REAL-TIME HELICOPTER SIMULATION
USING THE BLADE ELEMENT METHOD

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SUMMARY

The National Aerospace Laboratory NLR has initiated a program focused on extending its moving-base research flight simulator facility with real-time helicopter simulation.

In this paper the background of the program, its objectives and the approach to accomplish them are discussed.

The available hardware systems (e.g. a multi-processor computer system, a modelboard/TV camera visual system and motion systems) in combination with the developed software, contain sufficient capabilities to establish a helicopter research facility for research concerning handling qualities, digital control laws, man-machine interface etc.. The procurements expected in the near future, a generic helicopter cockpit and a Computer-Generated-Imagery visual system, will not only support but also increase these capabilities.

Specific helicopter software modules have been developed, and tested separately. At present the modules are integrated within the comprehensive flight simulation program, and off-line validation is in progress. The helicopter software modules developed are briefly described and suggestions for further improvements are given.

1. INTRODUCTION

For many years now, the research flight simulator has been playing an important role in the development of fixed-wing aircraft. Wind tunnel measurement in combination with simulation makes it possible to estimate the dynamic characteristics of aircraft even before they have ever flown. This approach minimises development cost and risks, and improves the quality of the aircraft being developed.

As the tasks to be performed by helicopters and their crews are becoming increasingly demanding, and new technologies (fly-by-wire, side-stick control, advanced displays and digital flight control systems encompassing complex control laws) are introduced in the powerful tool for integration of these technologies within the helicopter, environmental conditions and human operator, before actual flight testing is performed. Therefore the National Aerospace Laboratory NLR of the Netherlands started the development of a real-time helicopter simulation facility.

Since 1976 NLR acquired a broad professional knowledge with respect to moving-base flight simulations of both civil and military fixed-wing aircraft. The application of a moving base in many cases improves simulation fidelity, whereby the validity range of the simulation results is extended. This is especially true when research in the field of side-stick control and digital flight control systems is considered. As a motion system with a high level of fidelity in the high-frequency motions is already available at NLR, moving-base helicopter simulation is obtained at relatively low costs.

This paper describes the development of a real-time nonlinear helicopter simulation facility at NLR. First, currently available hardware systems and software are described, followed by the objectives and realisation of the helicopter simulation facility. Finally, a description is given of the helicopter software modules that have been developed.

2. AVAILABLE HARDWARE SYSTEMS AND SOFTWARE

2.1 Hardware systems

NLR's flight simulation facility comprises a number of hardware systems of which the most important are:

- a Concurrent Computer Corporation (CCC, former Perkin Elmer) 3260 multi-processor computer system (MPS) with 4 processors
- a CCC 3220 computer system which is coupled to the 3260 MPS via a Processor-to-Processor Interface (PPI)
- an ARINC-429 Bus Interface System (ABIS)
- a 4 degrees-of-freedom (DOF) motion system
- a 6-DOF motion system operational late 1990
- a control desk with duplication of cockpit instruments
- a side-by-side transport cockpit
- a single-seat fighter cockpit
- a modelboard with single-channel TV-camera visual system
- wide-angle collimating display units with a field-of-view of 48° horizontal by 36° vertical each
- various recording and display devices
- 2 Silicon Graphics IRIS graphical workstations

The side-by-side transport cockpit is of a modular design which allows for a high degree of operational flexibility. Special mounting constructions allow both transport and fighter cockpit to be interchangeable on both motion systems. The transport cockpit is equipped with conventional (wheel-column) flight controls in the normal configuration, but can also be reconfigured with alternative controls like (left and right hand) side-stick controllers or a high-roll centre-stick. The servo-controlled throttle box allows simulation of aircraft with up to four engines. Both electro-mechanical cockpit instruments and Electronic Flight Instrument System (EFIS) displays can be installed. Simulator experiments have been carried out with the Collins EFIS displays (Fokker 100) and with the Sperry EFIS. The EFIS displays are connected via the ARINC-429 interface to the host computer, which generates the same input data for the displays as is done in actual flight.

The outside view is generated by a TV-camera and modelboard (scale 1:2000) system and is presented through Wide-Angle Collimating display units to each pilot. An upgrade to a more flexible Computer Generated Imagery (CGI) system is being considered, although in some cases, e.g. low-level flight, the level of detail generated by the TV-camera/modelboard combination can't (yet) be matched by a CGI system.

For helicopter simulations it will be necessary to design a flexible generic cockpit which allows for simulation of different helicopter applications. The generic cockpit concept is expected to be an essential part of NLR's simulation philosophy for the years to come.

