic control systems to aircraft have evolved from the earliest days of "wing levelers," to yaw and pitch dampers in the 1950's, to the point today where they can have major impact on an aircraft configuration. As their reliability increases, automatic control systems are being used to provide some of the safety margins that had traditionally been provided by the basic airframe. Relaxing design constraints on the aerodynamics and structures through use of controls, allows configuration optimizations not previously possible. Recent advances in such control concepts will be reviewed and discussed as they affect high performance fighters, commercial transports, business jets, helicopters, and shipboard V/STOL aircraft.

I. Introduction

Automatic flight controls have been used in a variety of ways throughout the history of aircraft. Mr. R. W. Howard noted in a 1973 article, entitled "Automatic Flight Controls in Fixed Wing Aircraft--The First 100 Years," that a Frenchman, Colonel Renard, tested an unmanned decaplane using an automatic control device to improve the glider's directional stability in 1873(1) (See Figure 1). In 1894 Sir Hiram Maxim designed and built an automatic stabilization for his steam powered aeroplane. Unfortunately his heavier-than-air flying machine was destroyed during initial tests before having an opportunity to test the stabilization device.

The Wright brothers realized that good lateral control would be essential to achieving manned flight. Through experimentation with manned gliders in the early 1900's, they invented the first effective lateral control system by wing tip warping and simultaneous control of a vertical tail. Control cables for both were connected to a cradle which the pilot controlled by positioning his hips laterally. The Wrights were awarded a patent for their control principle in 1906. The first sustained manned flight in a powered machine on December 17, 1903 required powerful controls flown continuously and skillfully by the pilot, Orville Wright, to overcome the effects of wind gusts (Figure 2).

Only eleven years after the historic flight of the Wright Flyer at Kitty Hawk, North Carolina, Lawrence Sperry won the Le Concours de la Securite en Aeroplane top prize of 400,000 francs for his fully automatic stabilizer and wing leveler in a Curtis Flying Boat(1) (Figure 3). As he flew past the judges to demonstrate the automatic stabilizer, he stood up in the cockpit with his hands over his head while his mechanic walked on the wings. The early automatic stabilizers to ease the pilot control task were the beginning of autopilots. The first commercial use of autopilots was in the 1930's by Eastern Airlines in a Curtis Condor(1) (Figures 4). Autopilots of various types and capability were the principle use of controls up through World War II.

A new use of automatic control in aircraft occurred in the early 1940's with the invention of the yaw damper. Dr. Karl Doetsch developed a gyro operated bang-bang servomechanism that drove an aerodynamic tab on the rudder to damp out yawing oscillations(1). It was first applied to a German Henschel Hs 129 attack bomber (Figure 4). The Hs 129 had a small vertical fin and high yaw inertia due to extensive armour plating which resulted in low aerodynamic damping. Dr. Doetsch's yaw damper provided artificial damping to improve its flying qualities.

The birth of automatic controls for augmenting the stability of aircraft in the modern sense, in which the pilot is totally unaware of the system's presence, was the yaw damper developed for Jack Northrop's YB-49 Flying Wing (Figure 5). In fact, the term "stability augmentation system" was coined by the inventers, Duane T. McRuer and Tom A. Fenney. They first called it a "stability derivative augmentor" but had to delete the middle word to fit the title block of an installation drawing. Shortly after the first flight of the Northrop Flying Wing Bomber in 1947, the Boeing B-47 flew with a similar type yaw damper. There followed a continued progression of developments in yaw, pitch and roll dampers which were vital to the development of the swept wing supersonic fighters in the 1950's and early 1960's. The inherent aerodynamic damping decreases drastically with increasing supersonic Mach numbers which made automatic damper systems mandatory.

Figure 6 shows several aircraft which represent a number of advances in automatic stabilization and control systems from the late 1950's to 1970's. The Lockheed Starfighter F-104 intercepter had pitch, roll and yaw dampers typical of the USA "Century Series" fighter aircraft of the 1950's and 1960's. The General Dynamics F-111 swept wing fighter has self adaptive flight control system that adapts its characteristics at different flight conditions. The McDonnell Douglas F-15 Eagle has a command augmentation which is representative of systems in most current high performance fighter aircraft. The supersonic Concorde represents the most sophisticated automatic flight control system in commercial transportation use today. It consists of six basic subsystems: autopilot / flight director; three axis autostabilizer; autothrottle; safety flight control; and, integrated test and maintenance. It has no less than 33 modes of operation including one mode that will automatically control the aircraft from an altitude of 5,000 feet to the supersonic cruise altitude. The Vought Corp. F-8 shown in figure 6 has been modified and used at the NASA Dryden Flight Research Center for digital fly-by-wire research . It was the first pure electrical flight control system for aircraft using digital computers and no form of mechanical backup or reversion capability. It represents the next step in flight crucial control systems technology.

We have entered an era where for most high performance aircraft, failure of certain elements of the automatic control system could cause loss of the airplane. That has spurred the development of technology for high reliability in automatic control systems. Tremendous strides have been made in control systems reliability through dual and triplex hydraulic actuators, redundant sensor and triplex or quadraplex flight control computers.

With the advent of highly reliable automatic control systems, the designer today can rely heavily on the augmentation system to provide some of the safety margins that had traditionally been provided by the basic airframe. Relaxing design constraints on the aerodynamics and structures through use of controls, allows configuration optimizations not previously possible. The use of such systems have become known as "Active Controls." There are several operational aircraft that employ active controls, for example: the Lockheed C-5A was retrofitted with an active lift distribution control system to extend the wing life; the Boeing B-52 G and H fleet were retrofitted with gust loads alleviation control systems to extend the wing structural fatigue life; the General Dynamics F-16 fighter was designed with a control system that allowed relaxed static stability to optimize maneuvering and cruise performance; and the new Lockheed L-1011/500 uses maneuver load control to extend the wing span without major structural changes in the wing. The NASA Space Shuttle Orbiter vehicle, which is to be launched next spring, was designed with a digital fly-by-wire system that provides necessary stability at some points during flight back to earth.

This paper first discusses some of the impact controls are having on the aircraft design process and the requirements placed on the control systems to implement flight crucial functions. Then, examples are presented on the impact controls are having on high performance fighters, commercial transports, business jets, helicopters and shipboard V/STOL aircraft. Finally some projections are made about the effect of controls on aircraft in the future. In preparing for this paper several noted technologists associated with each of the vehicle classes mentioned above were asked to provide a brief statement about the impact of advanced controls on their class of aircraft. Those quotes are used to introduce each section.

There are several references treating the impact of advanced control concepts on aircraft design, for example 4 - 9, which present more details on the subject. Extensive bibliographies are presented in references 7 and 9.

II. Design Process

Aircraft design process has been changing as controls have become important in optimizing the configuration. If the flight control specialists, as well as aerodynamics, structures, and propulsion specialists, are involved in the preliminary design process, the synergistic effect of an integrated design can be exploited to an extent not previously possible. This design philosophy has been referred to as the control configured vehicle (CCV) approach(4) or the application of active controls technology (ACT).

The more conventional aircraft design process(9) is outlined in Figure 7. System studies are performed to define a parametric airplane (wing area, weight, thrust, etc.) that meets the mission and performance requirements. Then the propulsion, aerodynamics and structures designs begin and trades are made among them. Penalties and degradation are often incurred in one area to achieve performance benefits in another; for example, the weight and drag penalties of large tail volume may be accepted to achieve positive aerodynamic stability. Once all the compromises have been made lead to an aircraft configuration, the vehicle's subsystems are designed including the flight control system.

In the design cycle by the active control approach (Figure 8), the capabilities of a full-time, highly reliable "fly-by-wire" control system are considered during the preliminary design of the aircraft. Trades are made assuming it is possible to relax the constraints in the aerodynamics, structures, and propulsion system areas and to rely on the control system to provide the same effective margins artificially. For example, it would be possible to reduce the aerodynamic stability to neutral or even negative to gain performance and rely on the control system to stabilize the aircraft artificially.

The type of ACT functions that can be considered are listed in Figure 9. Any one of these functions may or may not provide a performance improvement depending on the specific configuration and mission requirements. Ancillary requirements must also be considered, such as the system complexity, cost and maintenance. The process is iterated several times to define the final vehicle design which meets the mission requirements and provides the best return on investment.

III. Control System Requirements

Control system requirements for ACT are quite severe but achievable. In some applications, such as static stability augmentation of an aircraft with negative inherent stability, loss of the flight control system means loss of the aircraft. High reliability is mandatory. The same is true of course for the primary structure. Loss of the wing means loss of the aircraft. The difference is that designers have had years of experience in designing the structure and have well developed accelerated life testing techniques. Control systems technology for very high reliability is still evolving and reliability assurance techniques depend heavily on predictions and extrapolations of limited test data.

The state-of-the-art is such that the necessary reliability is obtained through providing multiple redundant systems. If one element fails, such as a sensor or computer, or one whole channel fails, there are alternate elements or channels that continue to operate with no change in system performance. A good example is the fly-by-wire system used in the General Dynamics F-16 airplane(10).

The most significant capabilities and feature of the F-16 flight control system are: longitudinal relaxed static stability; three-axis command and stability augmentation; automatic angle-of-attack limiting; full fly-by-wire control system; fail-operative/fail-operative redundancy (i.e. no degradation in performance with two channels failed;) and built-in self-testing. Figure 10 presents a functional diagram of the pitch axis system as an example. It has four independent electronic channels (quadruple redundant systems) including pilot sidestick sensors, motion sensors, and computers. This redundancy is managed by active signal selectors that compare the signals from all four channels and always selects the healthy signal. The control of the airplane depends totally on electrical signal transmission. There is no mechanical backup such as push rods or cables as other operational aircraft do. The principle elements of the redundancy concept are shown in Figure 11.

The F-16 system used analog computation. The trend in the future is definitely towards digital computation. NASA has demonstrated a digital fly-by-wire system in an F-8 airplane and is using a similar system in the Space Shuttle. Similar digital technology is beginning to be applied to operational aircraft but retaining some form of mechanical backup. A projection of where the technology is heading is given later in the paper.

IV. High Performance Fighters

"New and advanced fighters are utilizing fly-by-wire flight control systems--in some cases, digital systems. These digital control systems enable the designer to provide more handling and maneuvering versatility over a much broader envelope of speed, altitude, and load factor. Of even greater import is the much greater integration of flight controls, in combination with advanced cockpit displays and controls, with other major systems in the aircraft, such as propulsion, avionics, and armament systems. This area of control integration with other major aircraft systems will continue to develop and expand".

A. L. Jarrett
Director, Program Engineering F-18
McDonnell Douglas Corporation

Fighter aircraft have typically lead the way in applying advanced control concepts because they need high performance and maneuverability near operating limits. The General Dynamics F-16 is a particularly good example of the impact of advanced controls on fighter aircraft design. The details of this example are presented in reference 10.

Relaxing the longitudinal static stability constraint in the design of a fighter allows the airplane to be balanced to achieve improved maneuvering performance and increased range during cruise. Figure 12 shows a comparison between conventional (positive static stability) and relaxed static stability force balance at subsonic and supersonic conditions. At subsonic speeds, the conventional design requires a download on the horizontal tail to trim the airplane. Moving the center of gravity aft of the aerodynamic center requires an up-lift on the horizontal tail to trim the airplane. That means that the combined lift at the wing body and tail needed to balance a given weight can be achieved at a lower angle-of-attack. Hence for a given lift, the induced drag is lower. The active controls make up for the loss of stability. At supersonic speeds the situation is similar except that aerodynamic center is further aft and the tail load is still down but less than in a conventional design. The effect on the lift/drag characteristics is shown in Figure 13. Typical performance benefits from relaxed static stability as compared to a conventionally balanced airplane are shown in Figure 14.

There is a limit to how far aft the center of gravity can go. Reference 11 points out one of the limiting factors which is illustrated in Figure 15. Pitching moment is plotted vs angle-of-attack for 9% and 4% negative static margin with zero and full nose-down pitch control. In both cases the airplane is unstable, e.g. an increase in angle-of-attach produces a positive pitching moment which causes a further increase in angle-of attack. Negative pitching moment is needed from the pitch control in order to control the airplane. The 9% unstable case would run out of control at 20 degrees angle-of-attack, where as the 4% unstable case would not run out of control until 45 degrees. A system could be designed to artificially stabilize the 4% unstable case and prevent it from exceeding 45 degrees angle-of attack. The 9% unstable case may have had better lift/drag characteristics but there is insufficient control power to make use of it. Other limiting factors and design considerations are discussed in references 11 and 12.

Reference 13 discusses several areas in addition to relaxed static stability in which controls can impact fighter designs including direct lift and side force control; maneuver load control; gust alleviation; active flutter suppression; flight path control; and push button flight management. A paper at this meeting(14) discusses a specific flutter suppression system.

V. Commercial Transports

"The commercial air transportation industry has grown from a novelty, at its inception 50 years ago, to a vital element of the world community today.

Recent dramatic increases in the price of jet fuel and the prediction of reduced availability threaten the long term health of the world's airlines, and as a result, pose a challenge to the commercial transport designer to produce more fuel efficient transports. Advanced control concepts--including Active Control Technology--can be a powerful component in the development of more fuel efficient transports. These concepts will potentially allow a 5 to 10 percent improvement in fuel efficiency (2000 nmi airplane) through airplane drag reduction (reduced unaugmented airframe stability) and reduction in airplane structural weight (reduced empennage size and aerodynamic load control and/or alleviation). Realization of these potential improvements will require definition of acceptable operational strategies, appropriate development, test, and demonstration of the particular control concepts, followed by a gradual introduction into airline service".

Henry A. Shomber
Boeing IAAC*Project Manager,
NASA Energy Efficient Transport
Technology Program
Boeing Commercial Airplane Company

A comprehensive treatment of this subject in 1976 is reported on in reference 15. Several ACT systems are now certified and in service on commercial transports. A ride improvement system has been certified for the Boeing 747(16). The Lockheed L-1011 yaw stability augmentation system allowed a 20% reduction in design load on the vertical fin(17). Wing fuel management controls the center of gravity on the Concorde supersonic transport to minimize cruise drag. An active maneuver load control system is incorproated in the new L-1011-500 going into service in 1981(18).

The Lockheed L-1011-500 active maneuver load control system is a good example of the impact of advanced controls on commercial transports(17,18,19) Figure 16 illustrates the basic concept. The basic wing lift of normal level flight is nearly elliptical for optimum cruise performance. By automatically deflecting the outboard ailerons to spoil the lift on the outer portion of the span during maneuvers the lift is redistributed inboard, which reduces the root bending moment. Lockheed made use of this principle to extend the wing span of the L-1011-500 by 6%, as shown on Figure 17, without major structural modifications. The effect of the extended span could be used to increase range or payload. The use of active controls rather than a structural beef-up results in a significant improvement as shown. The 3% improved fuel efficiency at current fuel prices would save over $2 million in 10 years on each L-1011.

Greater benefits are anticipated if active controls are incorporated into the initial design of a transport. NASA has sponsored a major study with the Boeing Commercial Airplane Company to explore the integrated application of active controls (IAAC)(20). Boeing is exercising the active controls design cycle discussed above and comparing the results to a baseline configuration designed by current conventional practices. Figure 18 gives a flow diagram of their study. The output is to be a credible assessment of the potential benefits of ACT in a new transport design. They have only completed and reported on the study through the initial ACT configuration stage at this time.

*Integrated Application of Active Controls

The baseline configuration and design mission against which the ACT design will be compared are shown in Figure 19. The ACT functions considered were: pitch augmented stability (for relaxed longitudinal static stability); lateral-directional augmented stability (for relaxed directional static stability); angle-of-attack limiting; wing load alleviation (maneuver and gust loads); and, flutter mode control. An example of the design implications is the sizing of the horizontal tail with relaxed longitudinal static stability (Figure 20). The horizontal tail volume coefficient is plotted vs center of gravity location with the pertinent limiting boundaries, such as stall recovery, takeoff rotation and stability limits. The required loading range for fuel, passengers and cargo is shown as a heavy black line. By incorporating the active control functions mentioned above, it was possible to reduce the horizontal tial size by about 45%. The sizing was dictated solely by the control requirements for stall recovery and takeoff rotation. The typical cruise center of gravity was shifted aft approximately 9% relative to the wing and 5% aft of the maneuver point at 1.2 times the stall speed.

