ELEVENTH EUROPEAN ROTORCRAFT FORUM

Paper No. 59

Flight Control System Philosophy For Active Control Of A Helicopter

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YEOVIL, ENGLAND

September 10-13, 1985
London, England

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ABSTRACT

Conventional helicopter flying controls with mechanical control runs and limited authority augmentation systems have inherent deficiencies that limit their suitability for many future helicopter applications. This paper describes the WHL programme for improving helicopter flight controls by the introduction of Active Control Technology. The initial phase of this programme, a two year applied research study funded by the Royal Aircraft Establishment, has been completed. Its purpose was to establish the scope for the introduction of ACT on future helicopters, to address the associated system implementation problems, and provide a technical base for later phases of the programme.

During the applied research studies, a number of control concepts were examined and simulation trials were carried out to assess their effectiveness. Development of these concepts led to the demonstration of control responses suitable for highly agile nap-of-the-earth flight. Detailed system implementation studies were undertaken with the aim of identifying high integrity, high performance and cost-effective system solutions. The studies included an examination of actuation options and addressed the problems of actuator control and failure management. The effectiveness of the control concepts and system solutions in future helicopter applications was assessed with encouraging results. Analysis showed that, compared with conventional flying controls, an Active Control Technology Flight Control System would offer improved handling qualities, reduced pilot workload, improved survivability and substantial weight savings without cost penalties.

This paper describes important aspects of the work carried out during the applied research study and discusses the major results.

Notation

p	roll rate	(rad/sec)
q	pitch rate	(rad/sec)
r	yaw rate	(rad/sec)
ϕ	roll attitude	(rad)
θ	pitch attitude	(rad)
ψ	heading	(rad)
PDEG	roll rate	(deg/sec)
QDEG	pitch rate	(deg/sec)
RDEG	yaw rate	(deg/sec)
PHID	roll attitude	(deg)
THETAD	pitch attitude	(deg)
BETAD	angle of sideslip	(deg)
PSID	heading	(deg)
VBAR	total airspeed	(m/sec)
A1	lateral cyclic blade pitch	(rad)
B1	longitudinal cyclic blade pitch	(rad)
X	aircraft ground track measured	
Y	in North orientated axes	(m)
$\hat{}$	denotes best estimate, derived from sensor amalgamation	

1.0 INTRODUCTION

Traditionally, helicopters have been controlled by means of mechanical links between the pilots inceptors (sticks and pedals) and the actuators that move the rotor blades. To enable the pilot to cope with the inherent instability of the vehicle, stability augmentation systems have been provided. These are usually limited in authority, mechanically, to typically ten percent of total blade pitch range.

In manoeuvring flight, helicopters with conventional flight control systems test the pilots skills to the limit. Simultaneous movement and co-ordination of all limbs, as well as considerable mental agility, are required to cope with the cross coupling between control axes whilst maintaining the desired vehicle attitude and flight path, and avoiding engine, airframe,and dynamic system limits.

The low authority control augmentation facilities provide only limited assistance to the pilot. Indeed, in manoeuvring flight, they can pose additional difficulties by opposing pilot control inputs and rapidly saturating during sudden flight path changes leaving the pilot to contend with raw vehicle characteristics. Contact with service pilots suggests that these augmentation systems are often disengaged prior to periods of manoeuvring flight.

In the past, the limitations of conventional flying controls have had to be accepted, even though they might limit the mission performance and flexibility of the helicopter and impose a very high workload upon the pilot.

In many future helicopter applications, particularly those requiring operation in a battlefield environment, these limitations will pose serious problems. On the battlefield, the helicopter will be forced to fly low and fast (NOE) to avoid detection and engagement by enemy ground forces. Increased agility will also be needed to successfully evade attacks by enemy fixed and rotary wing aircraft and possibly, to enable enemy aircraft to be engaged by 'self defence' weapons.

To compound the difficulties faced by the pilots of future battlefield helicopters it is likely that there will be increasing emphasis on operation at night and in poor weather forcing the pilot to use limited field of view vision aids on a high percentage of missions. Using conventional flying controls in the battlefield of the late 1990's and early 21st century may lead to an intolerable pilot workload and result in the helicopter being flown insufficiently low or fast to avoid detection by the enemy.

With these and other future helicopter requirements in mind, WHL have initiated a programme aimed at significantly improving helicopter handling qualities by providing :-

- crisper response to control inputs
- reduced cross-couplings between control axes
- consistent handling qualities throughout the flight envelope
- manoeuvre demand control modes

Early investigations soon highlighted the difficulty of providing the desired improvements by developments of the existing control philosophy. A new approach was needed, placing greater emphasis on the use of full authority, closed loop control systems to assist the pilot.

For several years, WHL have examined the application of control systems of this type, termed Active Control Technology (ACT) Flight Control Systems, to future helicopters. Over the last two years a detailed applied research study has been carried out in conjunction with the Royal Aircraft Establishment (RAE) with the following objectives :-

- to evaluate and assess new control concepts
- to address associated control system implementation problems
- to assess the benefits and costs of introducing the new concepts

In the next sections of the paper, progress towards these objectives will be described.

2.0 CONTROL LAW STUDIES AND SIMULATION

Control law studies were supported by real time piloted simulation on the Royal Aircraft Establishment single seat moving base facility at Bedford.

These piloted simulations were intended primarily to identify desirable handling qualities for the next generation of military helicopters and then to assess control systems designed to impart these handling qualities to a full non-linear helicopter model. The trials concentrated on the NOE flight regime at speeds of 50 to 100 kn.

To make best possible use of simulator time it was necessary to be able to readily modify the controlled character of the helicopter. To this end, a system of 'conceptual' modelling was adopted to represent the helicopter with its control system.