Since its early beginning, the research flight simulator uses a moving base for almost all simulator experiments. Especially when evaluating handling qualities of aircraft, the motion perception enhancement can considerably affect pilot actions. Recently a second, synergistic six degrees-of-freedom motion system was added to the simulation facility (ref.1). It was developed especially for NLR, with specifications based on requirements for fighter and helicopter simulation. It can be considered a very high-performance system (bandwidth of 4 Hz with no more than 45° phase lag, no resonance below 20 Hz). Some operational limits of this system are given in table 1.

The Silicon Graphics Integrated Raster Imaging System (IRIS) workstations are used for a large number of applications. Among others, it is used for stand-alone evaluations of (EFIS) display symbology and formats, 3-dimensional animation of aircraft (movements), limited CGI applications for out-the-window views and generation of Head-Up Displays for both civil and military aircraft to be used in conjunction with the outside view from the modelboard.

An important improvement of the facility is the replacement of the host computer (CCC 3260) currently in use, by a Concurrent MicroFive MPS. The MicroFive as ordered will be three times as powerful compared to the present system. Figure 1 shows the new computer configuration.

2.2 Software

During the years of operating its research flight simulator, NLR has developed a large amount of simulation software which is based on fixed-wing aircraft operations. Using the concept of modularity within the software environment has led to a high degree of commonality between the mathematical models of the currently available aircraft. It also has led to a firm basis for developing specific helicopter mathematical modules and as such minimises the difference in the overall simulation software between helicopter and fixed-wing aircraft. In practice this means that general modules concerning the equations of motion, wind and turbulence, ICAO standard atmosphere, landing and approach aids like ILS and MLS etc., are not subject to change.

All software is developed in-house; aircraft mathematical models, Computer Aided Software Engineering (CASE) tools, device drivers etc.. One of the CASE tools developed is a software package called "COMmon-data Quality Assurance System" (COMQAS, ref.2). As can be observed, this tool is constructed around the labelled COMMON block definition of FORTRAN. Among others it defines a shared memory area of labelled COMMON blocks to be used by the different simulation software modules. Within such a block, type, dimension and (memory) location of symbolic variables are defined. Object related data is placed within one specific COMMON block for each object separately (e.g. for wind, inertial moments). All COMMON blocks together form a COMMON definition database. A precompiler checks the FORTRAN modules by comparing the variable names used in the source code with the variable name entries in the COMMON definition database. When encountering a matching variable the precompiler performs an automatic declaration of the variable in the precompiled source code according to the type and dimension of the variable stated in the database. As such it does not only prohibit illegal use of variables within different modules, but also prohibits multiple usage of the same variable name in different COMMON partitions.

Another powerful feature of COMQAS is the debug option. This option enables the user to display COMMON block variables and modify data parallel to simulation task execution.

Simulation data can be distinguished in fixed and variable (computed) data. The COMMON definition database is subsequently divided in partitions for fixed and variable data. By means of data files all fixed data is read into the simulation program before real-time execution. The modular structure of the mathematical models can also be found in the data-file organisation in which a hierarchic procedure applies to specific simulator (hardware) system control and aircraft (software) configuration control.

A strict distinction is made within the simulation program between the real-time phase and the non real-time phase. In the latter case the aircraft configuration is selected and the initial condition is computed. In this way a short turn-around time between simulator experiments can be accomplished.

The actual real-time simulation is executed by using the four parallel processors, of which three are used for simulation computations and one for rendering the necessary input/output.

The latter enables continuation of software development in the processor's "spare time" while running the real-time simulation program.

Using the concept of parallel processing, it is necessary to have a tightly controlled scheduling of task execution on the remaining three processors (Auxiliary Processing Units). By means of a scheduler data-file, the real-time executive processes all relevant modules (e.g. navigation, aerodynamics, flight control system) in a predefined sequence, every frame-time.

Application of COMQAS and the data-file structure, among others, has led to a very flexible software environment with a high level of reliability and maintainability. National and international recognition of delivering high-fidelity simulations has been attained in the many simulation projects using aircraft models of e.g. Boeing B-747, Fokker F-28, Fokker 100 and the General Dynamics F-16.

3. OBJECTIVES AND REQUIREMENTS

In order to make a reasonable choice with respect to the extent and complexity of the helicopter simulation modules, it was necessary to determine the main objectives to create a helicopter research simulation facility.

