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# HELICOPTER FLIGHT CONTROL
# STATE OF THE ART AND FUTURE DIRECTIONS

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**Abstract**

Helicopter missions place strong demands on the precise control characteristics of aircraft, particularly in bad weather conditions and in military roles under terrain-flying tactics NOE for survival and high combat effectiveness. In this context, careful design and development of flight control systems is of major importance, to make flying easier so that the pilot can concentrate on fulfilling the primary mission task under reduced risk.

The development of helicopter flight control in the past decade has undoubtedly made enormous progress in the areas of new Handling Qualities criteria, improved modelling and flight control design methodologies, side-arm inceptors, sensors, computing and signalling technologies, and in the integration of the various components.

The paper gives an overview about the current status of the various aspects and emphasizes the interdisciplinary coupling of handling qualities criteria and analysis methodologies with flight control design and hardware technologies. It is concluded that development and application of advanced flight control systems has an immense potential and offers substantial improvements in safety, mission performance and cost effectiveness of future helicopters.

## 1. Introduction

Vertical flight aircraft, including helicopters and other VTOL-concepts, place specific requirements on human perception, control and performance for achieving their intended missions. Because of their unique characteristics, helicopters are often employed in extreme weather situations, with low to moderate speed and at very low altitude. In the military field, new tactical requirements for battlefield operations are likely to place an increasing emphasis on performance and agility during NOE-tasks. Operations in poor visibility or darkness, made feasible by advances in sensor technology, further increase the demands on the pilot. In fact, due to the constantly changing requirements, human factors are the main causes of mishaps.

In this context, careful design and development of flight control systems is of major importance, since it significantly contributes to making flying easier so that the pilots can carry out their primary task more effectively and indeed perform missions which up till now have resulted in a too high safety risk.

Flight controls technology has undoubtedly made considerable development in the past decade: Enormous progress has been made in the development of new Handling Qualities Criteria and mathematical modelling and analysis techniques. Real-time simulation with the pilot in-the-loop, both ground-based and in-flight, has substantially improved and shows a rapidly increasing application during research, development and complete system integration, particularly in the flight controls and cockpit/MMI area. Flight control design methodologies and software development tools have been very much refined in the past years, allowing now task-tailored flying qualities to be realized. Finally, enormous advances and significant maturing is observed in electronics and micro-systems, reflected in the development of advanced inceptors, computing technology, new sensors and signalling techniques and smart actuators.

In the light of those achievements it is now possible to make a brief overview of the state-of-the-art and to project future directions in helicopter flight control.

## 2. Development of Handling Qualities Criteria and Specifications

The commonly used definition for aircraft handling qualities is: "Those qualities and characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of the aircraft role". Handling qualities may, therefore, be thought of as being the ultimate measure for evaluating the integrated pilot-helicopter system with respect to mission or task performance. As shown in Figure 2.1 the integrated system includes the helicopter configuration, the control system, the information system, the cockpit interface, and the human pilot himself. The characteristics of these elements or subsystems, such as pilot inceptors (section 6.3.1) integrated in the overall pilot-helicopter system, determine the handling qualities and with that, the capability to complete the intended task in the given environment with the required flight safety and mission performance.

While the certification authority is mainly concerned with the flight safety in compliance with the specification, the helicopter user asks for demonstration of the mission performance of the integrated system. This required helicopter qualification has to be