2.1 CONCEPTUAL HELICOPTER SIMULATION

Simplified conceptual models of the helicopter with its flight control system were developed to explore a range of alternative control concepts, Ref 1. This was necessary to overcome the difficulties inherent in the design of control laws suitable for a detailed helicopter model. Such difficulties arise through the need to maintain satisfactory handling characteristics throughout the flight envelope and the need to suppress inherent helicopter cross couplings.

These conceptual models had the natural aircraft cross couplings removed. Furthermore, the system equations for the rotational degrees of freedom were replaced by simple low order differential equations which directly related pilot action at the inceptor to an angular aircraft response. In this way, idealised response characteristics could be specified and subsequently modified, according to pilot opinion.

Translational freedoms were modelled more conventionally using a simple disc rotor model running at constant speed with drag and sideforce terms calculated directly .

Using these ideas, a number of control concepts were evaluated. These control philosophies revolved predominantly around a set of 'Body Rate' control laws, whereby pitch control resulted in pure pitch rate response, roll control, giving either pure roll rate, (with bank angle hold), or bank angle control directly. Control in the yaw axis consisted of sideslip demand with sideslip suppression for central pedals. A conventional collective control was retained.

Further augmentations were added to reduce pilot workload during manoeuvring flight and in particular turning flight. These included a pitch compensation to automatically apply appropriate amounts of pitch rate to co-ordinate turns and a collective augmentation to maintain a constant vertical thrust component independent of aircraft attitude.

These augmentations resulted in a turning or steering capability invoked by a single lateral control action applied by the pilot.

A set of low speed laws were also included and these differed from the high speed laws in that the augmentations were removed and the yaw axis controller blended to a yaw rate law. The low speed controller was used primarily to address the problems of an automated blend in control function in the yaw axis and also to widen the flight envelope and hence improve pilot acceptance of the simulation.

A number of sorties were flown by several experienced pilots. These sorties included a 'serpent' task consisting of a triple bend course through a tree lined corridor. The pilots were required to fly along the centre of the corridor at constant speed (70 kn) keeping height as low as possible . This task demanded aggressive use of the flying controls and necessitated the execution of turns of up to 2 'g'.

The results of these simulations have shown that considerable benefit may accrue through the use of ACT if handling qualities similar to those demonstrated in the simulator can be realised using a practical system. Pilots flying the 'body rate' conceptual model with full augmentation have returned Level 1 handling qualities (Cooper-Harper ratings of 3 or better). These results have also assisted with the sorting and ranking of the available control options and have set the design point for control law development on a detailed helicopter model.

2.2 DETAILED CONTROL LAW DEVELOPMENT

Using the early results of the conceptual simulations with a pilot in the loop, work proceeded towards the development of control laws suitable for incorporation with a full six degree of freedom non-linear helicopter model. Control laws were developed using a computer aided control systems design and analysis package (TSIM2) produced by the Royal Aircraft Establishment, Ref 2.

Control laws for a highly agile combat helicopter were jointly produced by WHL and Smiths Industries, with high speed (NOE) control law development undertaken at Westland and low speed and hover laws developed by Smiths. The high and low speed controllers were interfaced by incorporating a blend in control function in the yaw axis, and, by introducing a continuous gain scheduler into the pitch, roll, yaw and collective channels.

Considerable attention was given to the organisation of the control laws such that the overall system could be partitioned into the following distinct sections :-

(a) a minimum complexity core system element supported by a small suite of sensors.
(b) a set of lower authority loops which would enhance these core system characteristics as well as providing interfaces to autopilot modes.

In this way it was hoped that the amount of flight critical processing would be kept to a minimum.

Thus the idea of a Baseline System evolved whereby a set of simple but robust 'inner loop' laws were complemented by lower authority 'outer loops' operating over well defined interfaces.

The fundamental philosophy was to engineer a system whose baseline characteristics would impart crisp and decoupled control of primary aircraft parameters, but whose longer term performance could be less than perfect. These longer term imperfections or drifts would be taken out by augmentations based on processed simplex sensor information. The interfaces to the simplex data would be of limited authority and furthermore would be automatically severable by the high integrity Baseline System.

In this way a set of control laws was designed for a combat helicopter, using the baseline sensor suite for measurements of angular aircraft rates, translational accelerations, airspeed, and angle of sideslip.

Drawing upon the results of the conceptual simulations the following baseline system modes were chosen for detailed control law development.

(1) Hover Controller (airspeeds below 50kn)

- (a) Left Hand Inceptor (single axis)

  Conventional collective control with optional height hold.

- (b) Right Hand Inceptor (two axis)

  Longitudinal displacements proportional to pitch rate measured in aerodynamic body axes, with attitude hold for inceptor longitudinally centred.
  Lateral displacements proportional to roll rate measured in aerodynamic body axes, with roll attitude hold for inceptor laterally centred.

- (c) Pedals (single axis)

  Yaw rate control with heading hold for centrally aligned pedals.

(2) High Speed Controller (airspeeds in excess of 50kn)

- (a) Left Hand Inceptor (single axis)

  Conventional collective control with optional height hold.

(b) Right Hand Inceptor (two axis)

Longitudinal displacements proportional to pitch rate measured in aerodynamic body axes, with attitude hold for inceptor longitudinally centred.
Lateral displacements proportional to roll rate measured in aerodynamic body axes, with roll attitude hold for inceptor laterally centred. Optional turn co-ordination for roll attitudes in excess of 5 degrees and less than 70 degrees.

(c) Pedals (single axis)

Sideslip angle control with sideslip supression for centrally aligned pedals.

The control laws evolved using an heuristic approach, employing classical linear analysis techniques. Frequency Response, Root Loci and Time Response methods were used to derive optimum system gains and inherent helicopter cross-couplings were significantly reduced by employing feedforwards and high gain primary loops. Assumptions were made regarding some of the control system elements in order to expedite the study. These included performance improvements to the primary actuators in both bandwidth and maximum 'slew rate', and high iteration rates in the flight control computers such that the effects of discretisation could be ignored. Fig 1 shows the organisation of the control laws for the pitch axis. A Proportional plus Integral controller closes the primary loop around pitch rate with crossfeeds taken from both collective and roll loops. The main loop is supported by attitude and airspeed hold loops together with a pitch augmentation for co-ordinated turning flight. Proportional plus Integral controllers were similarly used in the roll and yaw axes, with Proportional terms only used in the collective controller.