This facility is planned to support the following topics:

- aircraft handling qualities
- man-machine interface
- task-tailored control laws
- advanced display formats
- side/center-stick controller
- operational procedures

To perform research in these areas, some hardware systems and software are already available at NLR as indicated in section 2.

Concerning the software, the approach is to use the existing comprehensive flight simulation program. This approach offers several advantages. In the first place the general software facilities as mentioned in section 2.2. can be used, resulting in a relatively short development time for software. An other advantage is that only the specific helicopter related software has to be developed.

One of the main applications of the flight simulation program is pilot-in-the-loop simulation. Therefore the software has to be real-time, implying predictable w.r.t. computing time (e.g. omitting iterative processes). The balancing between hardware systems and software has to result in an update rate of the main program of at least 20 Hz. If necessary, the flight simulation program allows specific modules to have an higher update rate than the main program. For example the main rotor model, using the blade element method will have an

update rate that is about ten times larger.
The optimal advantage of the parallel processing capability can be obtained by software that has a high degree of modularity. This enables the required total computing time of the flight simulation program to be easily distributed over the available processors.
An other requirement of the software is flexibility, meaning that several helicopter configurations can be represented. One way to accomplish this is using data files instead of fixed data in the software. Finally the software has to be easy to maintain, requiring a sound way of programming while at the same time making a minimum of concessions towards computation time and memory capacity. Where applicable data will be entered in tables instead of polynomials.

4. APPROACH TO THE REALISATION

4.1 Method of development

Prior to the development of software modules, literature on helicopter simulation has been studied extensively (ref.3-13). This provided a broad insight in typical helicopter modules which had to be developed, and at the same time provided an overview of the different approaches to real-time helicopter simulation at other research establishments.
The first step in the development process was to define a consistent set of reference frames that are used throughout the model. Next the conventions applied for new variable names have been defined according the COMQAS definitions. These activities were not only necessary to obtain compatibility with the existing simulation software but also to reach a high level of quality and maintainability of the software.
As already indicated in section 2.2, the modularity of the simulation software required only the development of helicopter related modules. Regarding the objectives as presented in the previous chapter, the following modules were considered necessary for a general representation of a helicopter:

- Main rotor
- Main rotor induced velocity
- Main rotor wake interference with other components
- Tail rotor
- Aerodynamic characteristics of fuselage and tailplanes
- Flight control system
- Engine
- Ground effect
- Undercarriage

Figure 2 shows a part of the flight simulation program, including these modules. For reasons of priority some modules (undercarriage and ground effect) have not yet been developed, as they are not indispensable for a helicopter out of ground effect. At a later stage of the project these modules will be added to the program.

The definition and functional description of each module is based on literature and on experience available at NLR where performance and handling qualities related non real-time simulation models have been in use for quite some time.

For the development of each software module a systematic object-oriented approach was applied which consisted of the following steps:

- Definition of the problem
- Specification of the model, reference axes, equations and data
- Definition of module input and output
- Definition of COMQAS variable names
- Creation of data files (if applicable)
- Creation of FORTRAN source code
- Stand-alone testing of the module

After testing of each module separately, the modules were easily integrated within the existing simulation program to check the interaction. Each module can be modified or replaced separately whenever it is required, e.g. for future projects or when new modules are developed.

Further development of the helicopter simulation program exists in off-line validation and evaluation of helicopter dynamics, and finally validation and evaluation of real-time pilot-in-the-loop simulation using the 6-DOF motion system.

In the next paragraphs, a description will be given of the helicopter modules that have been developed. The forces and moments produced by the main rotor, tail rotor, fuselage and tailplanes, are calculated with respect to the actual centre of gravity.

4.2 Description of helicopter simulation modules

4.2.1 Main rotor. The main rotor has been modelled according to the blade element method. This method is based on physically representing the main rotor dynamics and is expected to have the capability of creating sufficient dynamic fidelity (e.g. ref.14-18).

Several descriptions of main rotor simulations using the blade element approach are available. For the development of the main rotor model implemented, ref.3-7 have been studied and used intensively. Fig.3 shows a block diagram of the main rotor simulation structure as it is presently implemented. This structure already allows for parallel processing of a maximum of four blades.