A comparison of the initial ACT configuration to the baseline is shown in Figure 21. The projected benefits are substantial: 14% range increase and 6% fuel savings. The next step on that study is to allow the wing aspect ratio and planform to be optimized in the ACT design process. Quantification of the full potential of ACT must await these results. John E. Steiner, Vice President, Corporate Product Development of Beoing, gave an estimate of the full potential of active controls (Figure 22) in reference 21 to be from 10-15% fuel savings.

A paper(22) at this meeting also discusses the implication of advanced controls for transports.

VI. Business Jets

"I expect that advanced control concepts will not impact any business jet airplane which will be in production in the early eighties.

An exception will be the use of electro-mechanical or hydraulic separate control surface technology (Diamond I and Learfan).

I also expect that in the late eighties and early nineties advanced electro-mechanical flight controls will be used to aerodynamically optimize business jets in each flight condition. Leading edge flaps, trailing edge flaps and primary longitudinal controls will be automatically adjusted (with microprocessor based control laws) to achieve L/D optimization, load alleviation and full-time artificial stability augmentation."

J. Roskam
Ackers Distinguished
Professor of Aerospace Engineering
University of Kansas

General aviation aircraft, including business jets, has had little or no applications of active controls. The performance requirements have not demanded stability augmentation even though it might improve flying qualities. The cost of implementing a reliable system of the type used in fighters or transports is prohibitive on this class of aircraft. A potential solution that could enable increased use of advanced control systems to business jets is the concept of a separate surface control system(23). The essence of the concept is to split the control surfaces, as indicated in Figure 23, using only a small portion for the automatic control functions. The larger portion would be connected to the pilot controls as usual and could override any possible failure of the servo controlled portion of the surface. Simple single string electronics and actuation could be used rather than sophisticated and costly redundant systems since the pilot would provide the backup safety. This concept has been demonstrated successfully in flight tests(24). The Mitsubishi Company of Japan is using a split surface control system for a 2-axis (yaw and roll) damper in their new Diamond I business jet. It is now being certified.

The relatively new rare-earth sammarium-cobalt magnets are revolutionizing electromechanical actuation(25). This technology should be particularly important to business jet aircraft for use in full-time artificial stability augmentation without the need for costly hydraulic systems. As the cost of the electronics is reduced through the use of microcomputers (possibly from the automotive industry) and the electromechanical actuator technology matures, it will be practical to consider load alleviation and even relaxed static stability for business jets. Ride smoothing(26) and gust alleviation(27) systems for improved passenger comfort are viable concepts for small commuter aircraft.

VII. Helicopters

"Rotorcraft offers a particularly fertile area for the application of advanced control techniques because their inherent characteristics on the one hand need the help active control can provide and on the other hand, are particularly adapted to its use.

The VTOL hovering task, with its 4 uncoupled degrees of freedom, demands gyroscopic stabilization that can only be practically provided electronically, and in forward flight the empennage required to provide aerodynamic stability in helicopters lead to low speed handling quality problems and high speed vibration problems. On the other hand, virtually all helicopters of any size already have the redundant powered controls necessary to implement active control and the main rotor is inherently capable of applying all the necessary control power for both trim and stability. It's therefore not surprising that helicopters since the early 1950's have employed to varying degrees what we now call active control, and today as the technology of flight critical fly-by-wire and fly-by-optic techniques matures, rotorcraft as a class stands to benefit perhaps more than any other configuration type from advanced control concepts."

E. S. Carter
Director of Technology
Sikorsky Aircraft

An important potential application of controls to helicopters is that for vibration reduction. Several research activities are underway to explore such systems(28-31). One concept(28), depicted in Figure 24 was developed and evaluated on a simulator using characteristics similar to the Sikorsky Black Hawk helicopter. The vibration control approach uses higher harmonic blade root cyclic pitch which modifies the blade airloads to minimize harmonic blade forcing. The control is made through the standard helicopter swash plate configuration. The control laws are derived from accelerometer sensors located in the cockpit, cabin, aircraft nose and near the rotor hub. Typical results of the simulation study (Figure 25) show that reduction on the order of 80% may be possible at some locations. Vibration reduction not only improves ride qualities, but also may significantly reduce maintenance costs.

The full potential of ACT for rotorcraft is yet to be determined.

VIII. V/STOL Aircraft

"Advanced digital fly-by-wire flight controls are critical to the success of shipboard based V/STOL. Fly-by-wire concepts make possible the precise blending of propulsion and aerodynamic controls required to provide the superior flying qualities that will be necessary to transition and land on relatively small moving shipboard platforms under all weather conditions. It is likely that a corresponding V/STOL control system utilizing mechanical mixing of aerodynamic and propulsion controls with automatic navigation and landing inputs would be prohibitively heavy and complex. Flying qualities resulting from the use of a mechanical system would probably be unacceptable for small ship operations."

John Louthan
Director of Vehicle Projects Development
Vought Corporation

V/STOL aircraft as used here refers to the class of airplanes (excluding helicopters) that can take off and land vertically or on short fields at dynamic pressures lower than that necessary for aerodynamic control alone. An example is the U.K. Harrier. Military requirements, such as Naval shipboard operations and Air Force operations from damaged runways, are the principle drives for this technology. A highly integrated propulsion/flight control system with advanced avionics and displays is a sine qua non for the operational effectiveness of V/STOL aircraft, particularly for shipboard operations at high sea states (Figure 26). One concept jointly studied by NASA and the Navy is a velocity command/position hold system depicted schematically in Figure 27. The pilot's control stick commands the desired inertial velocity in three axes. The control system compares that command to the measured inertial velocity and actuates the propulsive lift system guide vains to produce the desired velocity. If no command is given, the system automatically holds the hovering position. Simulator evaluations have shown such a system to be far superior to angular rate or attitude command control systems, particularly under conditions of high wind velocity over the deck.

In the case of V/STOL aircraft it is obvious that advanced controls have a major impact on the design and must be considered as an integral part of the design process.

IX. Projection to the Future

It seems clear that controls will have a continuing and increasing impact on the design of future aircraft of all types. The degree and timing will depend on how rapidly the technology is developed in ultra-reliable systems and interdisciplinary design methods.

One can conceive of control systems in the future for flight crucial functions implemented with inexpensive high density microelectronic chips with inherently high reliability, massive redundancy and reconfigurable architecture, self-monitoring and self-correcting intersystem communications networks, built-in and automated self-test and maintenance aids such that the entire system achieves a reliability equivalent to that of the airframe and requires no special maintenance (Figure 28). There would be no more need for crew monitoring of this "lifetime system" than there is for the airframe. Any defects which occur over the life of the system would be determined at infrequent periodic inspections, much like radiographic inspection of wing spars to assure a healthy structure. It should be possible to develop the technology to make such a system economically and technically feasible. Much work has already been accomplished in the area of fault tolerance for aircraft control systems(32-35).

Deyst's network architecture for fault tolerance (34) is one possible approach (Figure 29). That concept shares or pools a large number of microcomputer building blocks distributed through the aircraft system, but connected through a network communication system. A comprehensive redundancy management function would identify faults and reconfigure the system from the pool of elements to always maintain full system performance. With the rapid advances being made in electronics and related technologies, this is not only plausible, but should become cost effective.

Aircraft of the future may also be "all-electric: with electromechanical actuators and motors replacing hydraulically powered actuators and subsystems (36).

Figure 30 illustrates several of the advances in design methods that will allow more effective integration of controls into the design process. Significant advances are being made in interdisiciplinary design techniques through new theoretical studies(37) and extensive systems design studies(19). Various computer aided analysis and design methods(38) are being developed to be able to create aircraft designs better, faster, and cheaper. New wind tunnel testing techniques have been developed to incorporate active controls in early configuration testing(39).

Many future aircraft configurations ranging from fighters, supersonic transports, bombers, V/STOL and rotorcraft will require advanced control concepts to fulfill their missions (Figure 31).

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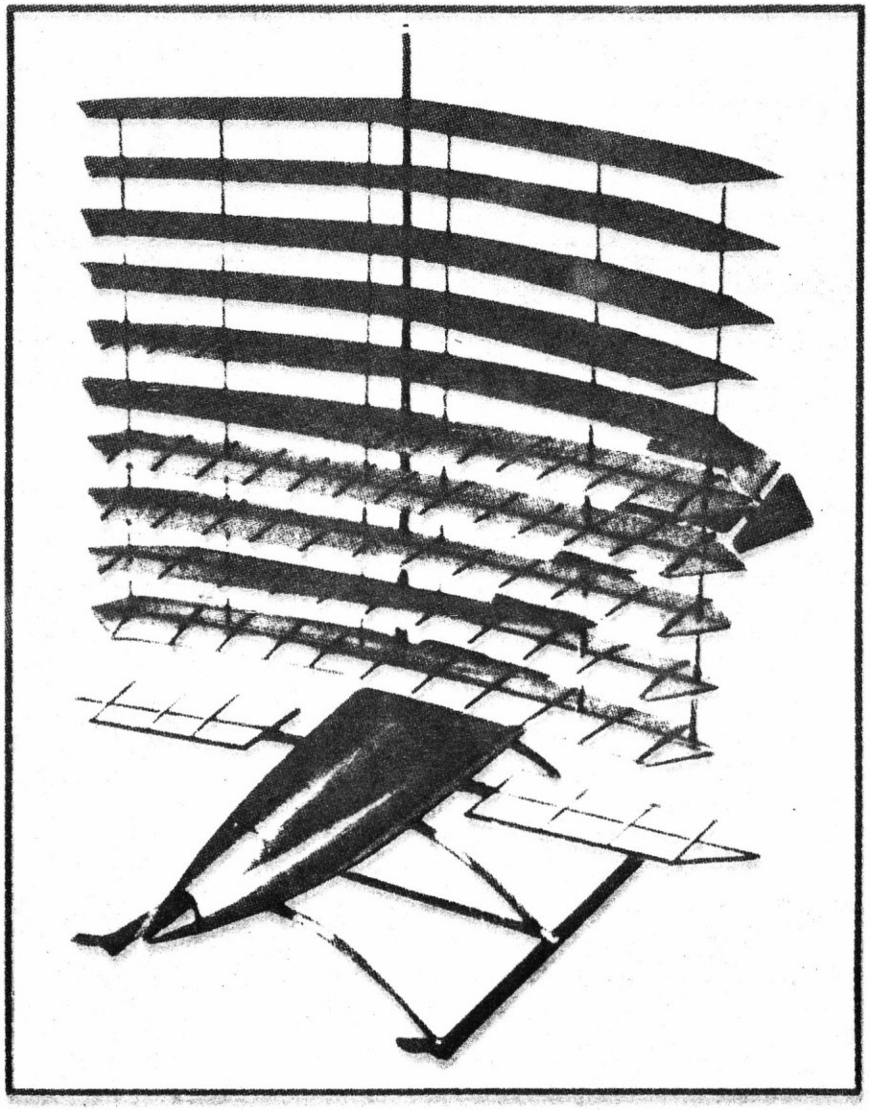


USED AUTOMATIC CONTROL FOR DIRECTIONAL STABILITY

Figure 1. Colonel Charles Renard's Decaplane - 1873

REQUIRED POWERFUL CONTROLS FLOWN CONTINUOUSLY BY PILOT

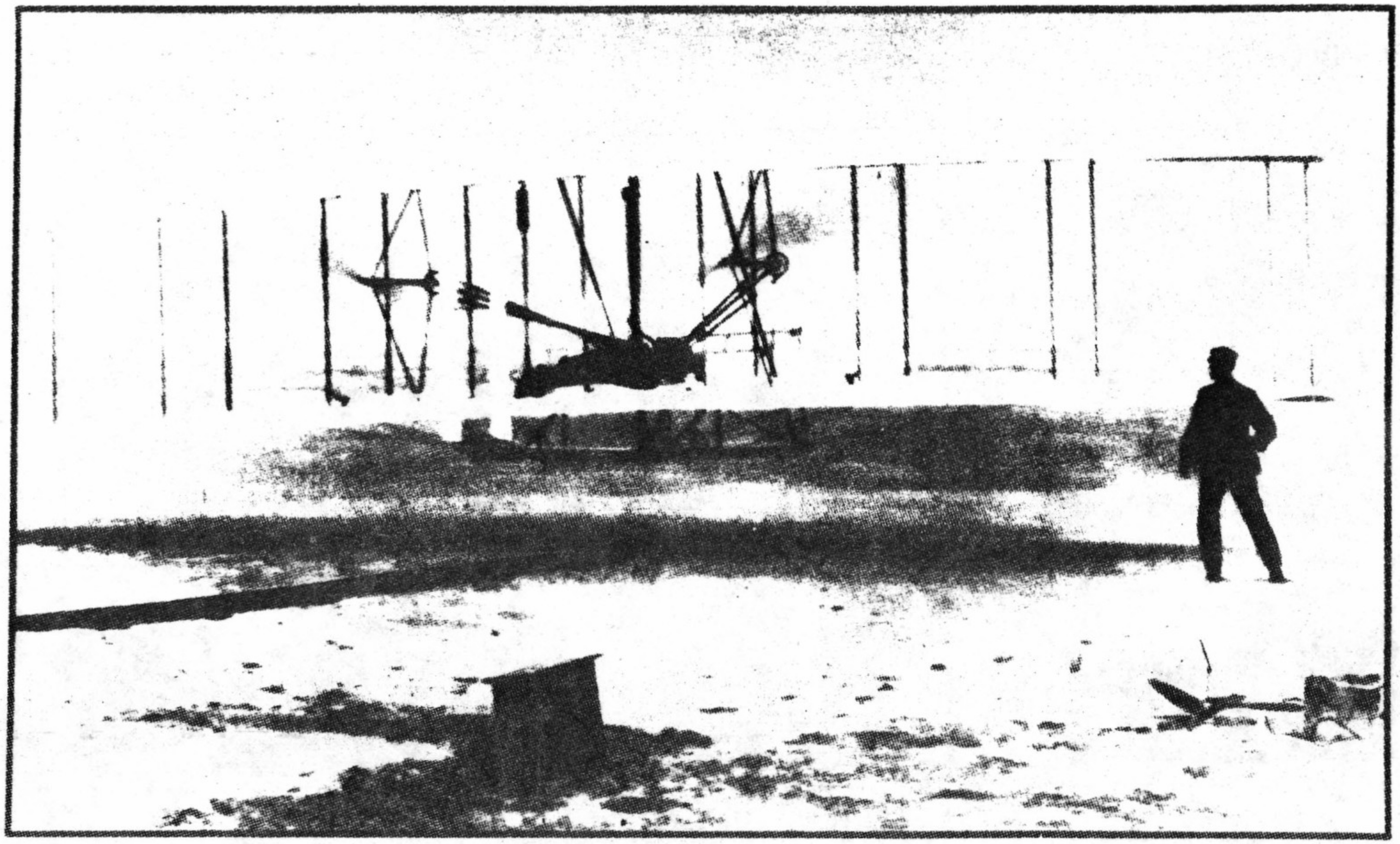
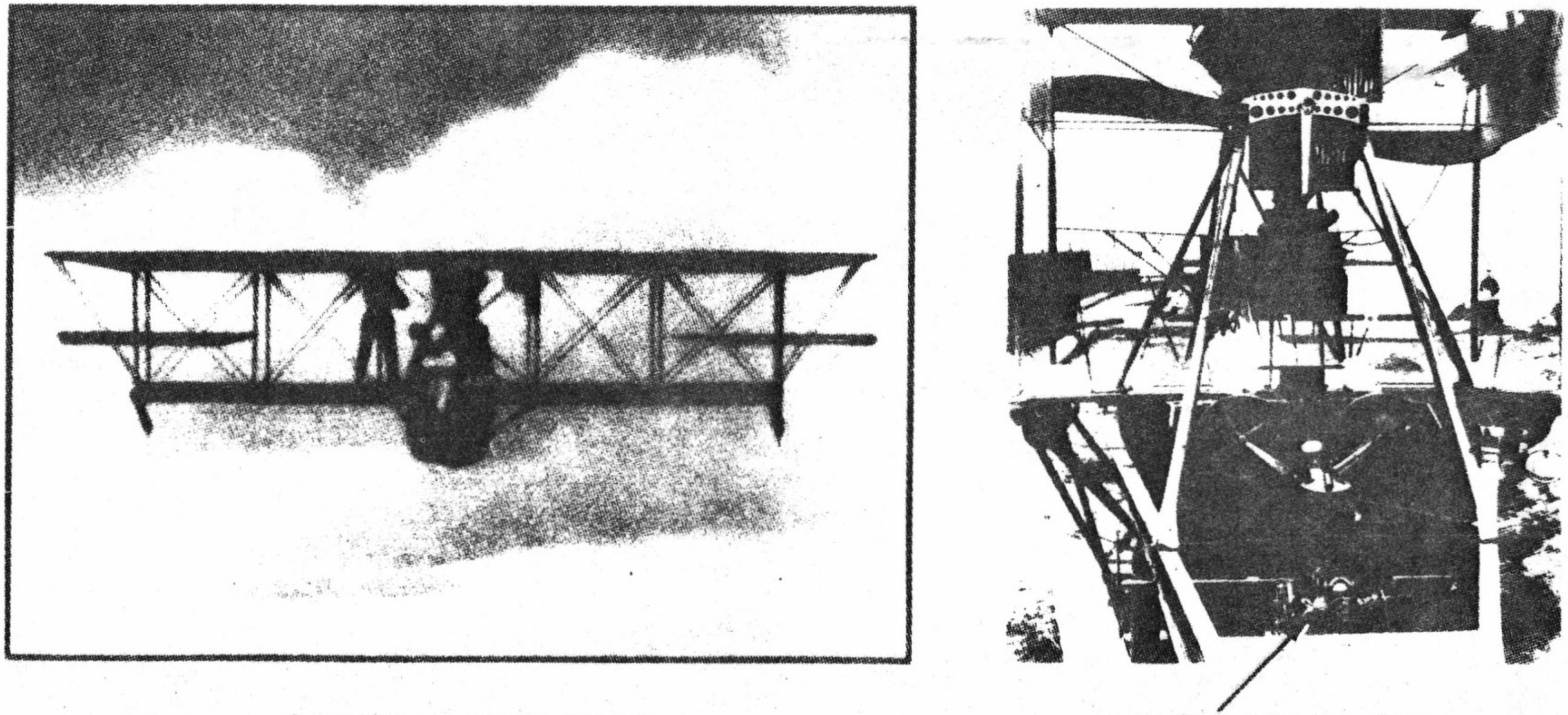