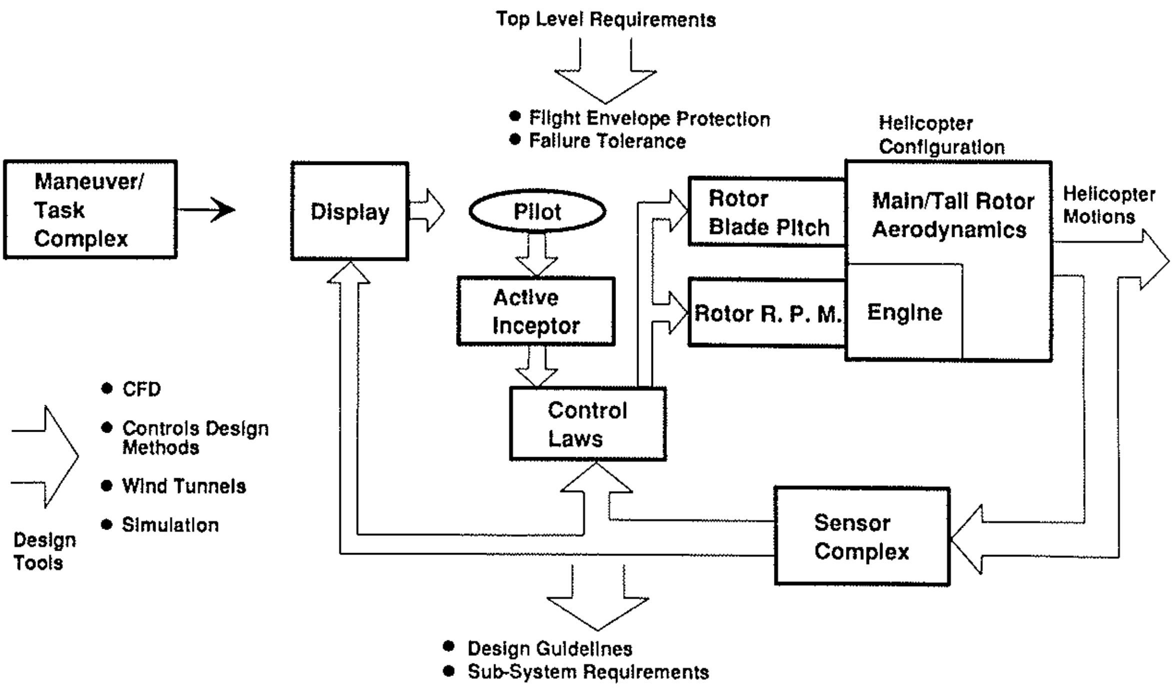



Figure 2.1: Integrated Helicopter - Pilot System and Design Environment

quantified for a specific project by means of the generic flying qualities specification including detailed criteria for specific characteristics of the integrated helicopter and of individual sub-system. The helicopter manufacturer may use these criteria during the development process as a design guide allowing the application of modern design and development tools like CFD, advanced control design methods, wind tunnel tests, and ground-based and in-flight simulation in order to achieve adequate handling qualities of the final product. The handling qualities criteria are based on the experience available from past development programmes, but in particular on dedicated simulation and flight tests using specific research facilities and considering advanced sub-systems and future key technologies. Realizing that helicopter technology progresses rapidly it becomes obvious that the specifications have to be updated from time to time.

| SPECIFICATION | DATE | APPLICATION | COMMENTS |
|---|---|---|---|
| MIL-H-8501 | 1952 | HELICOPTERS | SPECIFICALLY HELICOPTERS<br>CRITERIA INADEQUATE FOR ARMY MISSIONS<br>LACKS TREATMENT OF ENVELOPES & FAILURES<br>BASICALLY FOR VMC |
| MIL-H-8501A | 1961 | MINOR REVISION | |
| AGARD 408 | 1962 | V/STOL | |
| MIL-F-83300 | 1970 | V/STOL<br><br>(AND HELICOPTERS USAF ONLY) | BROAD COVERAGE<br>SYSTEMATIC STRUCTURE<br>CRITERIA INADEQUATE FOR ARMY MISSIONS<br>BASED ON V/STOL DATA<br>BASICALLY FOR VMC |
| UTTAS, AAH PIDS | 1971/3 | UH-60, AH-64 | BASED ON 8501A<br>MANEUVERING CRITERIA ADDED |
| AGARD 577 | 1973 | V/STOL | |
| 8501B (PROPOSED) | 1973 | HELICOPTERS | MANY NEW UNSUBSTANTIATED REQUIREMENTS |
| DEF-STAN 00-970 | 1984 | EH 101 | MILITARY SPECIFICATION USED IN THE UK |
| ADS-33C | 1989 | LHX (RAH-66) | BASIS FOR NEW MIL-SPEC |
| EURO-ACT | 1990/3 | FUTURE MILITARY HELICOPTERS IN EUROPE | REVIEW OF EXISTING REQUIREMENTS<br>COMPARISON WITH ADS-CRITERIA<br>GUIDELINE FOR OPTIMUM HANDLING QUALITIES OF MILITARY HELICOPTERS |
| TAILORED ADS | 1992/3 | TIGER, NH 90 | BASED ON ADS-33C |