The philosophy followed for the development of the model is to have a basic blade element model that can be easily modified and extended if necessary. For the description of the rotor model the vector and matrix notation is used extensively. For the implementation of this

comprehensive set of equations dedicated software has been developed, providing a very straightforward implementation and consequently a minimum of errors. Moreover, this notation makes debugging very easy by having a monitoring option supplied by the COMQAS environment which not only facilitates monitoring of single variables, but also of vectors and matrices in their appropriate format.
The main rotor characteristics in the simulation model can be described as follows.
The input variables of the main rotor model are :

- shaft rotation speed
- collective pitch
- longitudinal cyclic
- lateral cyclic

The blades are assumed to be rigid and fully articulated, where the flap and lag hinges are assumed to coincide. For the flap and lag degrees-of-freedom nonlinear damping can be added. At present the main rotor can consist of up to 4 blades. However, within the limits of the hardware systems, increasing this number does not create any fundamental problems. A blade can be divided into a maximum of 10 segments. Except for the tip segment, the annular area swept by each segment is constant. At the tip segment the tip effects are taken into account and therefore the size of this segment is defined separately.
The characteristics of a blade are given by :

- hinge offset
- linear blade-twist
- root cut-out
- blade radius
- data as function of the spanwise location (maximum 10 locations):
    - . blade chord
    - . type of airfoil

Four different blade airfoils can be defined. For each airfoil the 2-D aerodynamic characteristics are given by the following functions :

$$c_l = f(alfa, Mach)$$

$$c_d = f(alfa, Mach)$$

$$c_m = f(alfa, Mach)$$

These characteristics are entered in the form of tables, which provide the flexibility to model nonlinearities such as stall, reversed flow and compressibility effects. The induced velocity is calculated for each segment separately according to the method that will be described next.

4.2.2 Main rotor induced velocity. When taking into account the objectives for helicopter investigations, it is not sufficient to assume the main rotor downwash to be distributed uniform or linearly over the rotor disk. Especially as blade flapping is an important parameter in main rotor dynamics, the downwash must be calculated for each blade element separately.

Detailed aerodynamical computations of the rotor induced velocity field are quite complex and can not be used for real-time helicopter simulation. However, less detailed methods are also available. The theory applied in the main rotor induced velocity module, was developed by Mangler and Squire (ref.19), and assumes an infinite number of blades and symmetrical disk loading. This theory uses a Fourier series as a function of rotor disk angle of attack, blade azimuth, and the radial location of the blade element. For our application four terms of this series were considered to provide sufficient accuracy for the time being. The result is a velocity ratio with respect to the average induced velocity.

The average induced velocity is given by a theory developed by Shaydakov (ref.20). This theory yields the ratio of induced velocity with respect to the induced velocity in hover as a function of rotor disk angle of attack and flight speed.

4.2.3 Main rotor wake. The wake emanating from the main rotor seriously affects the flow around the fuselage, tailplanes and the tail rotor. Therefore the main rotor wake interference with other helicopter components is a part of the helicopter simulation program.

The wake interference model assumes the main rotor wake to be two-dimensional. Wake interference is expressed in terms of an additional airspeed experienced at a specified location. This airspeed is assumed to be parallel to the rotor shaft, and is given by multiplication of the average main rotor induced velocity with a wake-interference factor. The value of this factor depends on the considered location with respect to the wake. This location (e.g. the tail rotor) can be in front, inside or behind the wake, depending on the wake skew angle. This angle is a function of the flight speed.

The value of the wake-interference factor in case of a component passing through the wake, can be modified for each helicopter configuration to obtain an optimal approximation of reality. Modifications can be based on empirical data and/or wind tunnel measurement.

4.2.4 Tail rotor. The two main functions of the tail rotor are to counteract the torque induced by the main rotor, and to provide yaw motion control. Following ref. 4 and 13, a Bailey type rotor model (ref. 21) is used to represent the tail rotor characteristics. This theoretical method provides expressions for thrust, torque, drag/lift ratio, and flapping motion of a rotor with hinged, rectangular, and linearly twisted blades. The rotor characteristics are given as simple functions of the inflow ratio and the blade pitch. The blade pitch value accounts for a pitch/flap coupling. The coefficients in the expressions are a function of Lock-number, tip-loss factor, and advance ratio, and have been tabulated for advance ratio's ranging from 0.0 to 0.7.

The validity of the drag/lift ratio expression as it is defined by the Bailey model, is restricted to advance ratio's above 0.15. Therefore, the rotor drag expression was taken from the rotor theory developed by Glauert and Lock.

Similar to the main rotor module, the average induced velocity is given by Shaydakov. This velocity is necessary for computation of the inflow ratio.