Figure 2. Wright Flyer - 1903

FIRST GYRO STABILIZED AEROPLANE IN BOTH ROLL AND PITCH



CURTIS FLYING BOAT

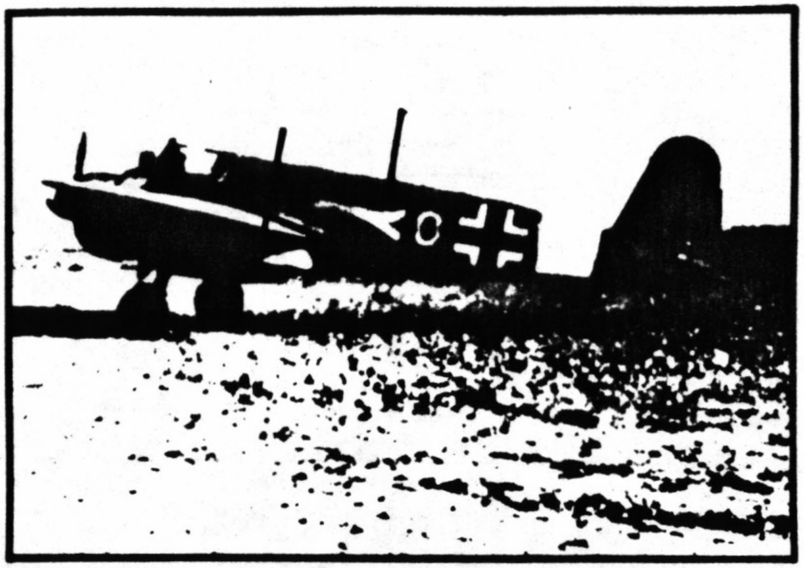
GYRO STABILIZER

Figure 3. Lawrence Sperry's Stabilizer - 1914

1930's
FIRST AIRLINE USE OF AN
AUTOPILOT (SPERRY AI)

EASTERN AIRLINE'S CURTIS CONDOR

1940's
FIRST YAW DAMPER
(DESIGNED BY KARL DOETSCH)