Figure 2.2: Evolution of Military Rotorcraft Flying Qualities Specification

In Figure 2.2 the evolution of military rotorcraft flying qualities is skeletonized together with some information on their applications (Reference 1). The specification MIL-H-8501 was originally written in 1952 and was used with limited revisions until recently. Late 1975 the helicopter community recognized the deficiencies of MIL-H-8501A and started, in particular in the USA, a major effort to develop a data base and design criteria for a new specification. By 1982, the specification development process was initiated by the US Army and together with essential contributions from Germany (Reference 2), Canada (Reference 3), and the United Kingdom (Reference 4) a first draft of the new specification was issued. This version, adopted by the US Army as an Aeronautical Design Standard (ADS-33C) is oriented at the US Army's LHX-Programme but it is also a sound basis for a credible generic specification (Reference 5).

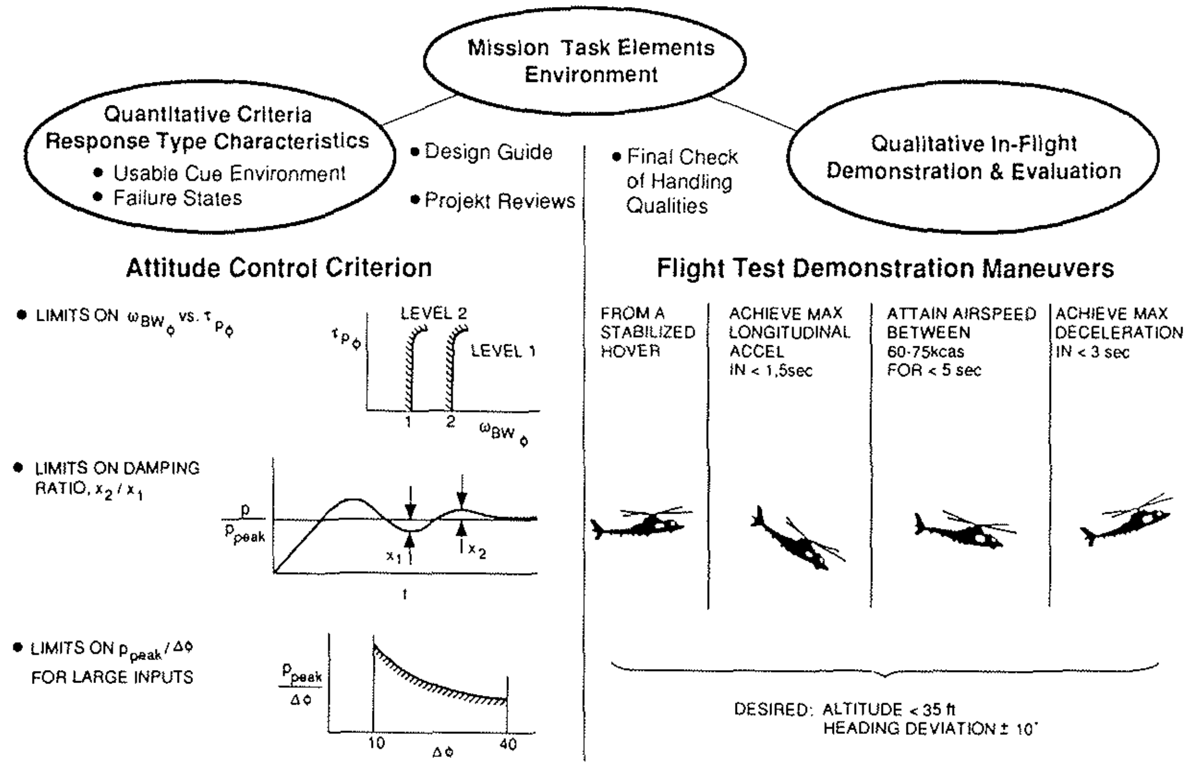



Figure 2.3: Handling Qualities Specification ADS-33C

This new specification (Figure 2.3) has adapted several features pioneered by the fixed-wing aircraft flying qualities specification, MIL-F-8785C. These include mission dependant criteria, a systematic definition of the flight envelopes, and the treatment of failures that relates the allowable degradation in handling qualities to the probability of incurring the failure. The most important innovation is to address mission tasks at night and in poor weather while flying close to the ground. To accommodate this, the stability and control response required is modified when the visual cues are degraded. Divided attention and single-pilot operations are also addressed.