In hover, the tail rotor downwash creates a fin force which is directionally opposed to the tail rotor thrust. This has been accounted for by a tail rotor blockage factor which reduces the theoretically derived rotor thrust. The blockage factor in hover is obtained from ref.22. This factor decreases with increasing flight speed, until finally the downwash passes along the vertical fin and blockage does not occur anymore.

For reasons of flexibility the tail rotor module has been developed such that no software changes are necessary to switch from a tractor to a pusher configuration. Also the main rotor direction of rotation has been taken into account.

The main rotor downwash as it is experienced at the tail rotor location, is computed by the wake interference module, which is described in section 4.2.3.

4.2.5 Aerodynamic characteristics of fuselage and tailplanes. The aerodynamic characteristics of the fuselage and tailplanes of the simulated aircraft may be estimated or obtained from wind tunnel measurement. For the helicopter that is currently simulated wind tunnel data were available. These data consist of non-dimensional force and moment coefficients for all six degrees of freedom. The nonlinear character of these coefficients is stored in tables, that are entered by the angle of attack and angle of sideslip. Both angles are specified for a full range of -180° to 180°.

The air flow around the fuselage and tailplanes is largely influenced by the main rotor downwash. Therefore the main rotor wake interference module is used to determine the downwash at the centre of gravity of each component. The resulting local velocities are used for computation of the angle of attack and the angle of sideslip.

4.2.6 Flight control system. In order to have control of the simulated helicopter a basic Flight Control System (FCS) has been developed. Control forces for pilot-in-the-loop simulation are generated by a control forces system which is part of the hardware systems available at present.

Within the FCS, two main parts can be recognised: a Primary Flight Control System (PFCS) and an Automatic Flight Control System (AFCS). The PFCS receives and converts the pilot control inputs. The conversion of these inputs to the demanded blade pitch values is defined by tables which contain the control characteristics (e.g. control sensitivity).

The AFCS is subdivided into a Control Augmentation System (CAS), a Stability Augmentation System (SAS) and an Auto Pilot (AP). The CAS represents the coupling between the tail rotor collective pitch and the collective lever, and also between the longitudinal cyclic input and the collective lever. The SAS takes care of the helicopter stability using feedback from attitude and rate gyro's. At present the AP consists of one function being heading hold.

The FCS outputs are transmitted to the main rotor swashplate actuators and the tail rotor actuator, which are represented by first-order lag filters.

From the description above it can be noticed that the implemented FCS is rather simple. However, preference was given to develop a functional FCS instead of a most advanced FCS that for the time being will not be used completely. The modular set-up, however, does provide a sound basis for creating modern digital flight control systems.

4.2.7 Engine and rotor speed governor system. Although the helicopter engine, contrary to a fixed-wing aircraft engine is not a pilot control, its characteristics do affect the handling qualities of the helicopter, particularly in critical areas of the flight envelope. Therefore engine performance and dynamics had to be carefully modelled.

The engine model consists of three different components:

- rotor speed governor system.
- gas generator.
- free turbine.

Deviations of the actual rotorspeed from a reference rotor speed due to rotor torque variations, are automatically controlled by the governor system. The reference rotor speed depends upon the selected engine mode (ground idle, flight idle or flight). When flight is selected the reference rotorspeed is set by a regulator which follows the steady-state line of the engine.

A rotor speed deviation demands a fuel flow change which is represented by a first-order lag filter. A change in fuel flow results in a change of generator speed of which the dynamics are modelled by a first-order lead/lag filter. The lead/lag time constants are a function of the actual generator rpm and are decreasing with increasing generator speed.

The rotor system is driven by a free turbine through a gearing. If main rotor (free turbine) overspeed occurs, the main rotor is disengaged from the turbine until the rotor speed reaches an allowable level again.

The output of the engine module, the actual rotor speed with respect to the helicopter fuselage, is obtained by integration of the rotor speed derivative which is defined as the difference between the delivered engine torque and the demanded torque (main rotor, tail rotor and accessoires), divided by the moment of inertia of the rotating system.

Losses which occur in the engine and the transmission system, are represented by a factor which reduces the generator power.

5. CONCLUSIONS

A major part of developing a real-time helicopter simulation facility has been accomplished. Software modules which are typical for helicopters have been developed, tested, and finally implemented within the existing simulation program.

The level of sophistication of the modules is such that with the resulting helicopter simulation program, research in the field of handling qualities, man-machine interface etc. should be possible.