HENSCHEL Hs 129

Figure 4. Early Milestones in Automatic Controls

FIRST MODERN TYPE YAW DAMPER

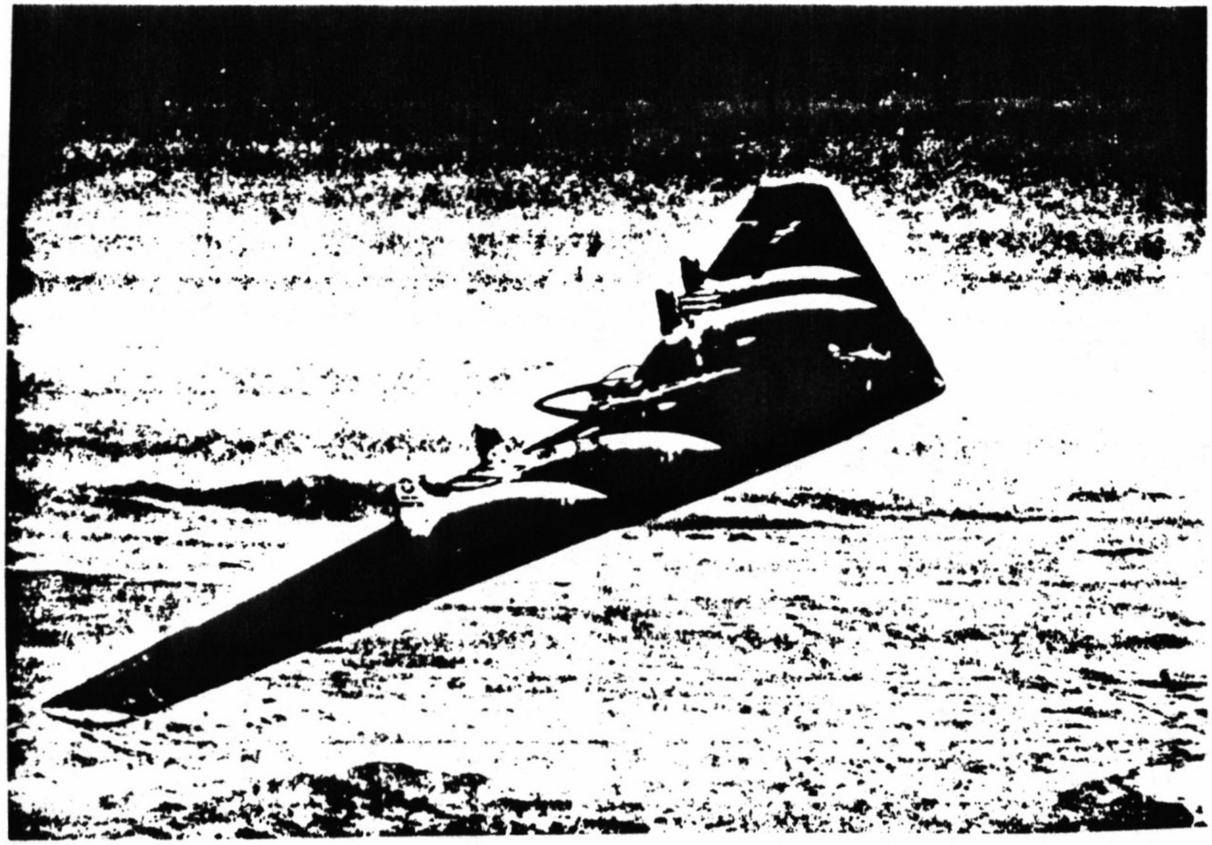


Figure 5. Northrop YB-49 Flying Wing - 1947

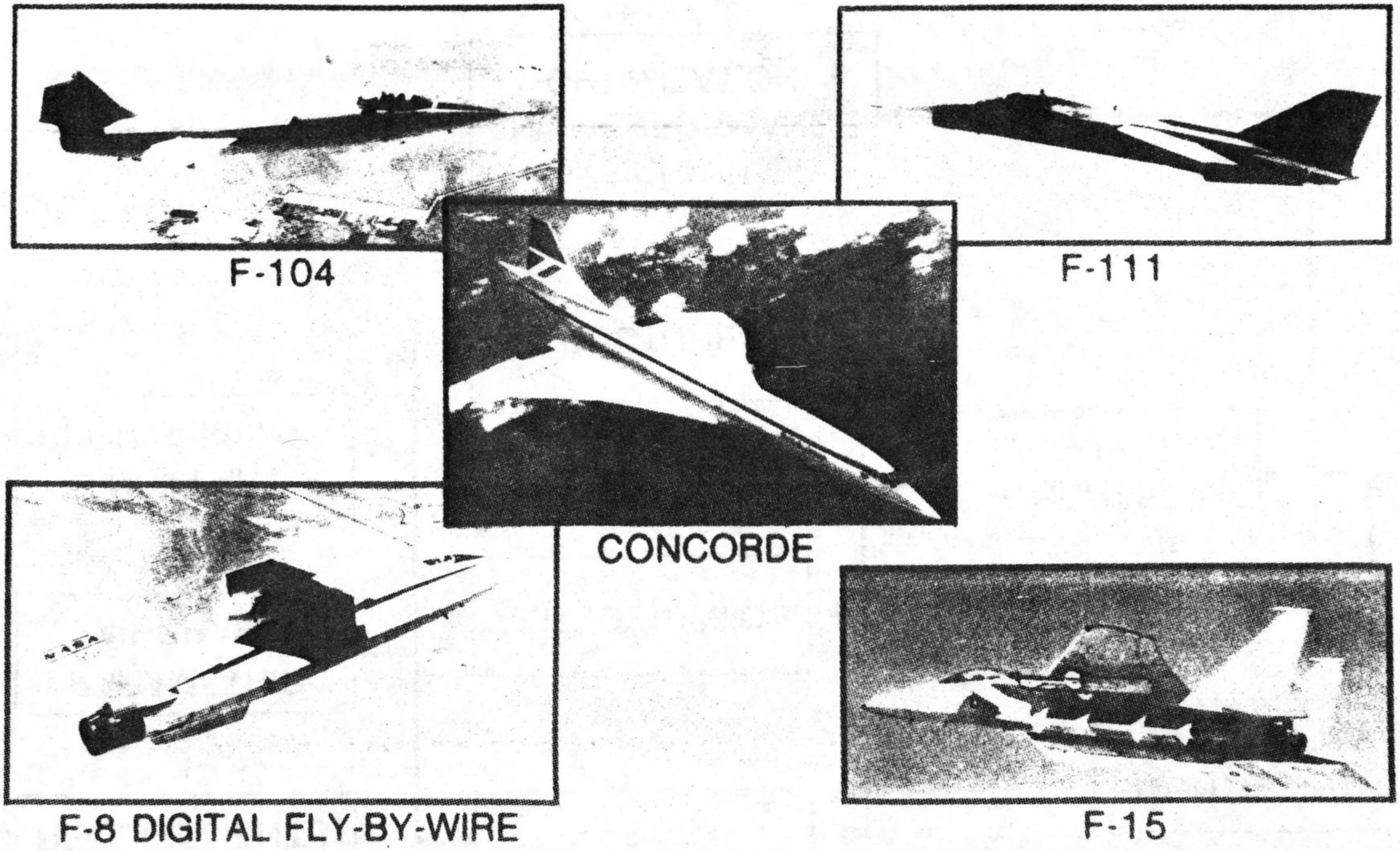


Figure 6. Advances in Stabilization and Control 1950's - 1970's

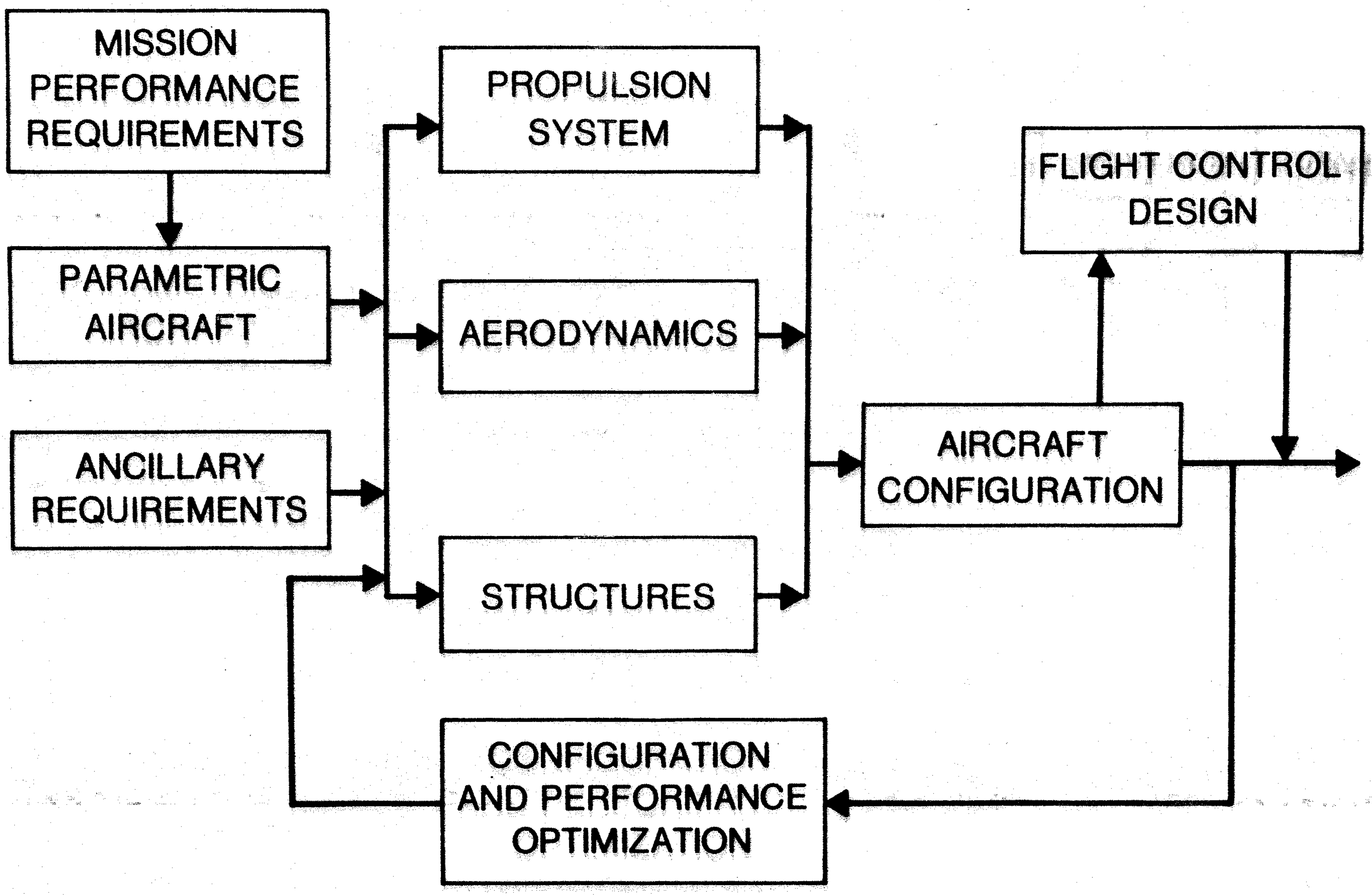


Figure 7. Traditional Aircraft Design Cycle

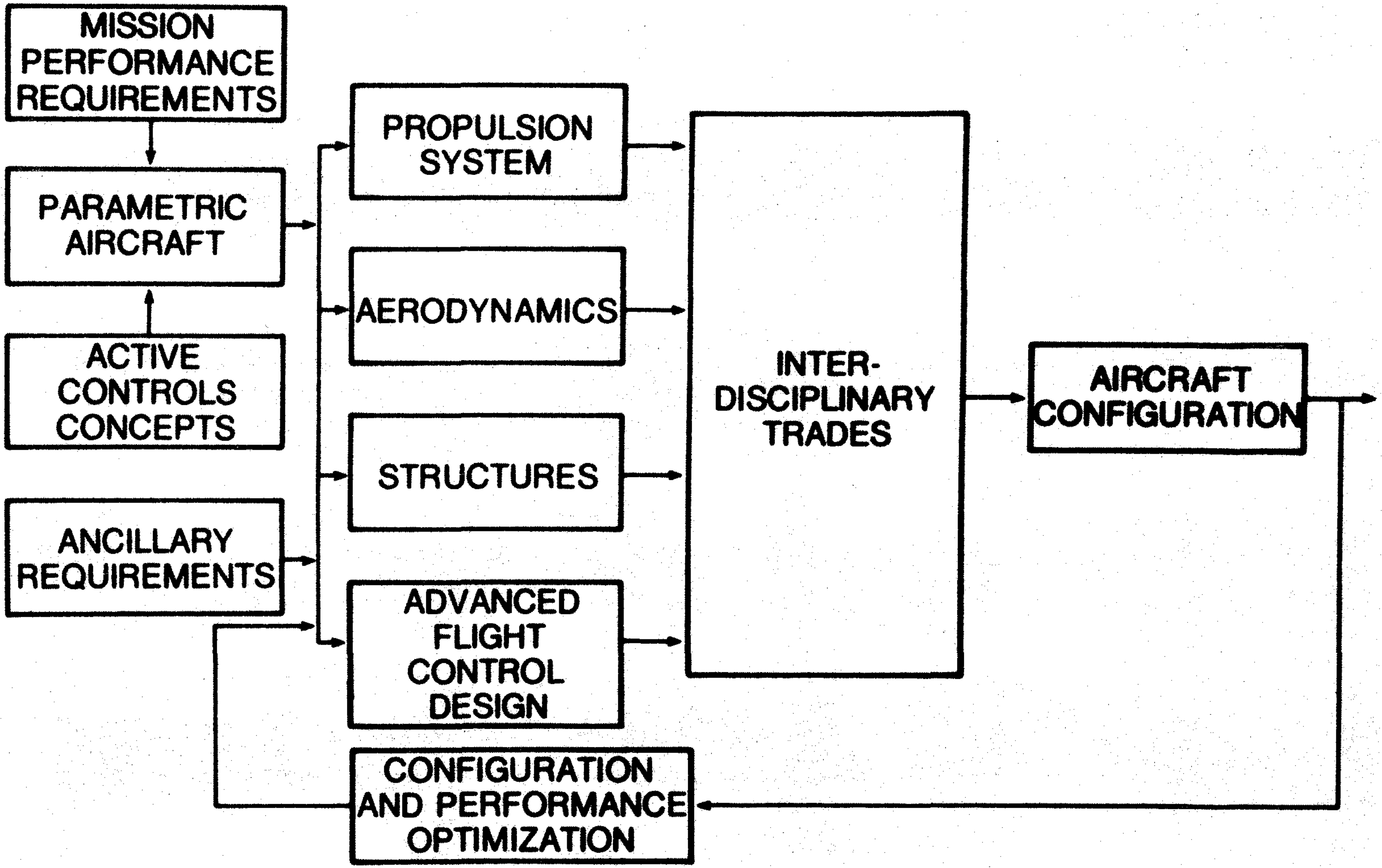


Figure 8. Active Controls Technology Design Cycle

LOADS ALLEVIATION AND STRUCTURAL MODE CONTROL

- MANEUVER LOADS
- GUST LOADS
- FATIGUE REDUCTION
- FLUTTER MODE CONTROL
- RIDE IMPROVEMENTS

RELAXED STATIC STABILITY AUGMENTATION

- REDUCE TRIM DRAG
- SMALLER EMPENNAGE

AERODYNAMIC CONFIGURATION MANAGEMENT

- FLAP LOADS CONTROL
- MISSION ADAPTIVE WING

MANEUVER ENHANCING OR LIMITING

- DIRECT LIFT AND SIDEFORCE CONTROL
- FLIGHT PATH COMMAND
- FLIGHT ENVELOPE LIMITING

Figure 9. Active Controls Technology Functions

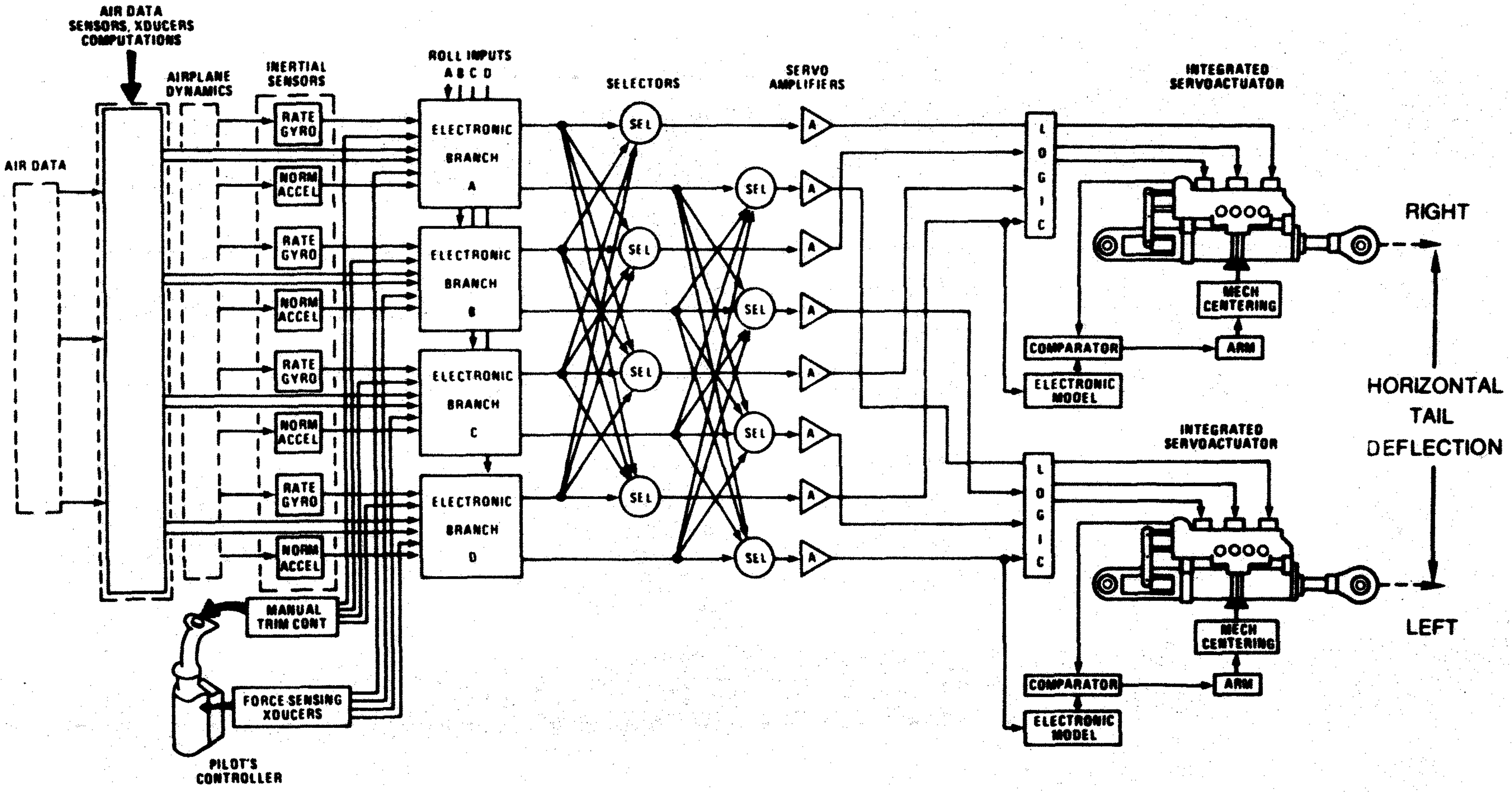


Figure 10. F-16 Fly-By-Wire Control System Pitch Axis Functional Diagram

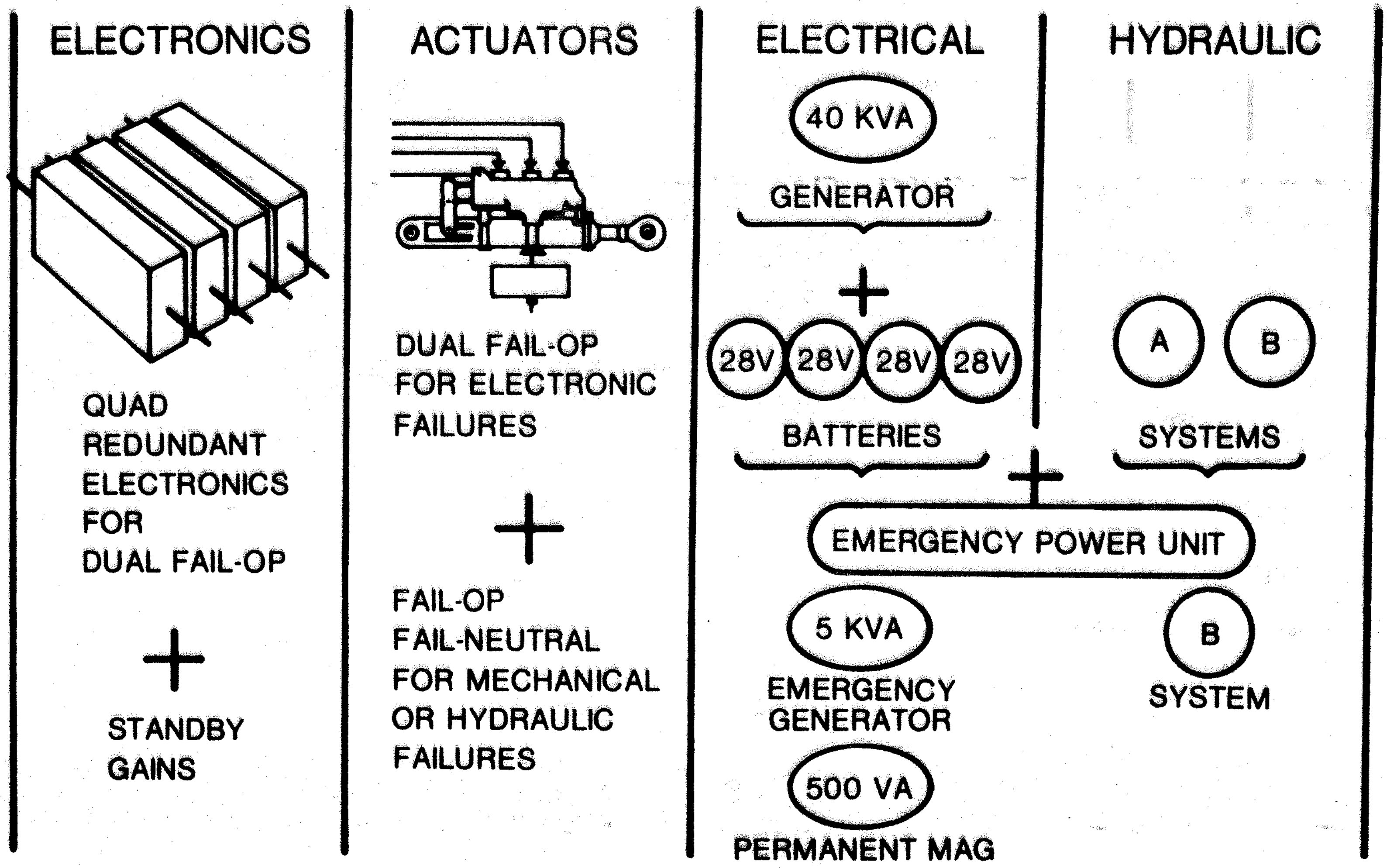


Figure 11. F-16 Flight Control System Redundancy Concept

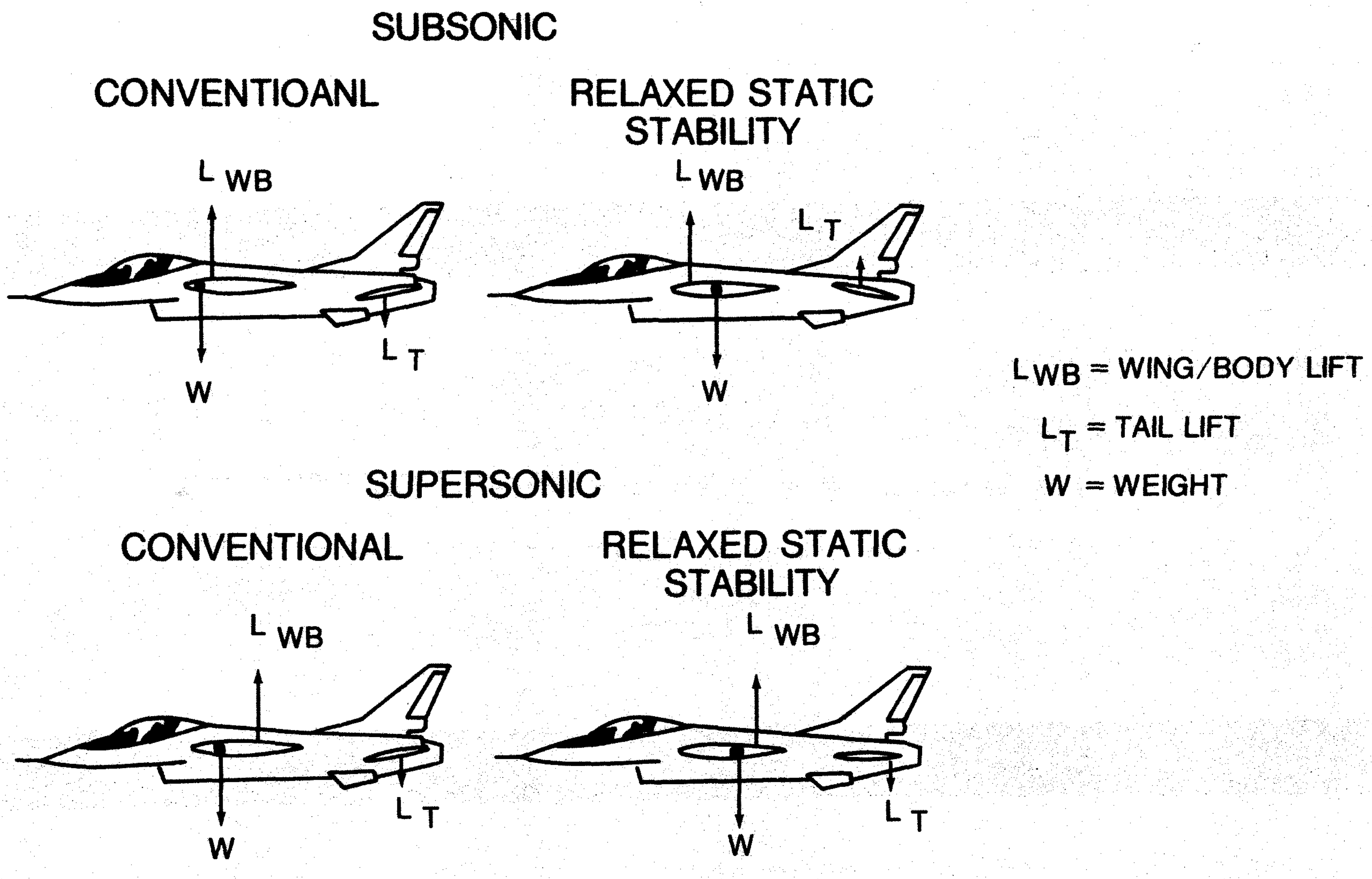


Figure 12. Conventional and Relaxed Static Stability Comparison

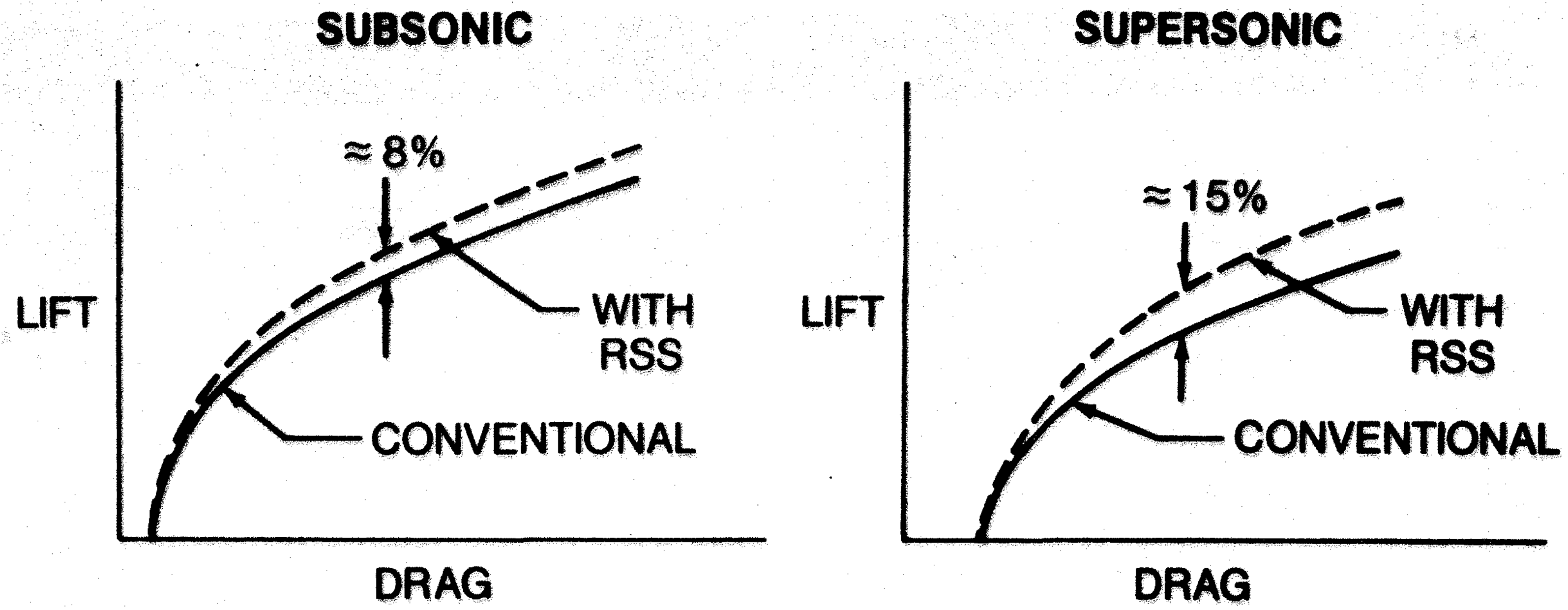


Figure 13. Lift/Drag Improvement from Relaxed State Stability (RSS)