In the specification the requirements and limits, based on simulation and flight tests, are drawn at levels which if not met will probably result in poor flying qualities. Thus the criteria are necessary, but may not be sufficient to guarantee a Level 1 helicopter. The final decision of acceptability needs flight testing of the actual rotocraft while performing its operational mission tasks. To aid in this qualitative in-flight demonstration and evaluation tests, a set of stylized flight test demonstration manoeuvres have been defined for representative mission task elements and incorporated in the specification. Since its adoption in August 1989, ADS-33C has been subjected to several evaluations, including the design process and simulator assessment of the LHX, and flight test evaluations of the BO 105, Apache, OH-58D helicopters (References 6, 7). These evaluations demonstrated the robustness of the format of ADS-33C criteria. They also uncovered some problem areas regarding applicability, repeatability and accuracy of the criteria, and led to several suggestions for refinements (Reference 8).

One of the most significant innovations of ADS-33C is the introduction of criteria using helicopter bandwidth and phase delay parameters, which are formulated in the frequency domain. The use of the frequency domain has led to the development of new

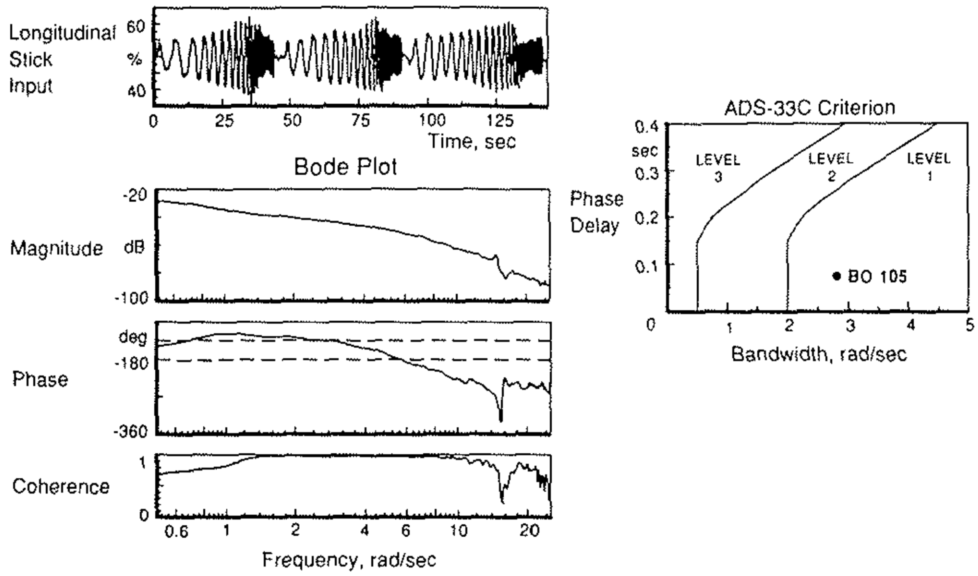



Figure 2.4: Determination of Bandwidth and Phase Delay (BO 105 Pitch Axis Flight Test)

flight test and analysis techniques. Figure 2.4 shows how pitch control bandwidth and phase delay are determined for the BO 105 from a longitudinal frequency sweep input. The use of frequency sweep inputs requires rigorous monitoring of the input frequencies to avoid excitation of the aircraft structural modes, and demands the use of filter-free, high frequency data acquisition equipment to avoid time shift errors during transformation of the data in the frequency domain. Generation of the Bode plots requires complex analytical tools capable of conditioning the frequency responses, such as the DLR program DIVA/MIMO (Reference 6) or the NASA program CIFER (Reference 7).