Figs 2 through 5 illustrate some of the controlled responses that were achieved using the control philosophies outlined above. These time records were all taken at a flight speed of 80kn in simulated still air conditions using a full non-linear six degree of freedom detailed helicopter model.

Figs 2, 3 and 4 show the responses in pitch, roll and yaw to the release from initial conditions of 0.2 rad/sec on pitch rate, roll rate and yaw rate respectively. These records illustrate 'crisp' responses with very little coupling to other axes.

Figs 5 and 6 show the aircraft response to a single lateral control input in roll with turn co-ordination and height hold loops active. This illustrates the manoeuvre demand feature which has been included as a baseline function, the control action resulting in a level 2 'g' co-ordinated turn.

The conclusion reached from these initial control law studies is that it should be possible to impart handling qualities similar to those obtained using conceptual models to a practical helicopter system. Further to this work, a programme has recently been proposed that will advance these control laws beyond their present state taking into account the effects of discretisation, computing delays, and the sensor and actuator performance characteristics necessary for effective implementation.

3.0 SYSTEM IMPLEMENTATION

3.1 STUDY GUIDELINES

The Baseline System concept outlined above was used as the basis for detailed implementation studies aimed at developing a system that could be used to investigate the application of Active Control Technology to helicopter flight control systems.

WHL enlisted the assistance of Smiths Industries (SI) in the system design studies. The first task undertaken was to develop a set of design guidelines which could be used as a basis for evaluating and assessing implementation options. Major guidelines chosen were :-

- Helicopter type / configuration - a Lynx-sized, 1990's combat helicopter
- Authority - a full authority system with no mechanical back-up controls
- Integrity - a high integrity target ($1*10^{-9}$) catastrophic failures per flight hour for the Baseline System.

These guidelines were supplemented by more definite requirements where necessary. Power supply characteristics, actuator loads and body motion rate limits, for example, were defined in detail to assist the implementation studies. Some of the options available for meeting the requirements are discussed below.

3.2 SYSTEM DESIGN OPTIONS

3.2.1 SYSTEM ARCHITECTURE

A variety of system architectures have been proposed in the past for flight critical flight control systems. For a near term application, however, many of the advanced configurations can be ruled out. For implementation of the high integrity Baseline System the most promising architectures were considered to be:-

- Conventional,cross-lane monitored quadruplex
- Triplex with self-monitored lanes

Failure analysis studies were carried out to assess the suitability of these architectures. Fig 7 shows the trade-off between lane MTBF and monitor effectiveness for a monitored triplex system with a $1*10^{-9}$ failure rate. The high level of monitor effectiveness required (99.9%) for near term predicted equipment reliabilities is considered to be beyond that achievable in the near future. This analysis led to the selection of a quadruplex architecture for the flight critical Baseline System.

In addition to providing greater integrity, the quadruplex architecture has other advantages:-

(a) A relatively simple failure monitoring and management system can be adopted. This helps to reduce the amount of flight critical software required in the system.

(b) The transients caused by disconnecting failed lanes can be kept within reasonable limits because there is always a majority of working lanes to "fight" failed lanes. This also allows more time to detect and disconnect failures, minimising the likelihood of nuisance disconnects.

The possibility of providing a reversion mode using direct electrical or optical signalling of actuators was considered but was thought to be impractical for the type of missions envisaged. It was felt that reversion would cause transient and piloting difficulties that would probably result in the loss of the aircraft.

3.2.2 SIGNALLING

With the advent of fibre-optic technology, there is now a choice between electrical and optical signalling techniques for flight control systems. The principal advantage of optical signalling is its immunity to electromagnetic effects such as radio and radar frequency interference and lightning strikes. These effects are a potentially serious source of common mode failures in flight critical systems. The electromagnetic environment in which the military helicopter operates is severe indeed and this is reflected in the test specifications for the electrical/electronic equipment they carry. Typically equipment is tested by the injection of 100mA interference signals in the 2-30MHz frequency band on all signal lines and by immersion in 200V/m fields. It is difficult to ensure that an electrical signalling system will continue to work in such a severe environment and lengthy testing is required (ref 3). Optical signalling is therefore preferable as most of these problems are avoided. WHL have considerable experience with the use of fibre-optics for signalling and studies suggested that the technology required for the dedicated signal links in the Baseline System was already available. A system using multimode fibres, LED transmitters and PIN diode receivers was chosen.

3.2.3 ACTUATION

WHL received considerable assistance from Fairey Hydraulics, Dowty Boulton-Paul and Lucas Aerospace in the definition of suitable actuators for an ACT flight control system. Studies suggested that requirements could be met with relatively conventional electrohydraulic actuators. Electromechanical actuators would not be competitive in weight and cost terms in the timescales considered, although an electromechanical, direct-drive first stage would be feasible. The inherent robustness of a direct-drive first stage makes it an attractive option. Against this, however, must be weighed the lack of flight experience with the technology and the cost and weight of the relatively high power circuitry needed to control and drive the motor.

Novel actuation systems were considered, primarily to see whether better failure tolerance or survivability characteristics could be achieved using unconventional configurations. A five-actuator swashplate system was designed around the Advanced Engineering Gearbox (fig 8). An assessment suggested that this actuator arrangement has a number of advantages :-

(a) It eliminates many of the single-point failure problems inherent in conventional configurations.

(b) It allows the helicopter to continue flying even after two of the actuators have been substantially damaged.

(c) It is a compact, relatively small system that can be accommodated within the central well of the gearbox.