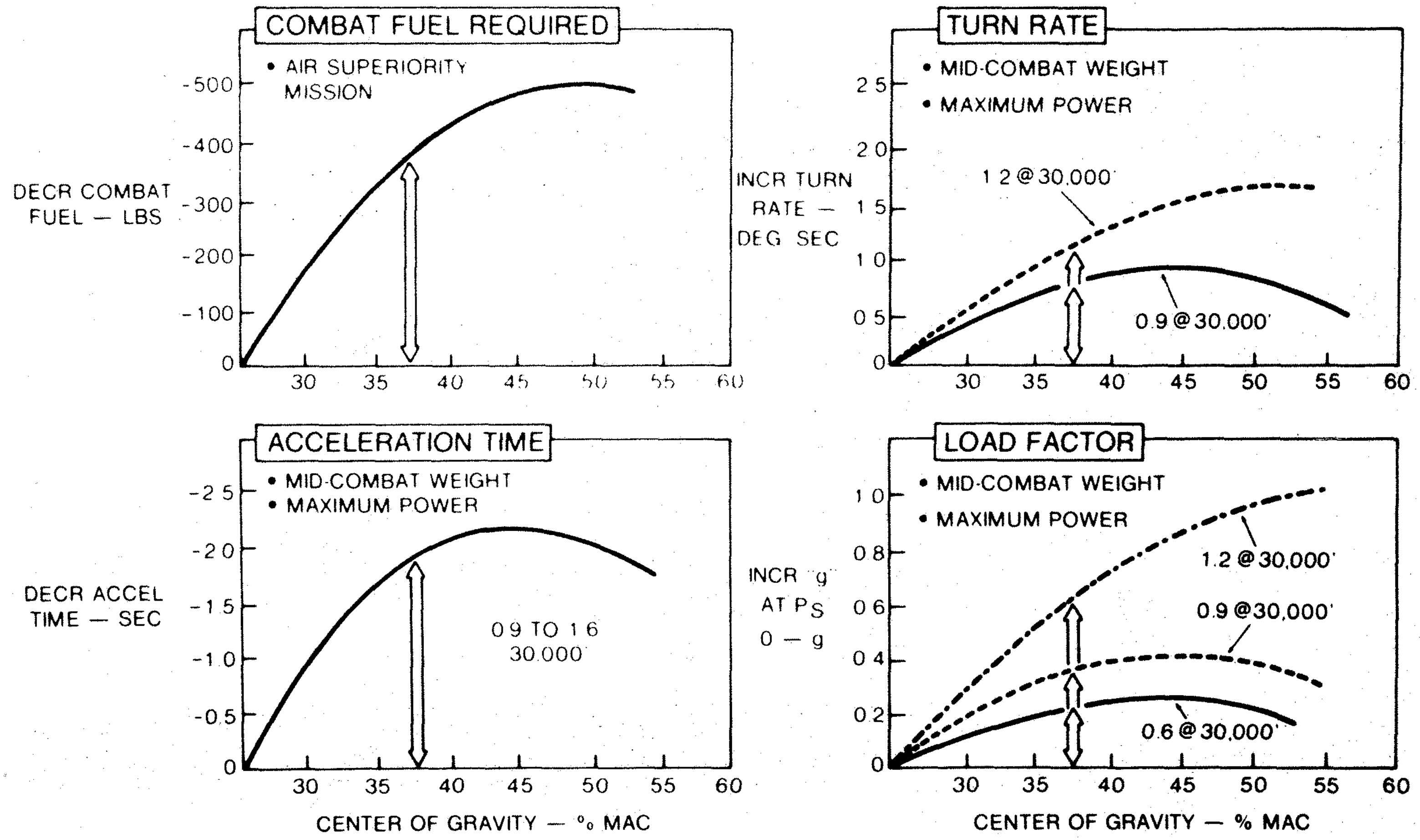


Figure 14. Fighter Performance Benefits from Relaxed Static Stability

Not for F-16

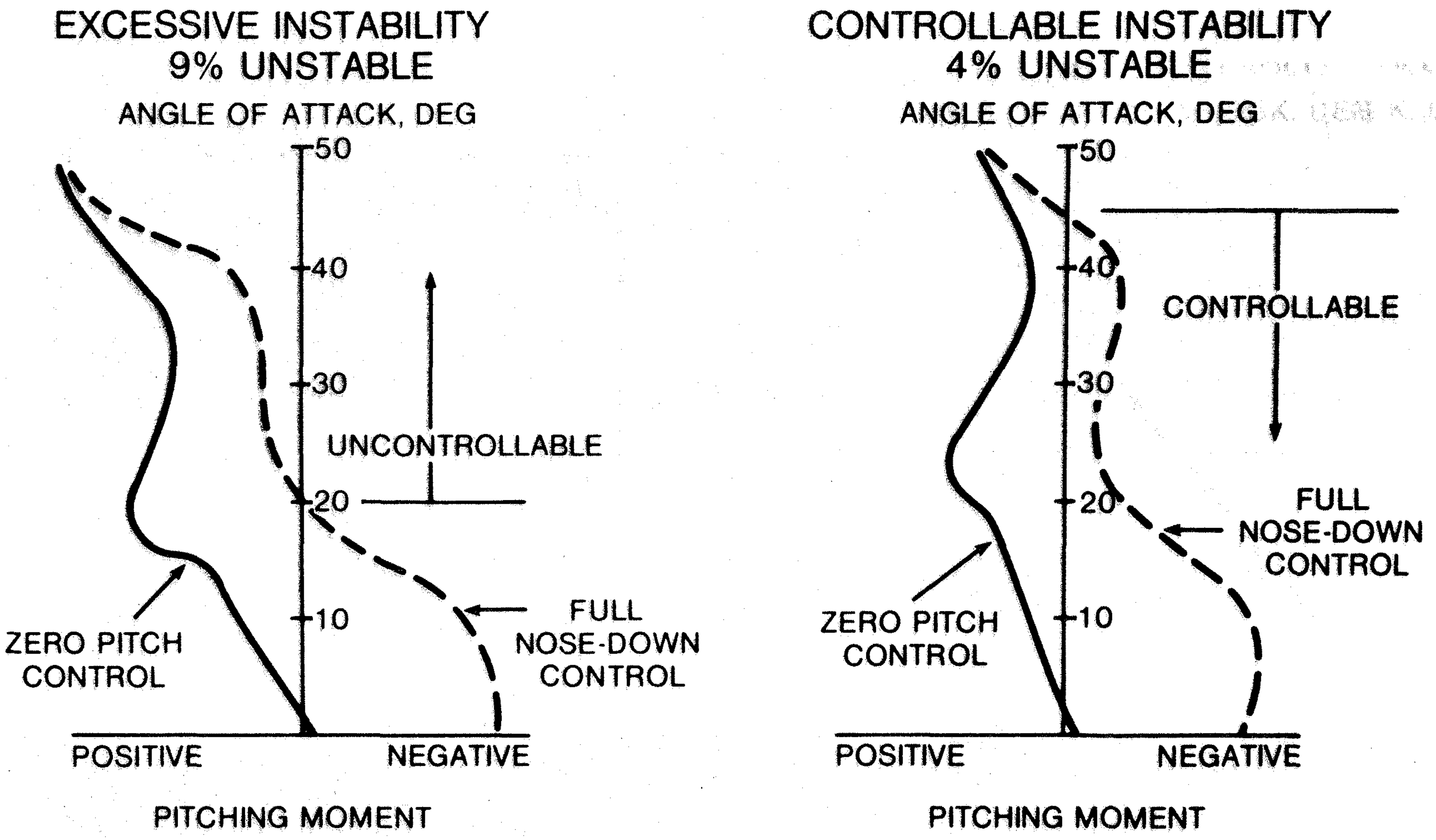


Figure 15. Typical Pitch Control Moment Limit for Relaxed Static Stability

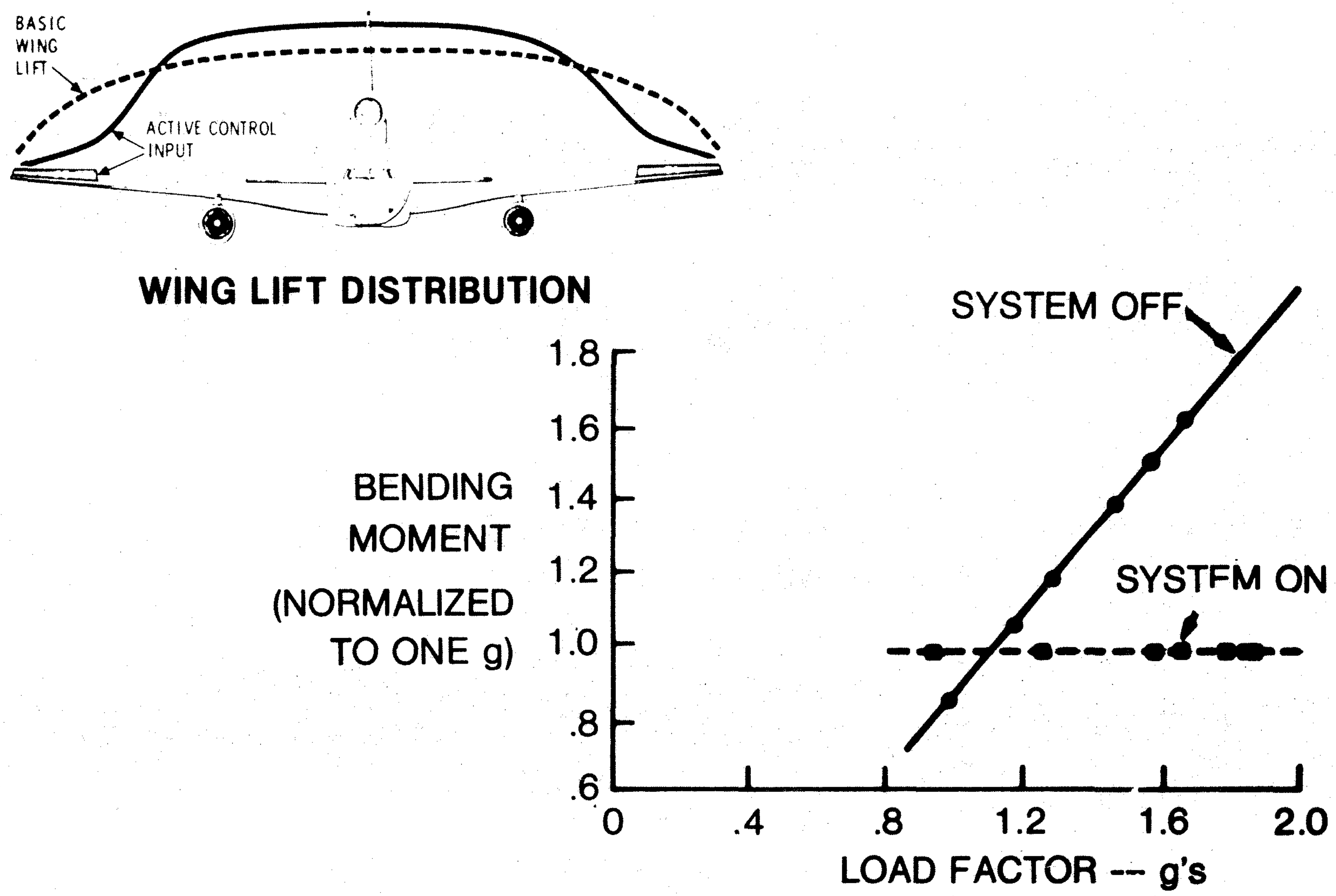


Figure 16. Active Maneuver Load Control - Lockheed L-1011/500

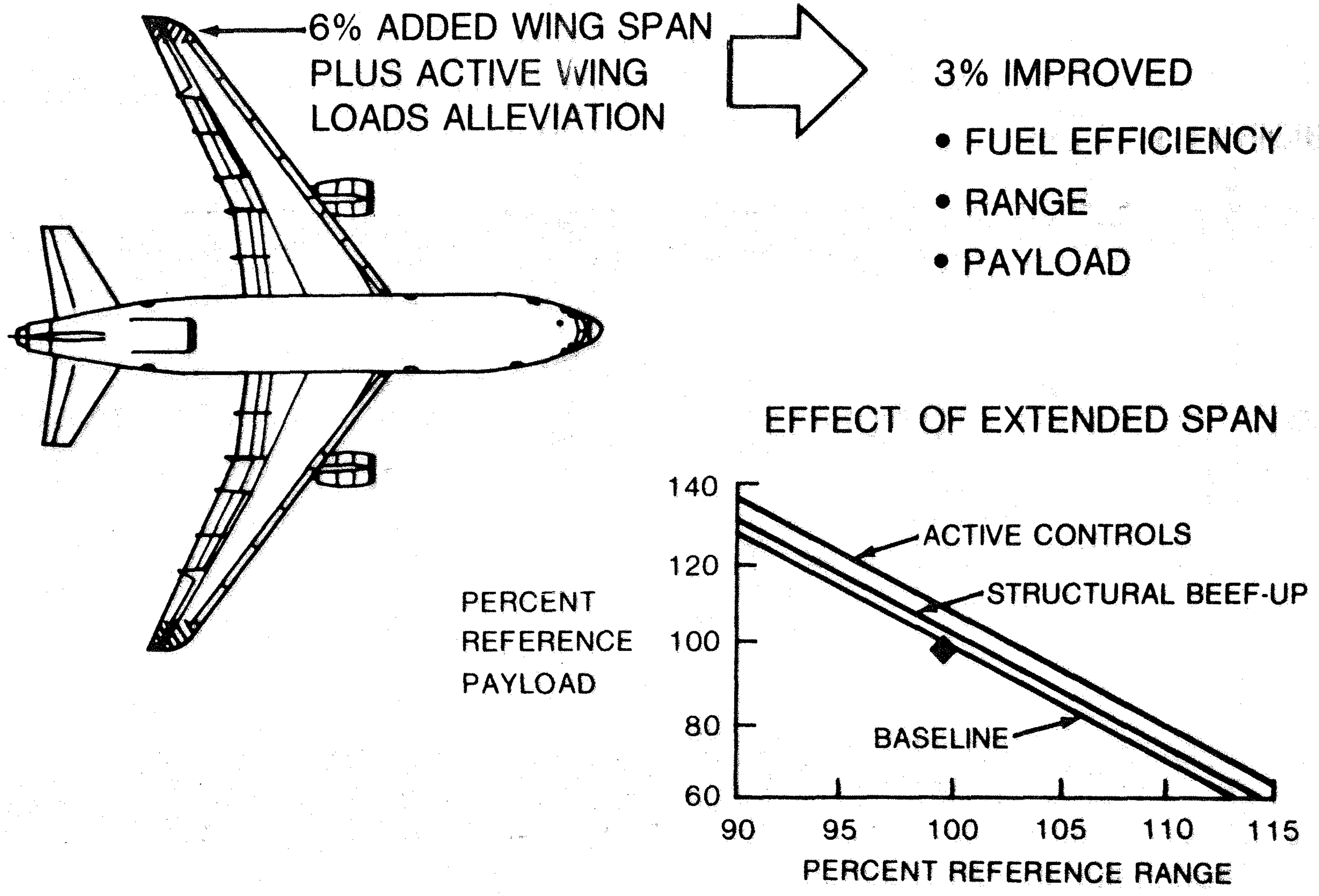


Figure 17. L-1011 Extended Span and Active Control Benefits

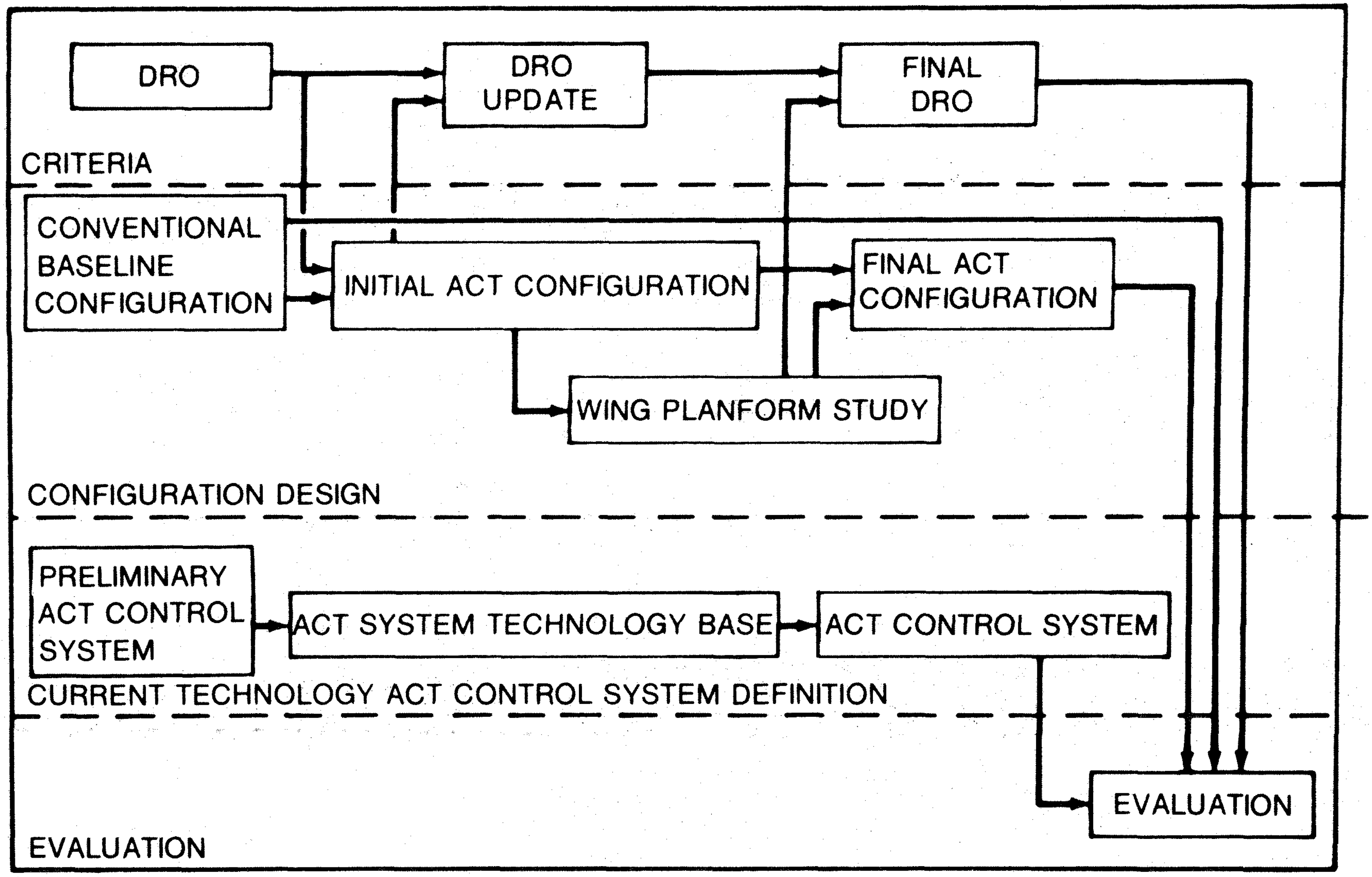


Figure 18. Boeing Study of Application of Integrated Active Controls of Future Transports

CONFIGURATION

- PASSENGERS 197
- ENGINES 2(CF6 -62D)
- CONTAINERS 22 LD-3A, OR 11 LD-3

DESIGN MISSION

- CRUISE MACH .80
- RANGE 2100 NM