Bandwidth and phase delay appraise the pilot's ability to control the helicopter during high pilot gain tasks such as tight loop tracking. The bandwidth parameter is a direct measure of the maximum closed-loop frequency a pure-gain pilot can achieve without

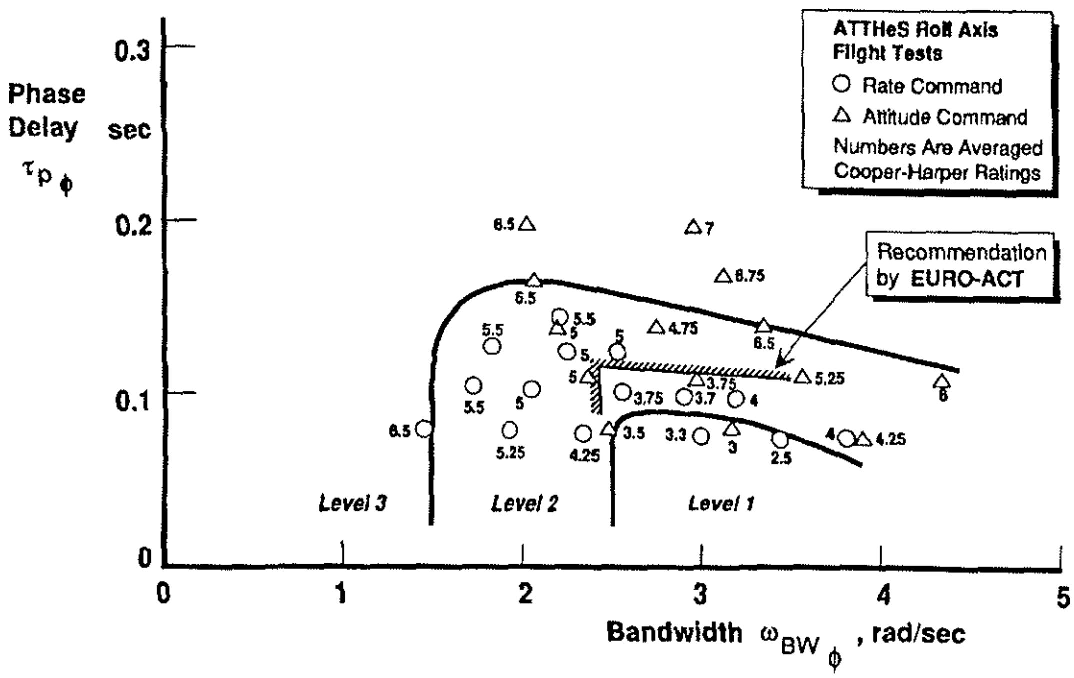



Figure 2.5: Refinement of Bandwidth / Phase Delay Criterion

threatening stability. The phase delay is a measure of how quickly the phase lag increases beyond the point of neutral stability. Aircraft with a large phase lag have been shown to be prone to pilot induced oscillations. As a design parameter, bandwidth is a direct measure of the bandwidth of the helicopter and its flight control system, and phase delay is measure of the time delays (such as those caused by rotor system, sensors, control computers, actuators, etc.). A recent investigation of bandwidth and phase delay on helicopter handling qualities during tracking tasks was carried out with the DLR's in-flight simulator ATTHeS (Reference 9). The results of this study (Figure 2.5) showed that a phase delay of less than 100 msecs was required for Level 1 handling qualities, thereby placing rigorous demands on flight control system design.

Handling qualities investigations within the European ACT-Programme (Reference 10) evaluated a recommended area for optimum on-axis response characteristics for rate command systems. These tests were performed in the Advanced Flight Simulator (AFS) at DRA. The results, included in Figure 2.5 are in agreement with the results found in Reference 9. The boundaries are different from the ADS-33C: They are more relaxed in terms of bandwidth, but more restrictive in terms of phase delay.