Inevitably, however, there are drawbacks with this arrangement. Extra drive circuitry is required, force fighting can occur between actuators and detection of failures can be difficult. Further research is needed to fully quantify the risks and problems associated with the five-actuator system. It is likely therefore, that a conventional arrangement would be preferred for near-term main rotor actuation applications.

3.3 PREFERRED SYSTEM DESIGN

The system evolved during the studies is shown in fig 9. The diagram shows the flight-critical Baseline System only. The emphasis was placed on simplicity in all aspects of the design with the aims of :-

- minimising flight-critical hardware
- minimising flight-critical software
- simplifying system failure management

The sensors shown are those required for the Baseline System functions. The strap-down gyros and accelerometers provide body rate and acceleration references. Sideslip and airspeed sensing systems are needed for the sideslip suppression and turn co-ordination facilities. Baseline Sensor data is consolidated at the flight control computers.

It is envisaged that each lane of the Baseline System would have a well-defined interface with other simplex and duplex sensors available on the aircraft such as attitude,altitude and heading sensors. These would provide the refinements referred to in section 2.2. Augmentation facilities using these sensors would be limited in authority.

3.4 ASSESSMENT OF COSTS AND BENEFITS

A "value engineering" analysis was carried out to assess the comparative costs and benefits of conventional and ACT flight control systems. For a 1990's 10,000lb A.U.W. combat helicopter it was estimated that:-

- Procurement and in service costs for the two types of system would be similar
- The ACT system would be approximately 40% lighter than a conventional system
- The ACT system would have other advantages that are

not easily quantified including :-

- improved post hit survivability
- improved helicopter crashworthiness
- reduced structural complexity

In the future, developments in technology should make the ACT flight control systems more competitive in cost and weight terms. VLSI (Very Large Scale Integration) semiconductor developments, for example should significantly reduce the cost and weight of the computing elements of the ACT flight control system which constitute a large part of the total system.

4.0 CONCLUDING REMARKS

The studies carried out to date suggest that :-

- The improved handling qualities required for future helicopters can be provided by a simple "body-rate" control system.
- A very high integrity flight control system can be engineered to provide "body-rate" control using well-understood technology.
- The resulting ACT System should have similar procurement and in-service costs to conventional flying controls for a 1990's battlefield helicopter.
- The ACT System would provide numerous additional advantages including substantial weight reductions, improved survivability, better crashworthiness and simpler structural design.

WHL have been encouraged by the results of these studies and hope to continue the programme to improve helicopter flying controls by the introduction of Active Control Technology. Work is currently underway to define the next steps in the programme which will include flight trials of a representative system.

Acknowledgements

The authors would like to thank all who contributed to the studies, particularly those at the RAE, Smiths Industries, Dowty Boulton-Paul, Dowty Electronics, Fairey Hydraulics and Lucas Aerospace.

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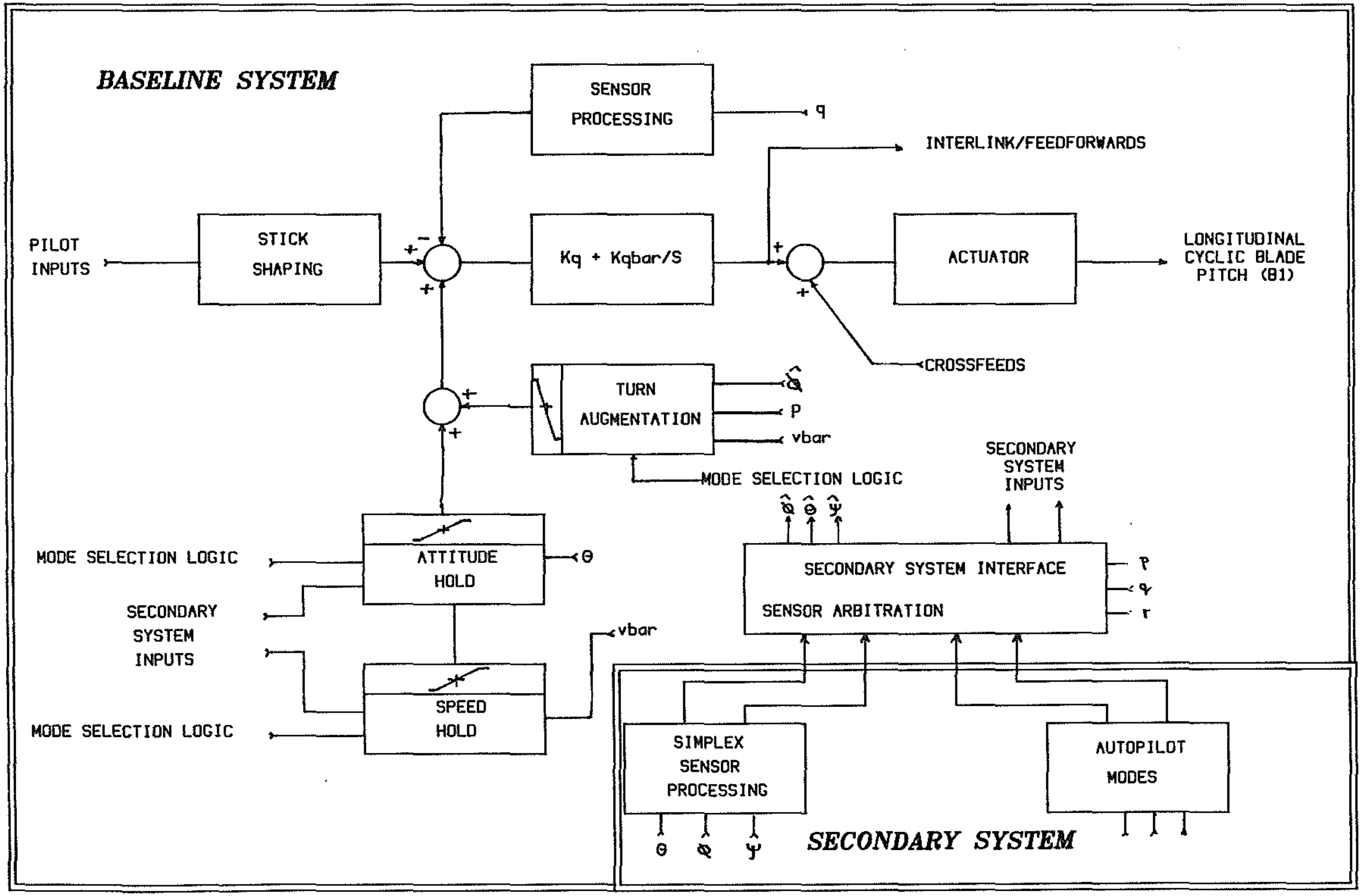
PITCH AXIS CONTROLLER