- TAKEOFF FIELD LENGTH 7250
- APPROACH SPEED 135 KTS
- NOISE FAR 36 STAGE III
- FLYING QUALITIES CURRENT COMMERCIAL PRACTICE

TECHNOLOGY

- CURRENT COMMERCIAL CONVENTIONAL TRANSPORT PRACTICE

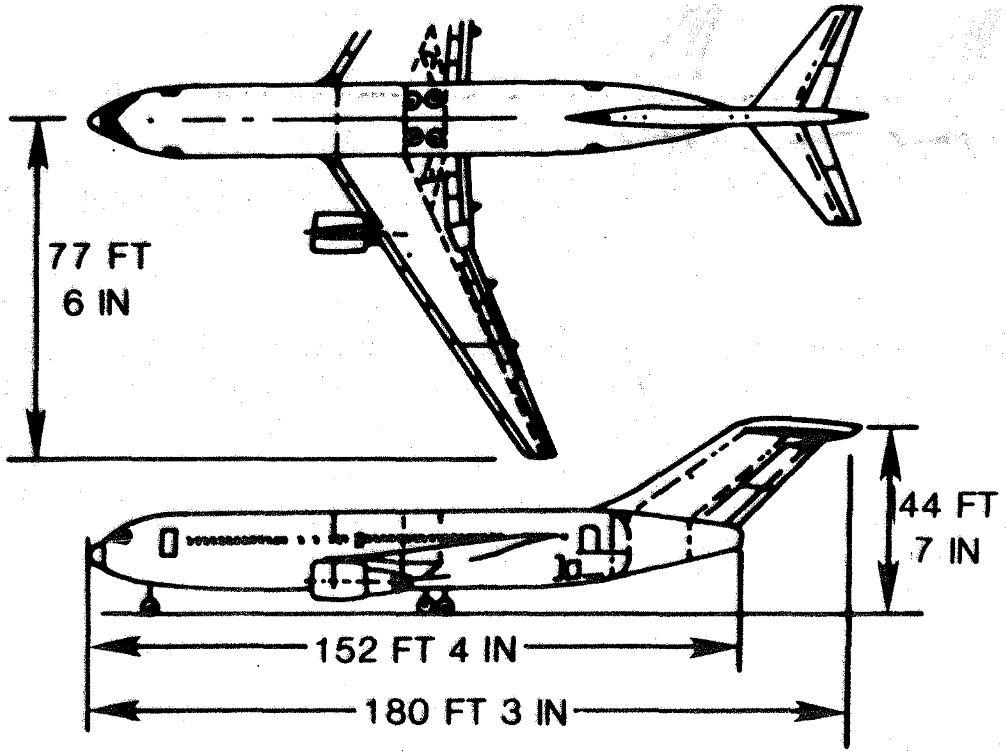


Figure 19. Baseline Configuration

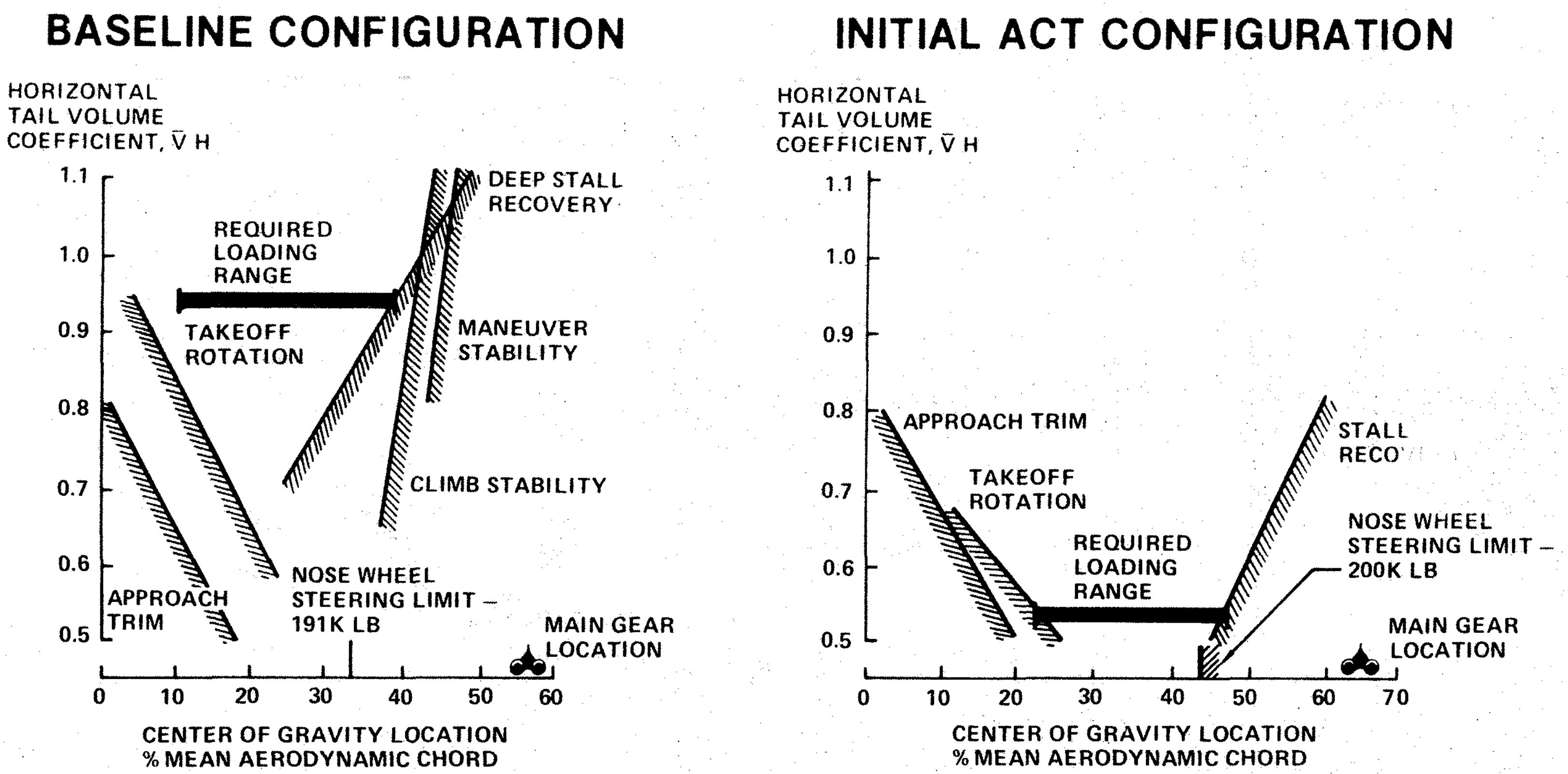
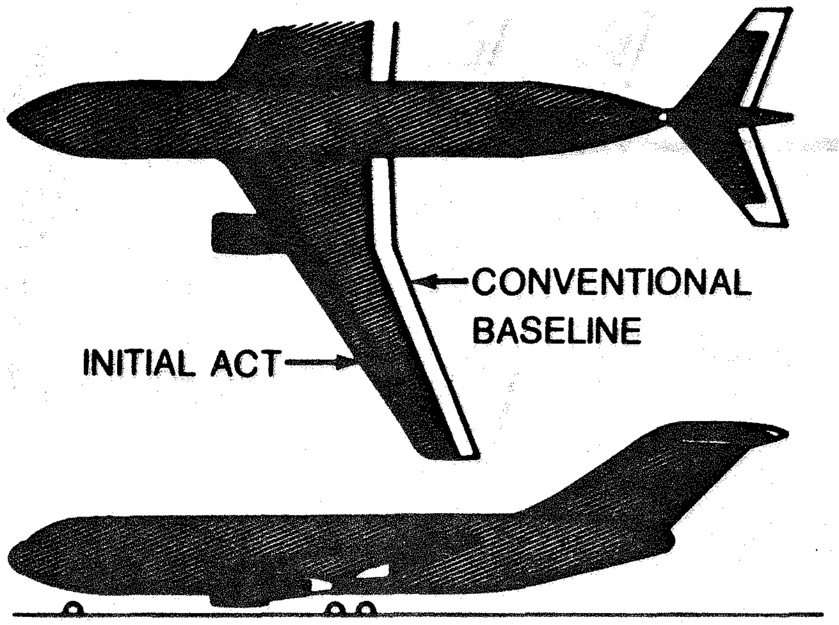


Figure 20. Horizontal Tail Sizing Requirements

ACT FUNCTIONS

- RELAXED STATIC STABILITY
- WING LOAD ALLEVIATION
  - — MANEUVER LOAD CONTROL
  - — GUST LOADS ALLEVIATION
- FLUTTER MODE CONTROL



CONFIGURATION EFFECTS

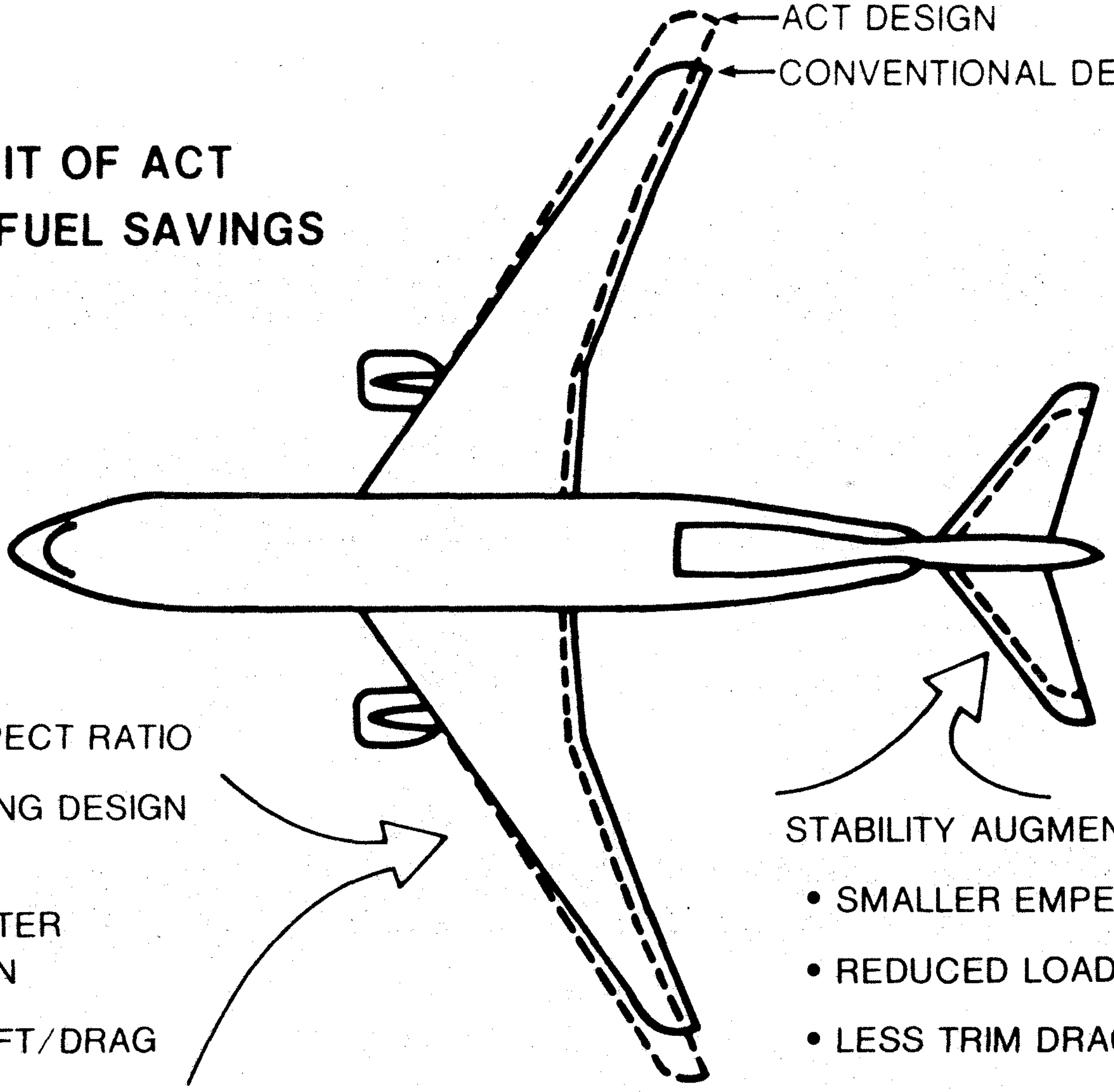
- HORIZONTAL TAIL REDUCED 45%
- VERTICAL TAIL REDUCED 6%
- CRUISE CG SHIFTED AFT 9.5%
- WEIGHT REDUCED 2,480 LBS