The modularity of the flight simulation program and the application of COMQAS resulted in a smooth implementation of the modules. The resulting comprehensive flight simulation program, that provides the means for moving-base pilot-in-the-loop simulation, is characterised by a high degree of flexibility and maintainability due to its modular set-up and the use of the data-file structure.

A highly-advanced six degrees-of-freedom motion system is expected to be available at the end of 1990, while within a few months the computer system will be upgraded with a powerful Concurrent Computer Corporation MicroFive multi-processor system. Many years of experience in parallel processing and moving-base simulation guarantee an optimal use of these systems.

With the development of a generic helicopter cockpit and the possible upgrade of the visual system, high-fidelity pilot-in-the-loop simulation can be achieved. However, off-line validation is still in progress, and thereafter the program has to be extended with mathematical models of ground effect and undercarriage dynamics.

For future improvements of the simulation fidelity, refinements can be considered like elastic blades (e.g. blade torsion), dynamic blade stall, 3-dimensional wake interference etc..

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TABLE 1

Specification for the operational limits of the 6-DOF motion system at NLR.

Operational System Limits

	Displacement pos	 neg		Velocity		Acceleration	
longitudinal	1.7	1.3	(m)	± 0.8	(m/s)	± 8	(m/s^2)
lateral	1.4	1.4	(m)	± 0.8	(m/s)	± 8	(m/s^2)
vertical	1.0	1.1	(m)	± 0.8	(m/s)	± 10	(m/s^2)
roll	30	30	(deg)	± 30	(deg/s)	± 200	(deg/s^2)
pitch	29	29	(deg)	± 30	(deg/s)	± 200	(deg/s^2)
yaw	41	41	(deg)	± 30	(deg/s)	± 150	(deg/s^2)