FIG. 1



FIXED STICK RESPONSES IN PITCH ROLL AND YAW

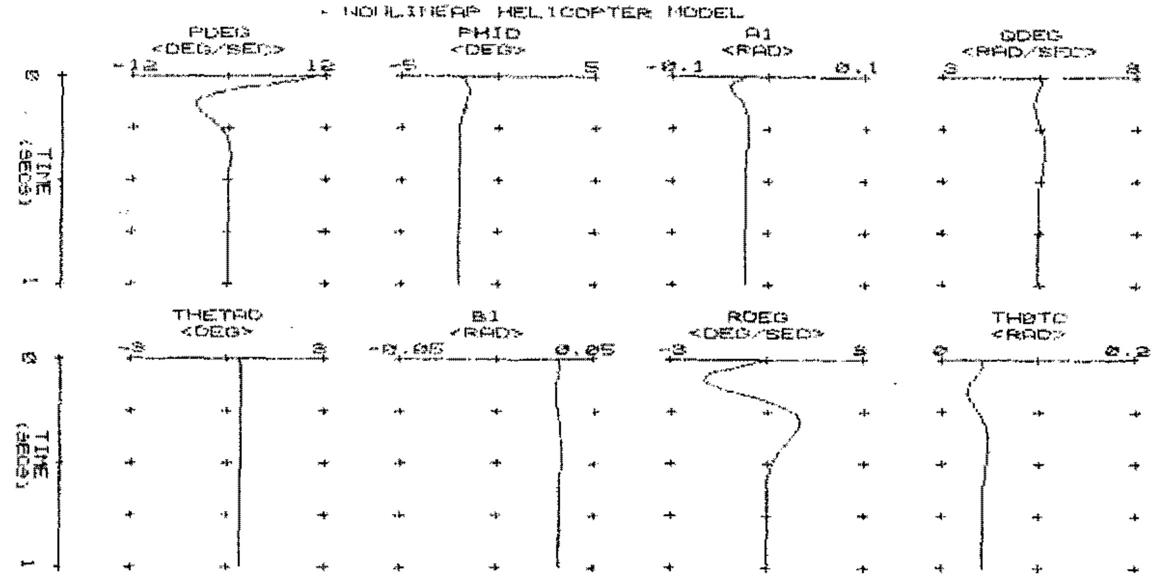


FIG 2

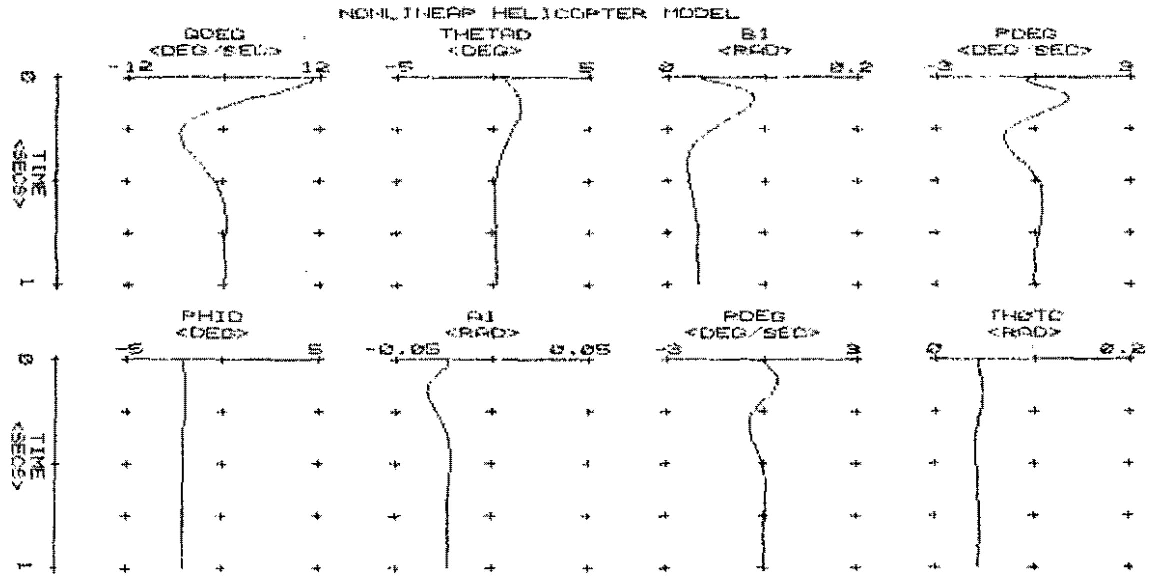


FIG 3