BENEFITS OF ACT

14% RANGE INCREASE
6% FUEL SAVINGS

Figure 21. Configuration Comparison

BENEFIT OF ACT
10 - 15% FUEL SAVINGS



INCREASED ASPECT RATIO

- REDUCED WING DESIGN LOADS
- ACTIVE FLUTTER SUPPRESSION
- IMPROVED LIFT/DRAG RATIO

STABILITY AUGMENTATION

- SMALLER EMPENNAGE
- REDUCED LOADS
- LESS TRIM DRAG

Figure 22. Potential of Full Active Controls Design

Figure 23. Separate Surface Automatic Control

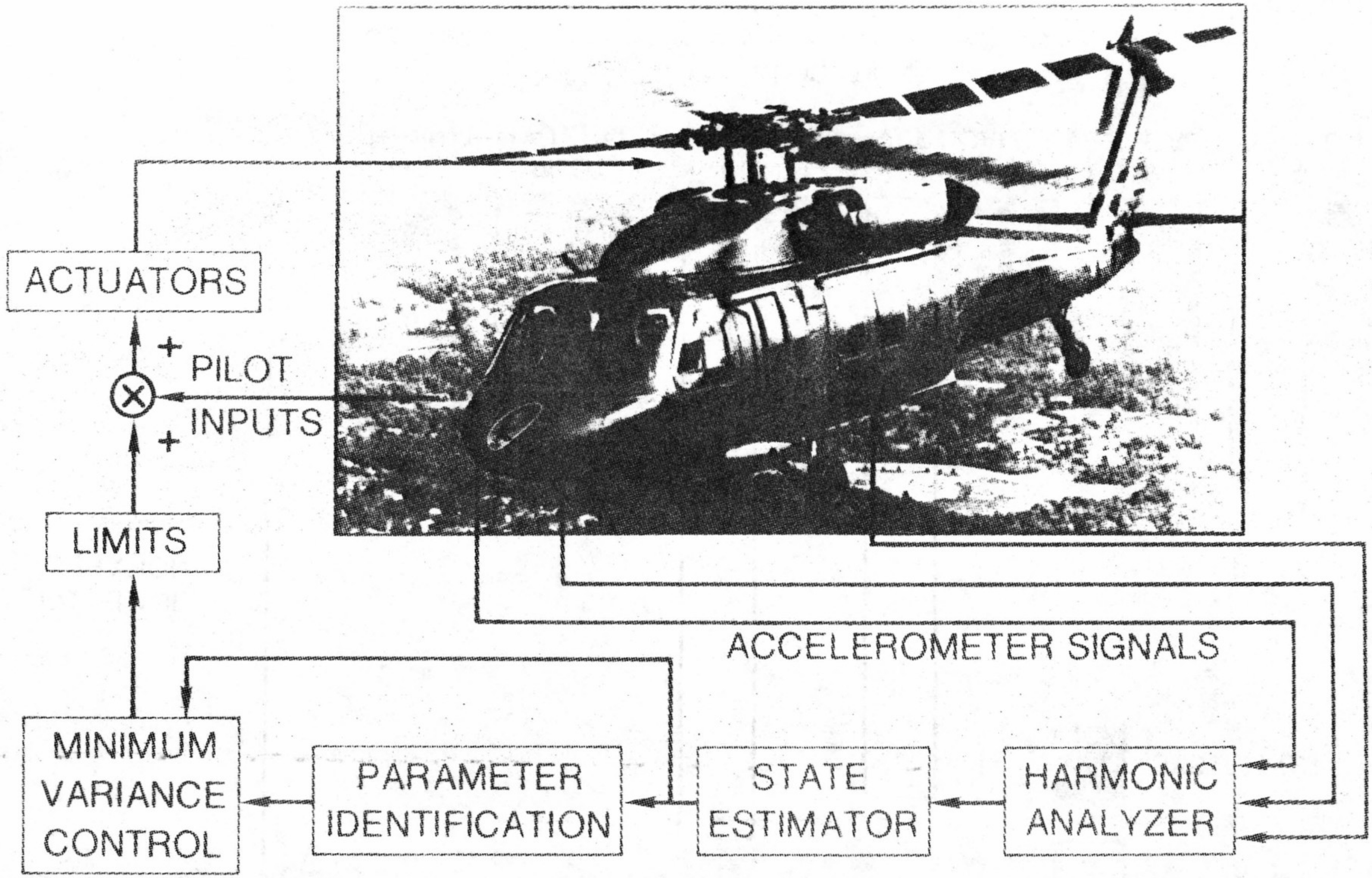


Figure 24. Vibration Reduction Control System

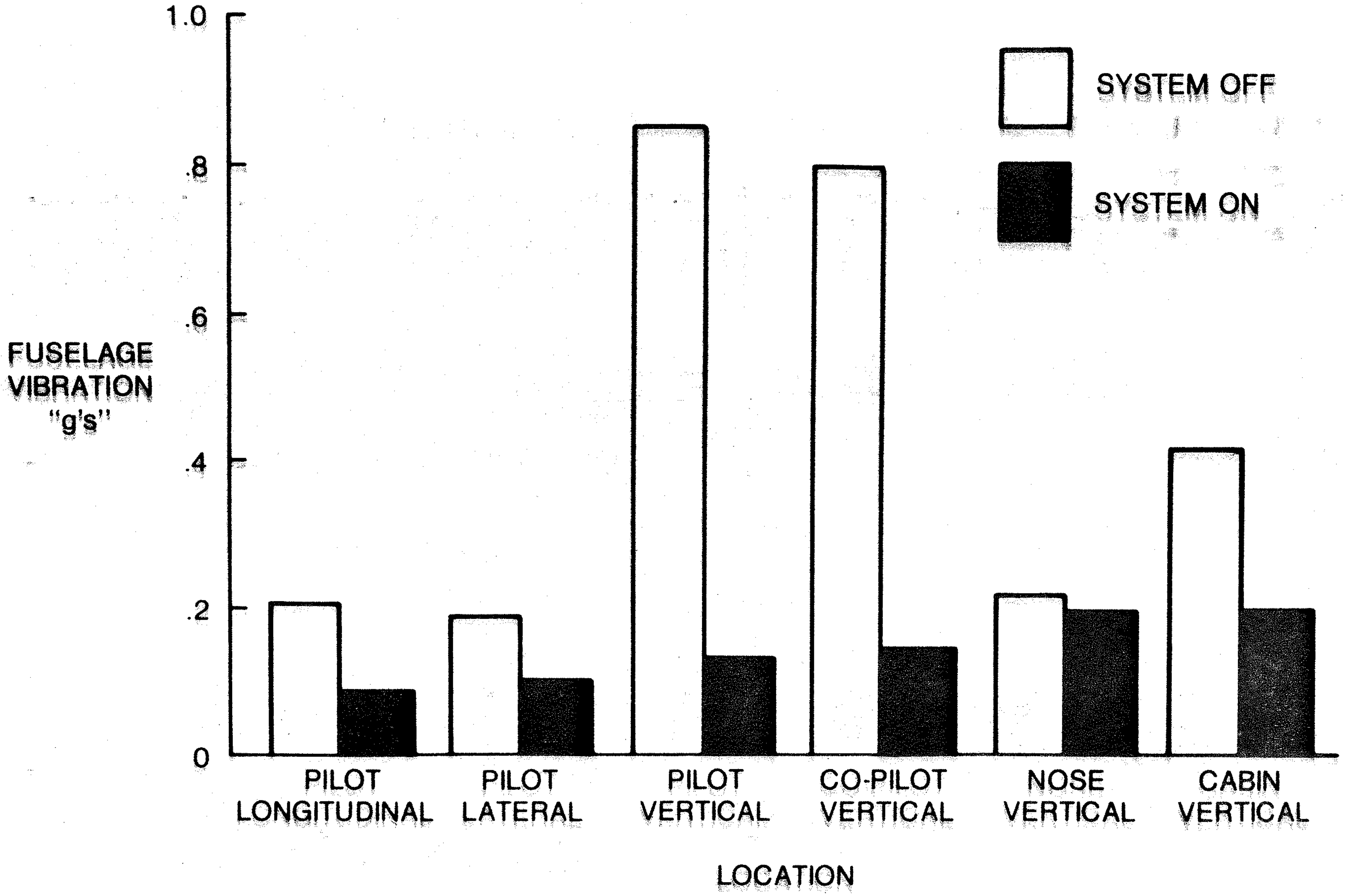


Figure 25. Effect of Vibration Reduction System

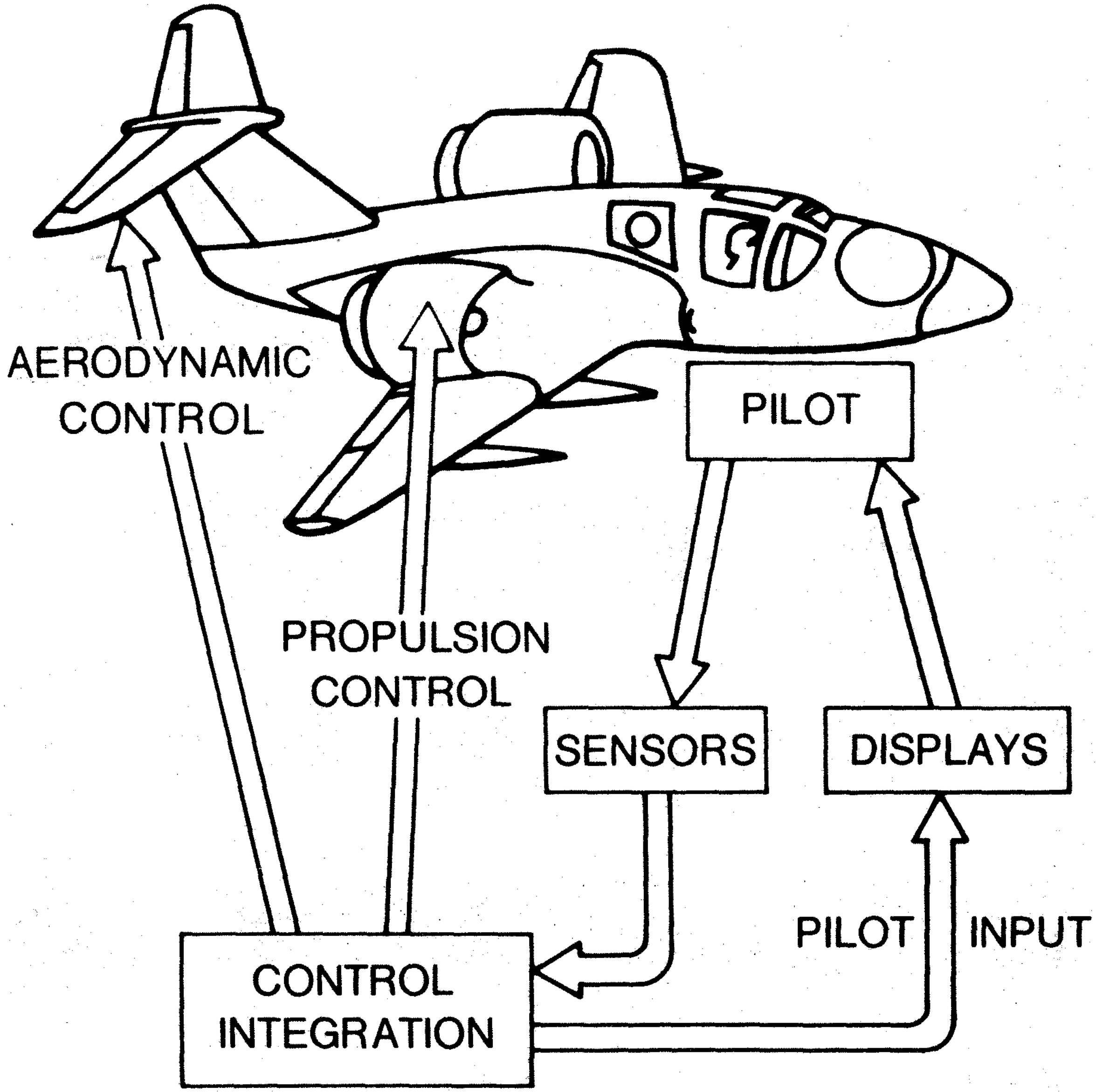