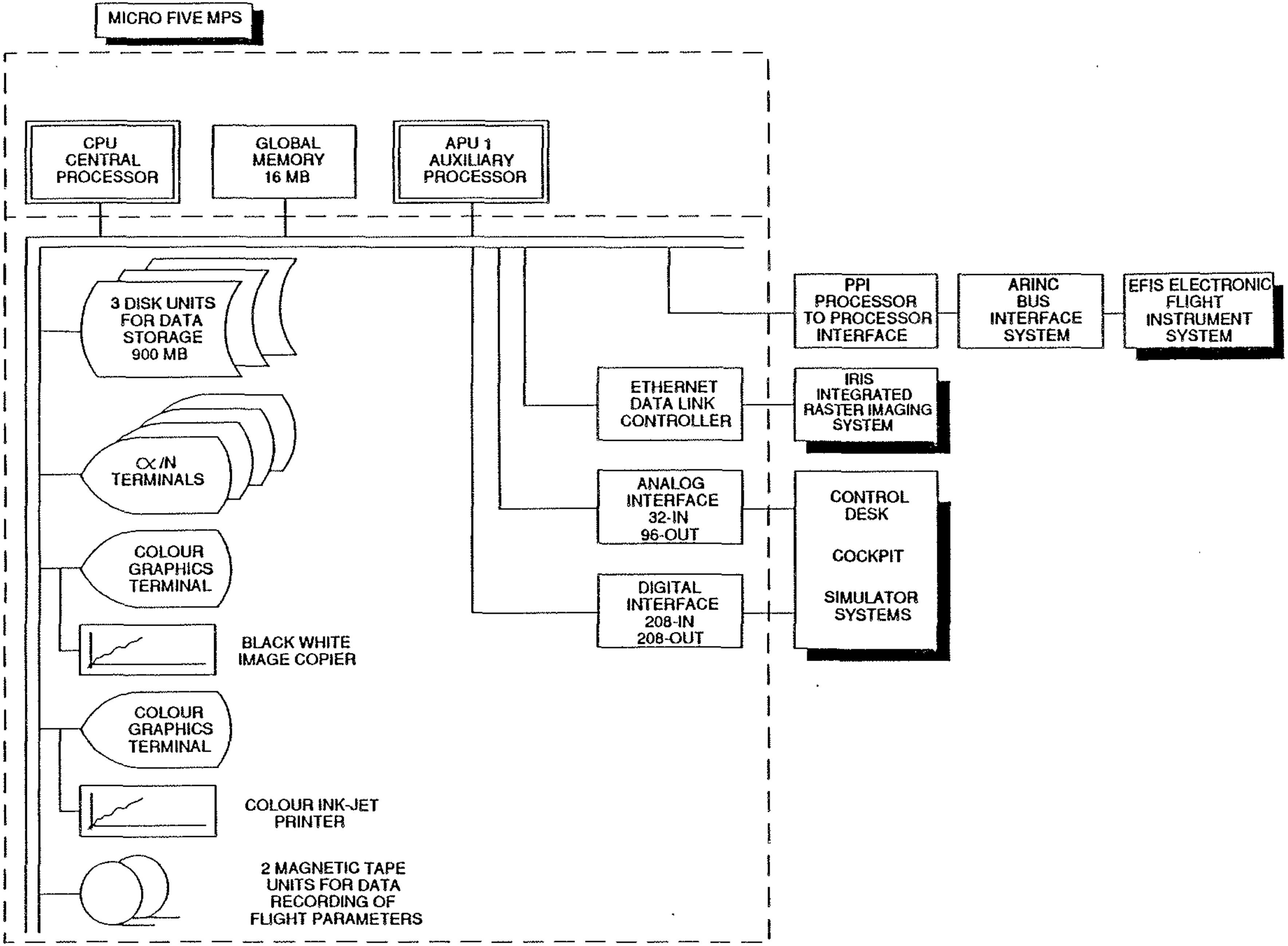

Figure 1: The computer configuration of the flight simulator after the upgrading

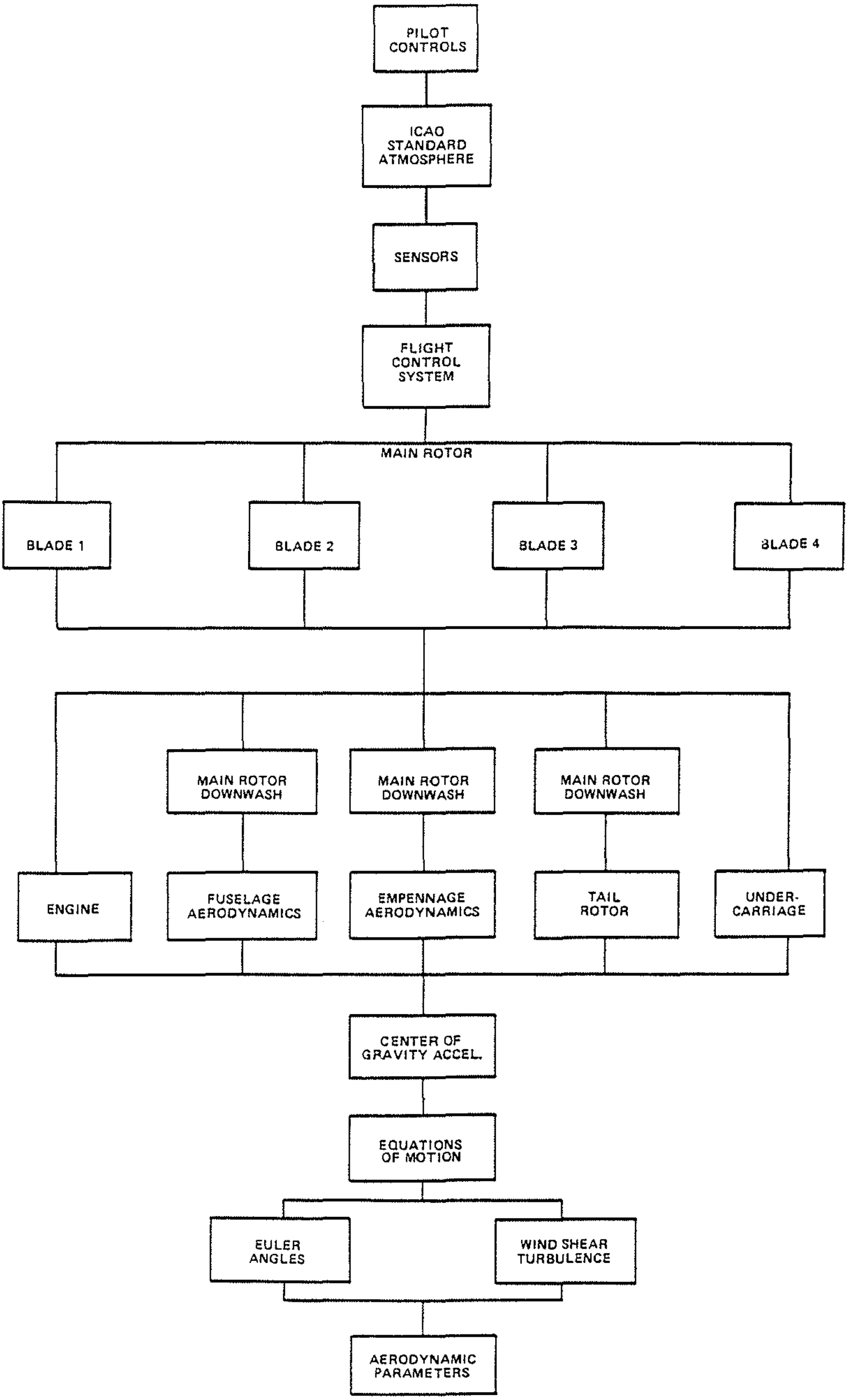