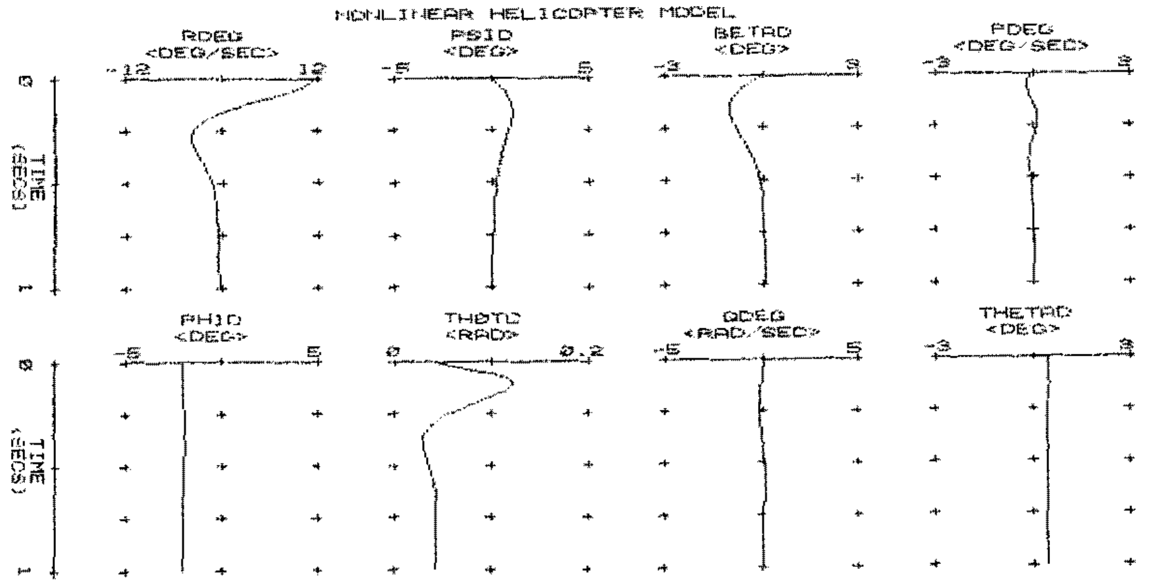


FIG 4

2 'g' LEVEL CO-ORDINATED TURN AT 80Kn

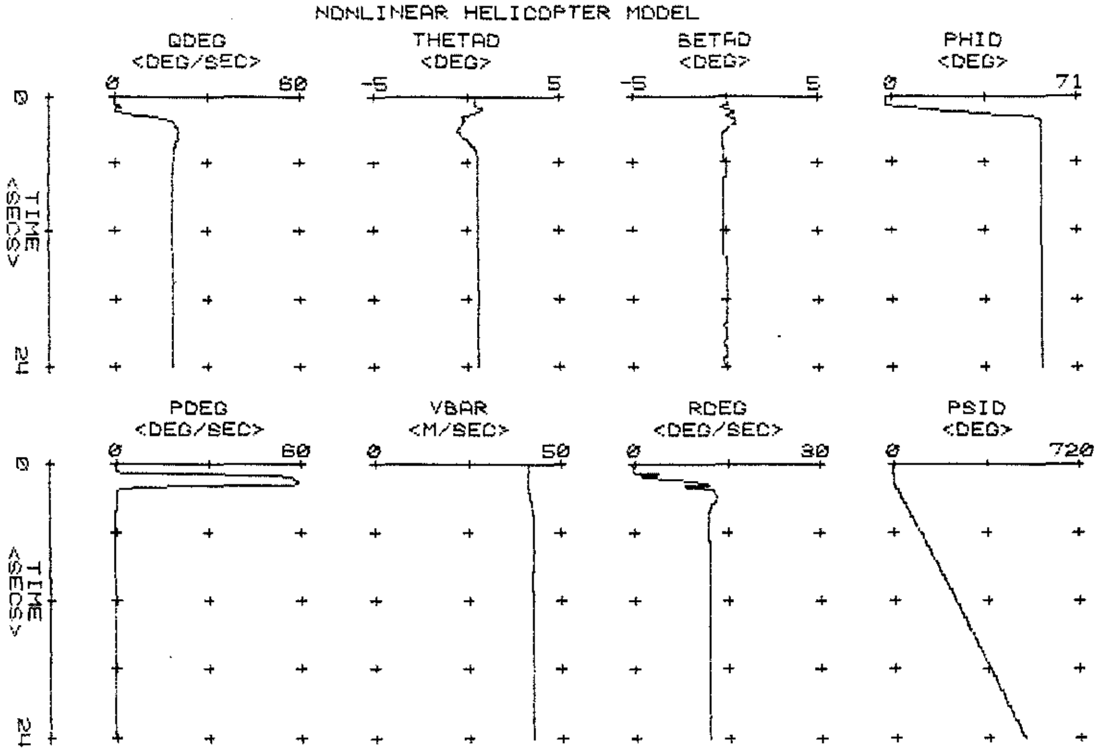


FIG 5

2 'g' LEVEL CO-ORDINATED TURN