Figure 26. V/STOL Integrated Propulsion and Flight Control

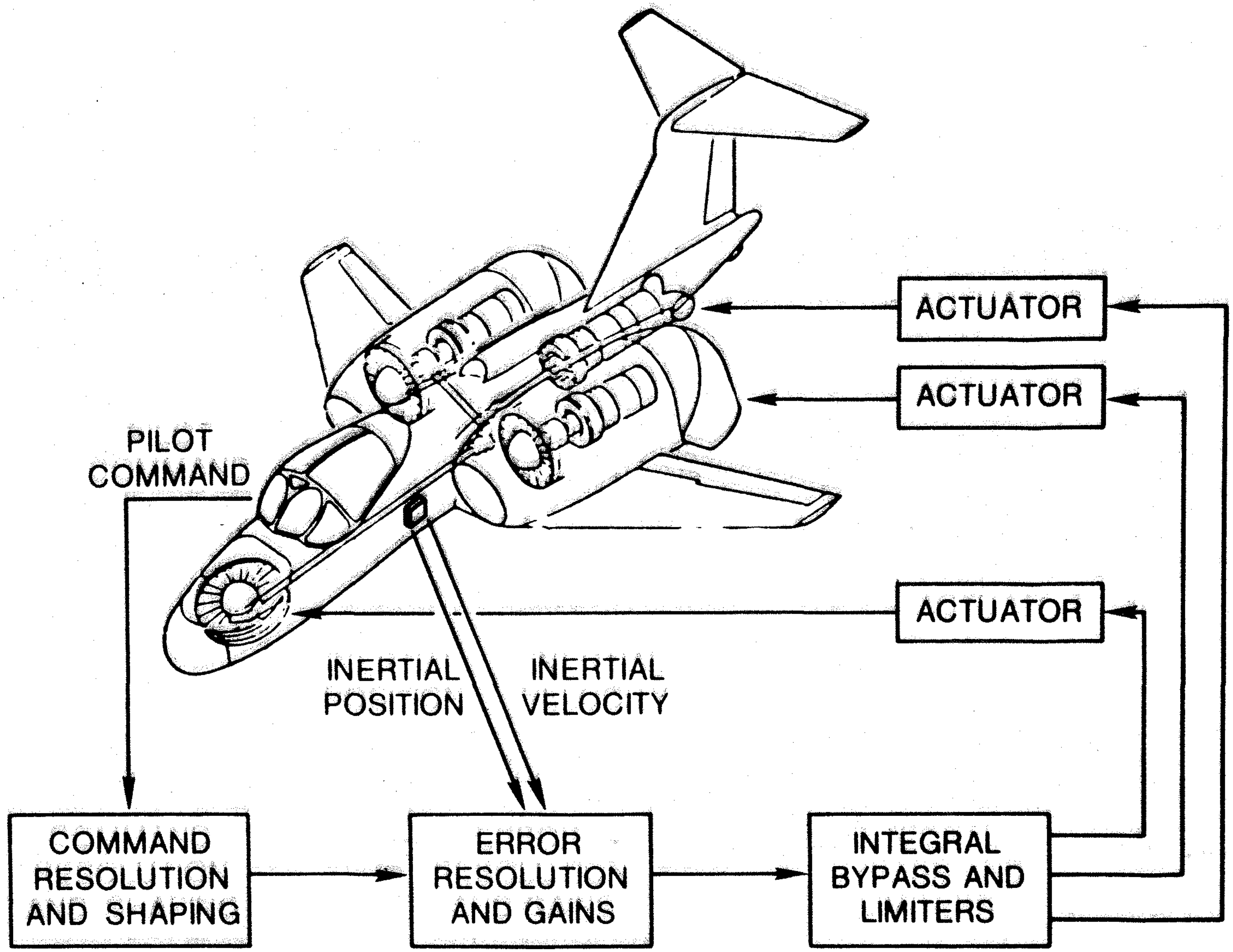


Figure 27. Velocity Command/Position Hold System

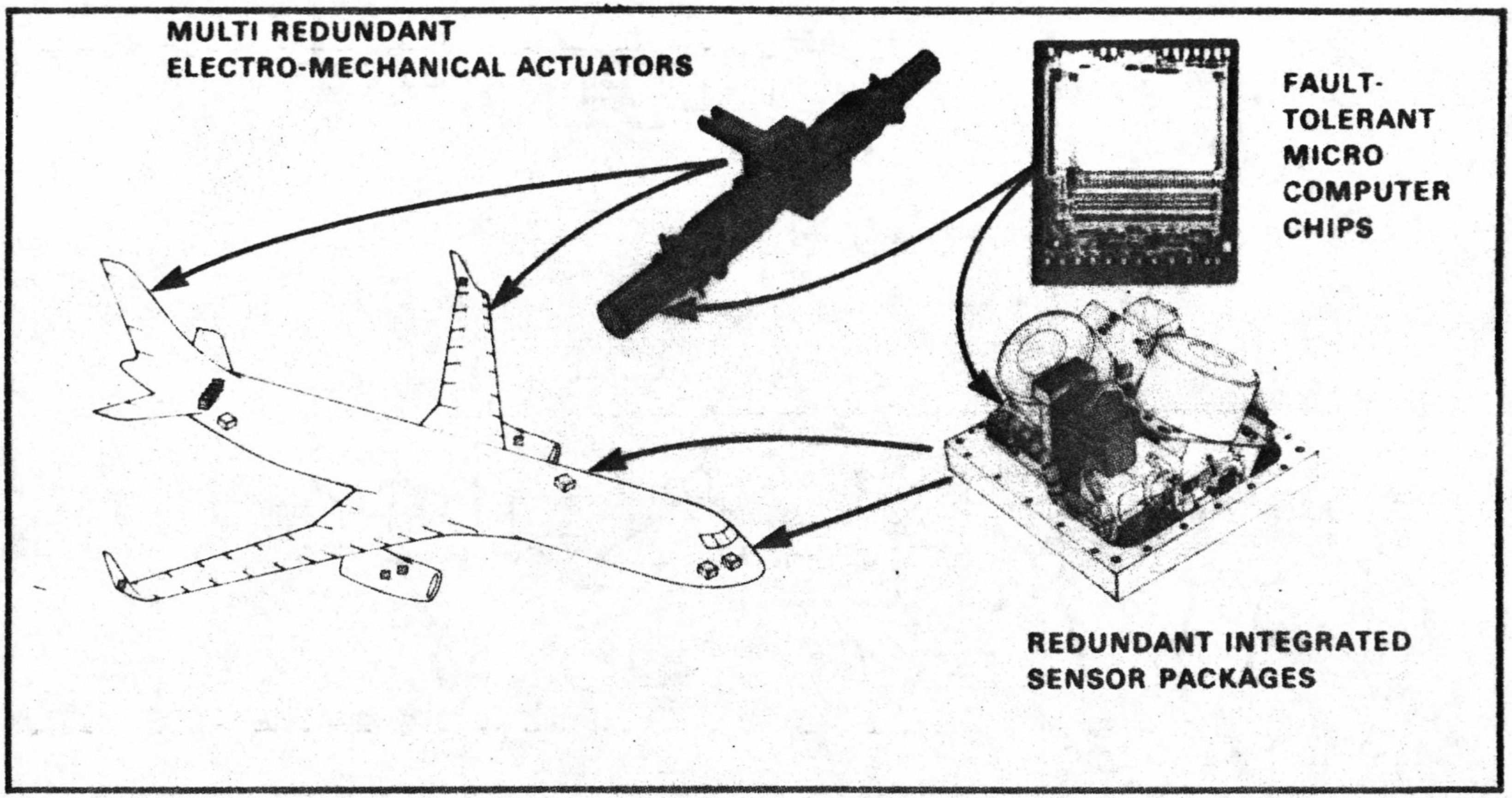


Figure 28. Ultra-Reliable Systems Concept

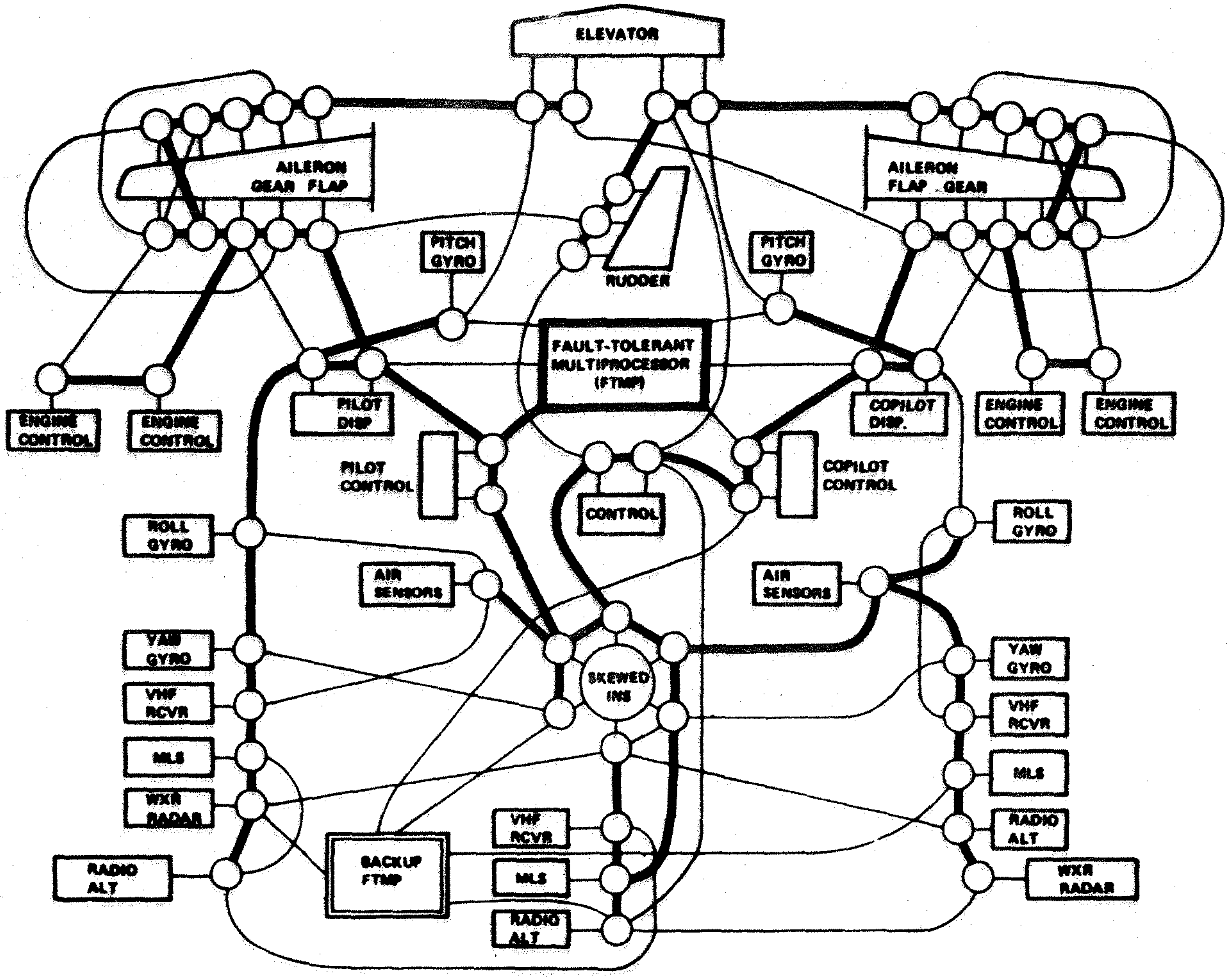
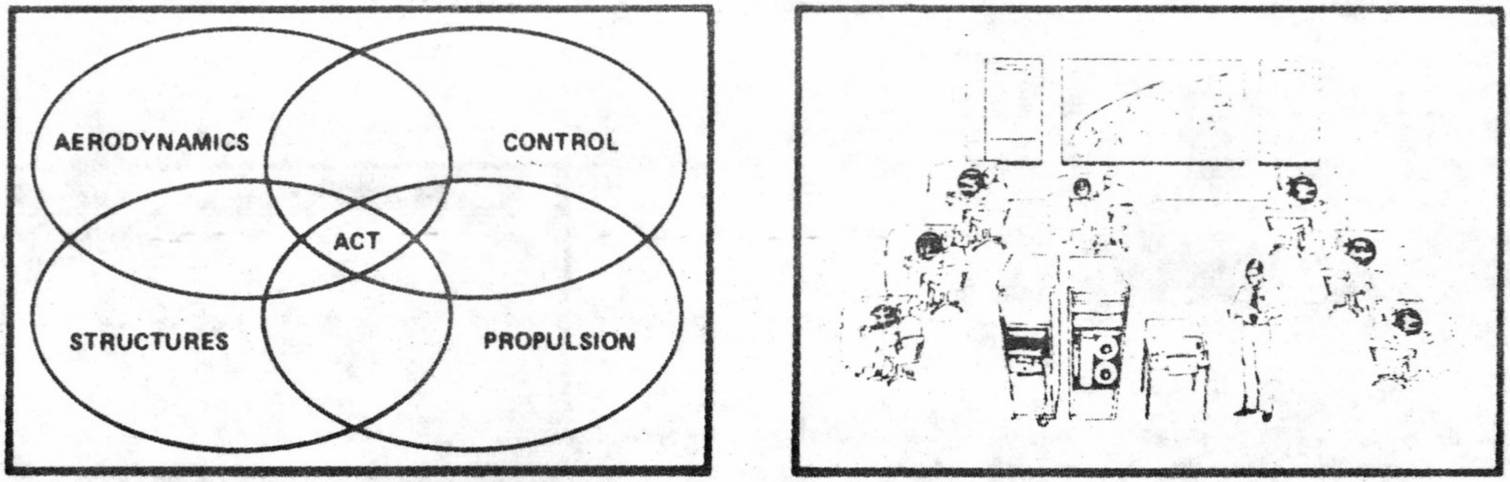
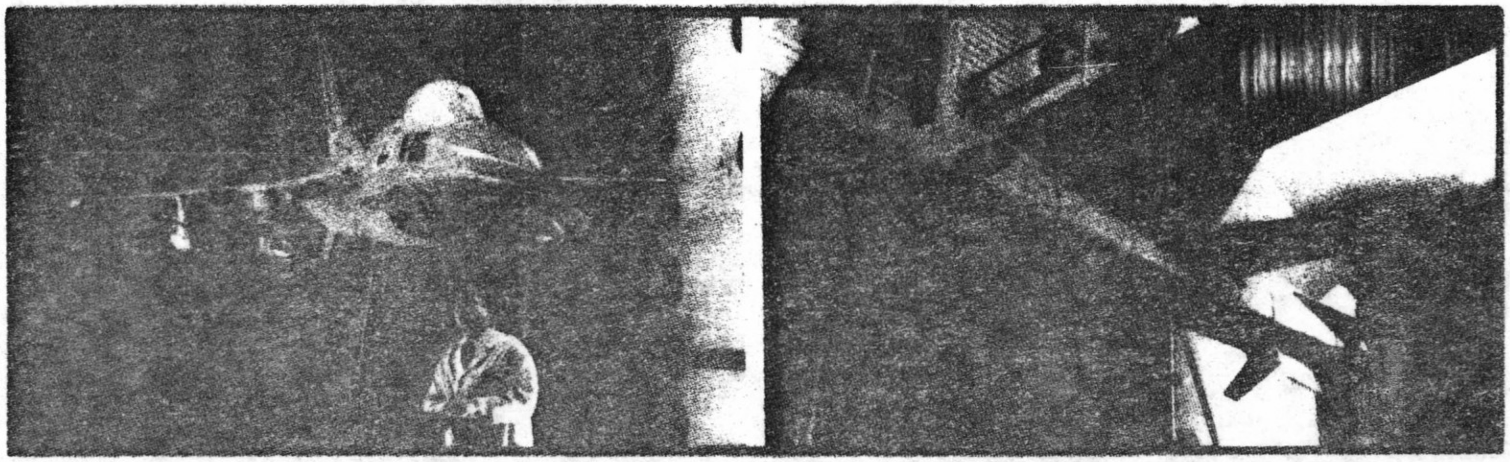


Figure 29. Deyst Network Architecture for Fault Tolerance



INTERDISCIPLINARY DESIGN

INTEGRATED COMPUTER AIDS



ACTIVE CONTROLS WIND TUNNEL TESTING

Figure 30. Advances in Design Methods

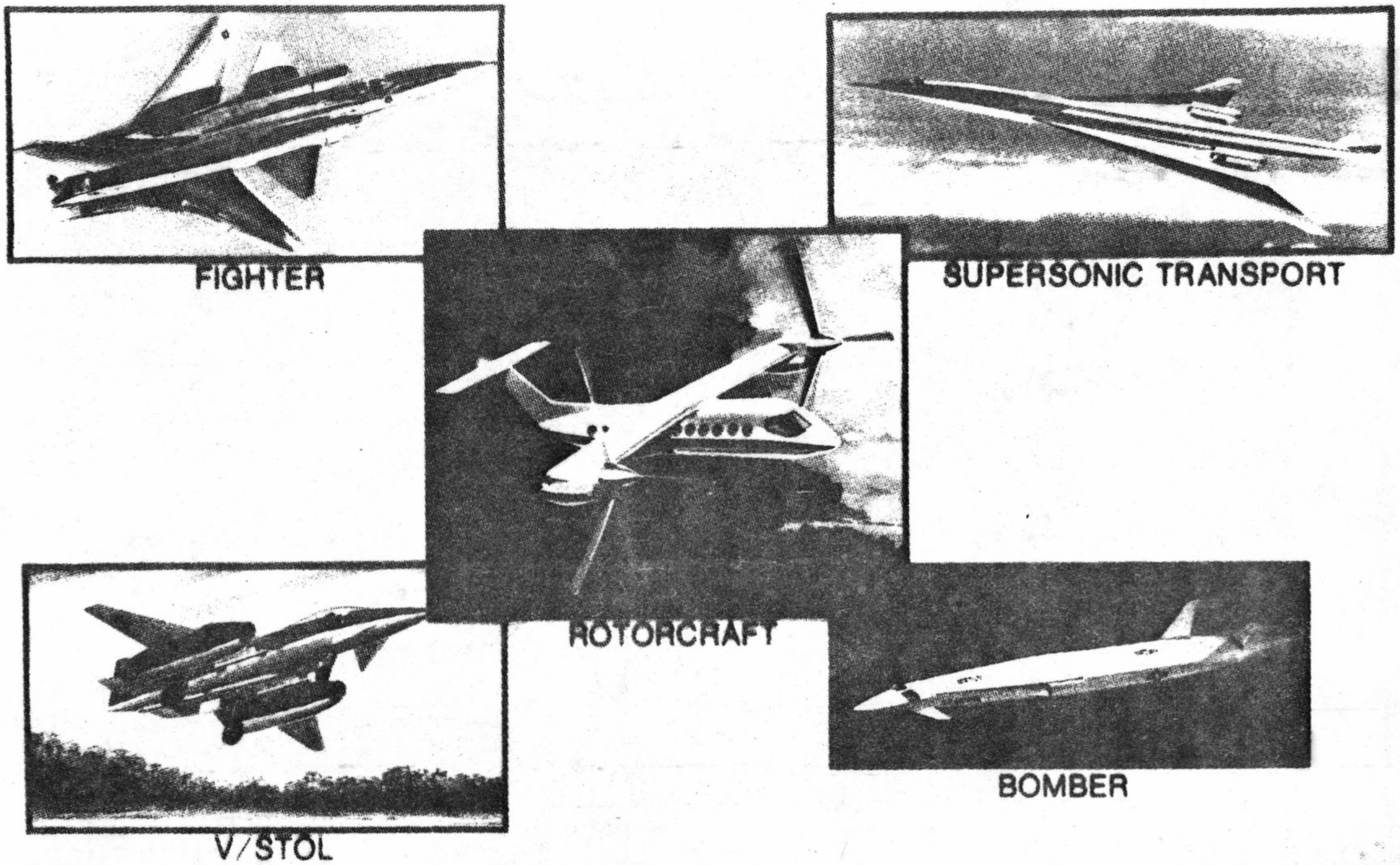


Figure [illegible] Future Advanced Control Concepts