Figure 2: Modular representation of the main modules of the simulation program

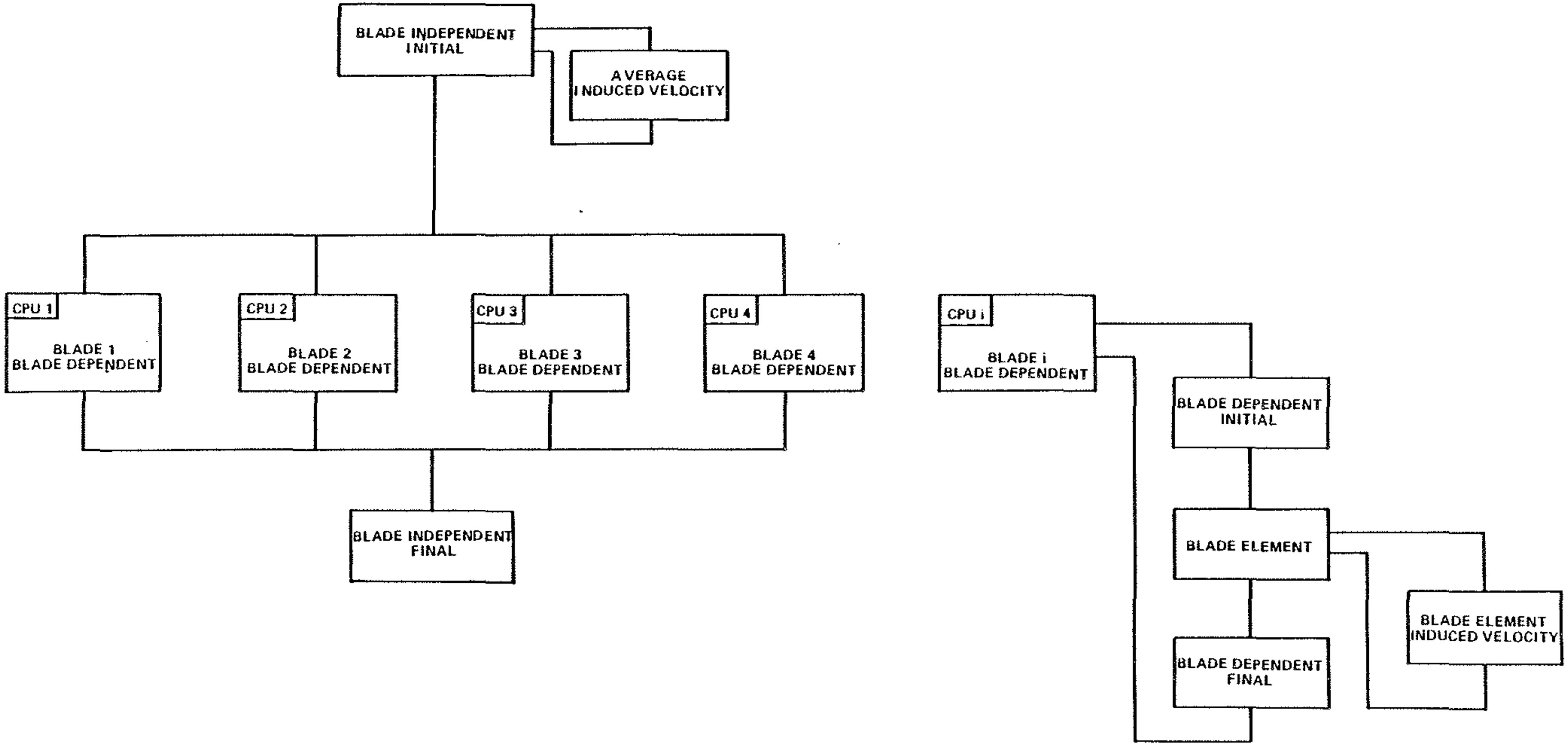

Figure 3: Block diagram of the main rotor computations