SHOWING TRACK OVER THE GROUND

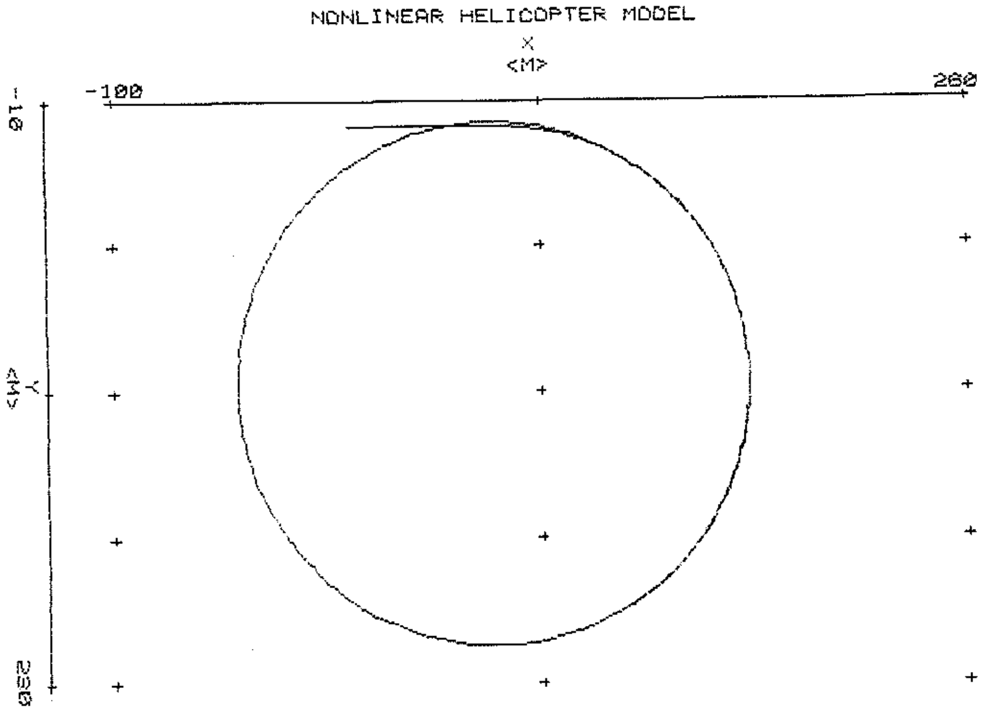


FIG 6

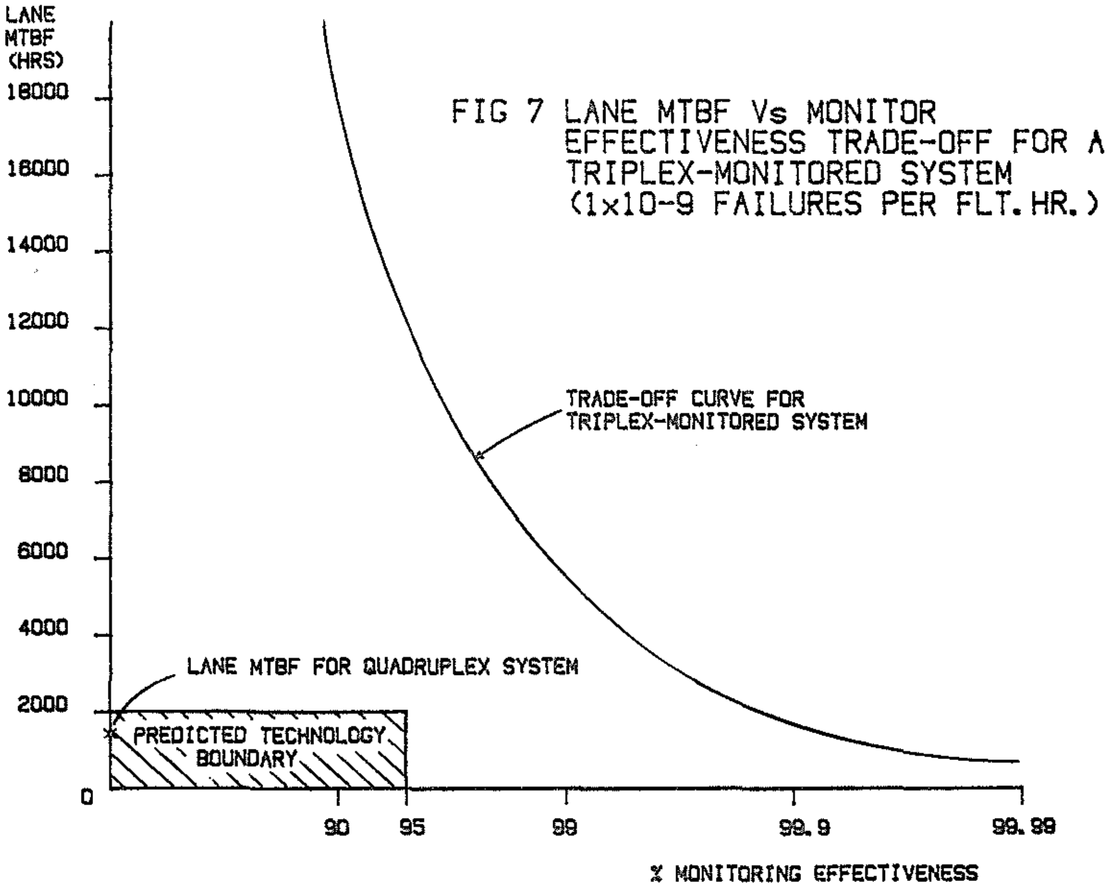
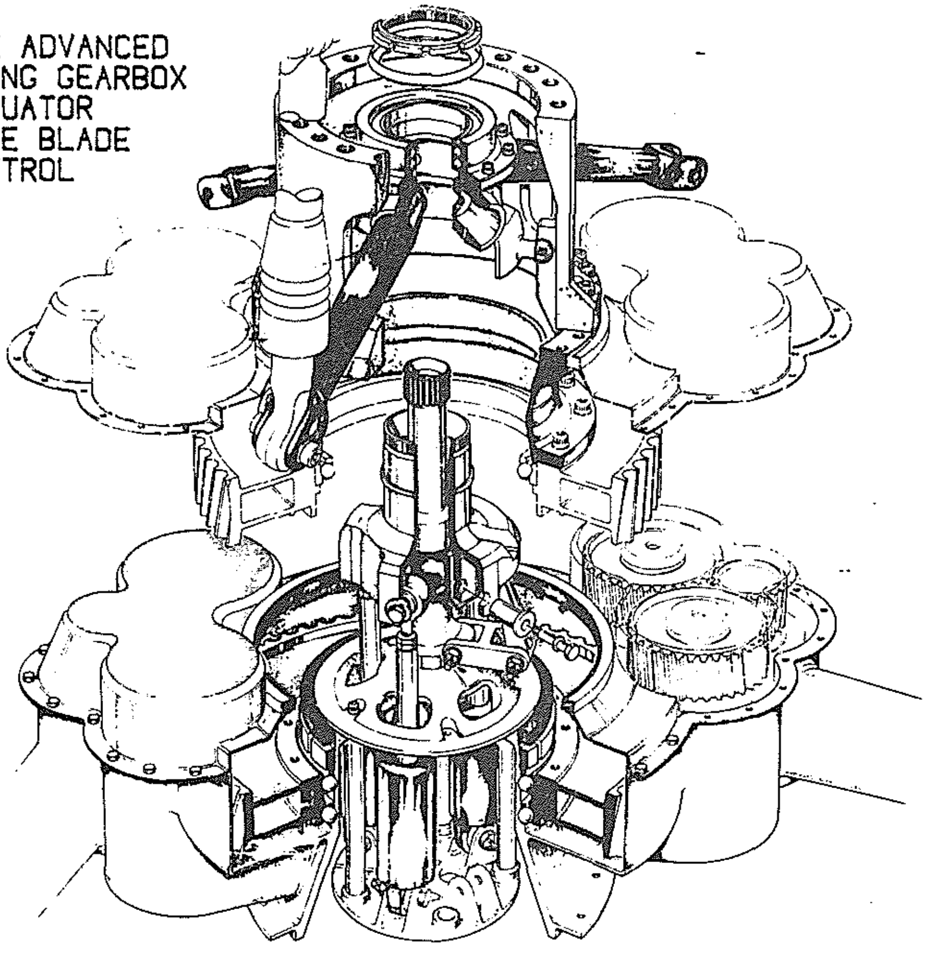