Also for other criteria, the introduction of full authority flight control systems has exposed the incompleteness of the handling qualities data bases. Figure 2.6 shows the results of an ongoing study into the effects of interaxis coupling on handling qualities (Reference 11). Curves (A) and (B) in the time history show a coupling response typical for conventional helicopters with large and small hinge offset. Response (C) shows the response of a helicopter with a basic coupling equal to that of helicopter (A), but with a feed back flight control system to alleviate the coupling. As can be seen, the handling qualities predicted with ADS-33C for the conventional type helicopters (A, B) correlated well with Cooper-Harper ratings from flight tests. However, pilot ratings for the simulated feedback flight control system, showed the handling qualities to be incorrectly assessed by the mid-term time domain requirement of ADS-33C.

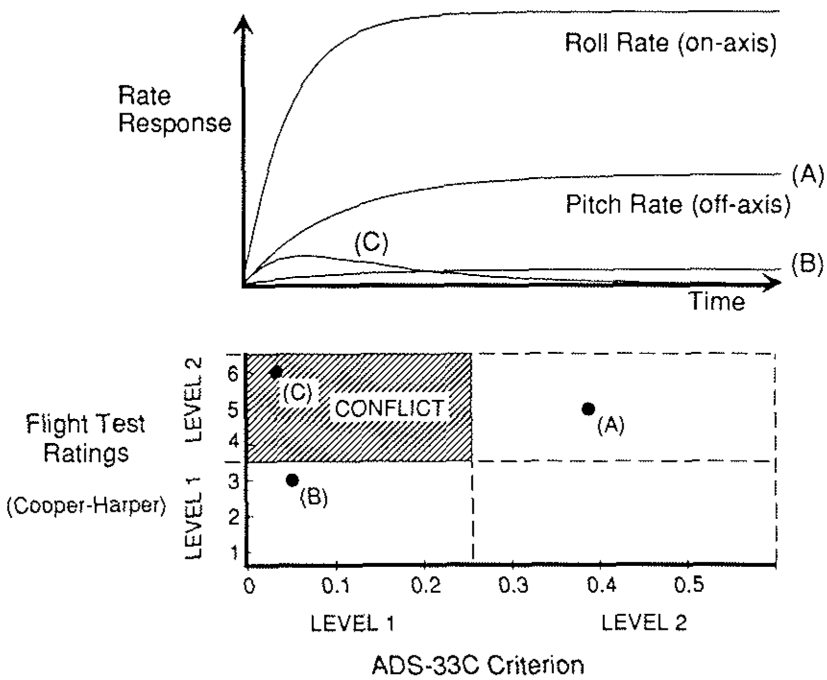



Figure 2.6: Evaluation of Roll-to-Pitch Coupling Criteria (ATTHeS Flight Test)

## 3. Flight Mechanics Models and Analysis Techniques

### 3.1 General

With full-authority electronic augmentation systems, the designer has the capability to tailor the flying qualities of the rotorcraft as desired for each mission task as discussed in chapter 2. Typically these advanced flight control systems are more sophisticated and characterised by higher order subsystem dynamics such as sensors, filter and servo actuators which may create new flying qualities problems (References 12, 13, 14).

From this it becomes obvious that the required level of the mathematical model describing the basic rotorcraft dynamics and the flight control subsystems has to be carefully evaluated to identify potential constraints on the maximum achievable control bandwidth.

The fundamental flight control design problem for highly augmented rotorcraft systems, therefore, is model uncertainty. This includes both uncertain parameters within a given model structure and unmodelled (hidden) dynamics yielding so-called structured and unstructured model uncertainties (References 15, 16).

This situation especially arises for rotorcraft systems because a variety of physical interactions must be considered in the modelling and control design process. They include rigid body flight mechanics, rotor and inflow dynamics, rotor-empennage interference and rotor-propulsion system dynamics. As already discussed of equal importance is the flight control system implementation itself adding higher frequency dynamics due to stick, sensor and associated filter dynamics as well as servo actuator dynamics and flight control law processing time delays of the airborne computer system. Therefore, approximate but accurate solutions are required to solve complex mathematical equations with uncertain parameters (Reference 14).