FIG 7 LANE MTBF Vs MONITOR EFFECTIVENESS TRADE-OFF FOR A TRIPLEX-MONITORED SYSTEM (1x10-9 FAILURES PER FLT. HR.)

FIG 8 THE ADVANCED ENGINEERING GEARBOX AND 5-ACTUATOR SWASHPLATE BLADE PITCH CONTROL SYSTEM



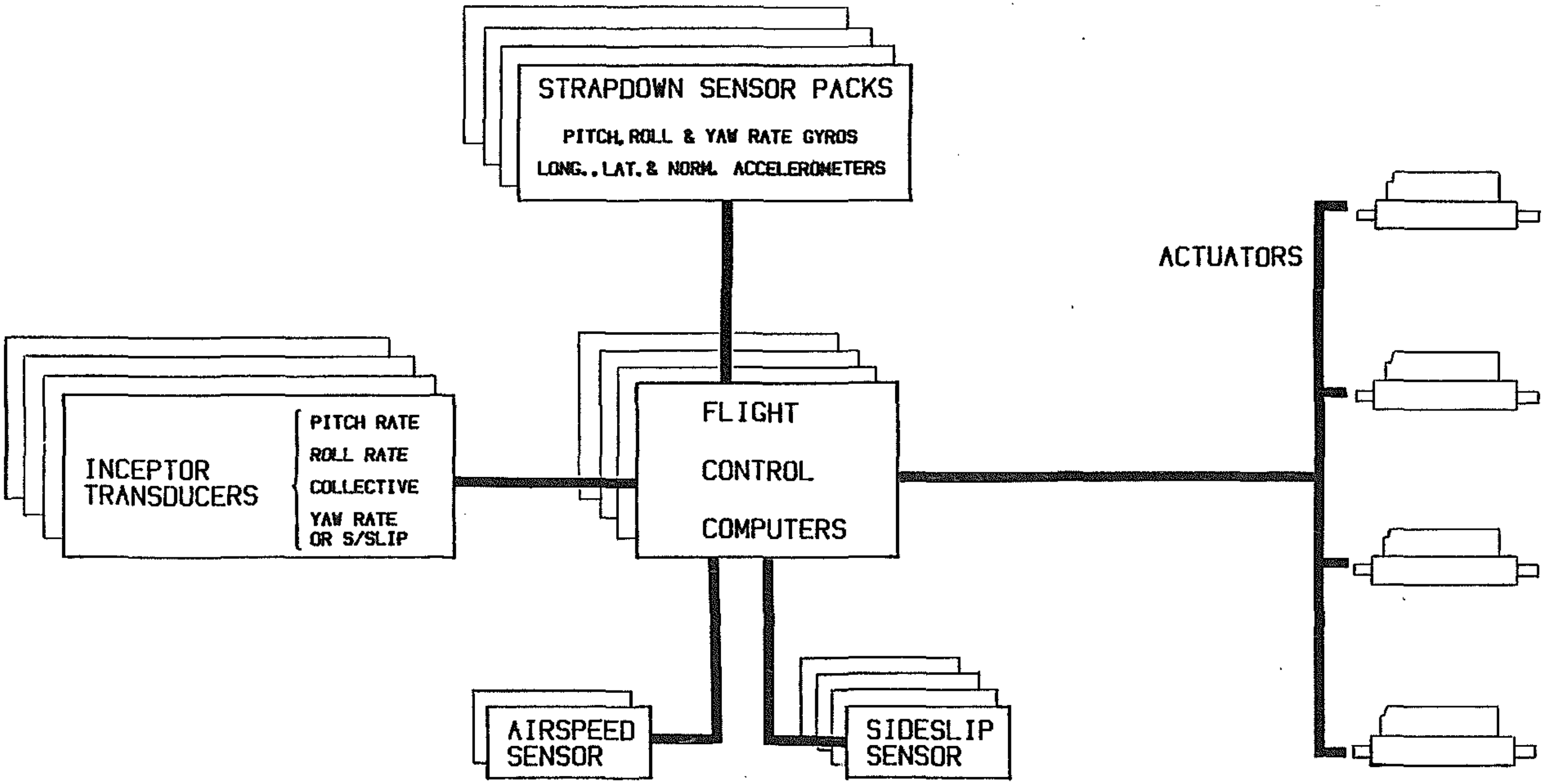


FIG 9 BASELINE SYSTEM SCHEMATIC