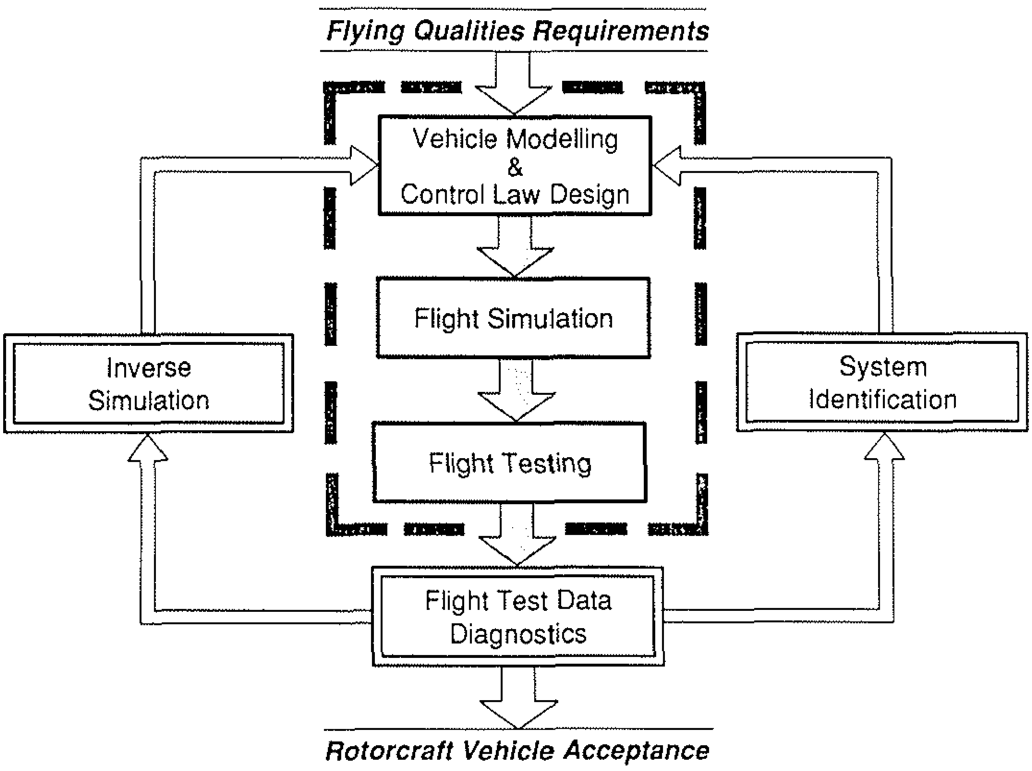



Figure 3.1: Rotorcraft Modelling and Control Law Validation

The main objective of this chapter is directed towards the application of four rotorcraft modelling and validation elements (Figure 3.1). First, the generic vehicle modelling including linear and nonlinear mathematical models used for offline predesign studies as well as for the ground based flight simulation.

A certain option of dissimilar validation redundancy is provided by the two elements of system identification and inverse simulation (Reference 16). A third validation element described in Figure 3.1 as flight test data diagnostics is often overlooked in its importance. It is concerned with the quality of flight test data and its interpretation from both a data handling and flying qualities standpoint.

In the following sections of this chapter, results of recent research and project support are described concerning the indicated validation elements.

### 3.2 Generic Vehicle Modelling

The linear model derived from perturbation analysis of a generic model is used from the very beginning during the control law design process. It is cost effective and flexible for the conceptual phase using SISO low order equivalent system models. For the design of decoupling modes, a coupled 7-DOF rigid body model is typically applied. Further refinement is necessary due to high order and nonlinear effects. The additional rotor DOF's (Flap, lag, torsion) lead to a more realistic but rather complex high order equivalent system. The introduction of an equivalent time delay term is very often used to modelize the high frequency domain more accurately but without increasing the complexity of the model. Typical applications of low and high order models and a comparison with system identification is given in Reference 36.

Whereas the linear model is typically used during the predesign and offline development phase of the control law, the nonlinear model is used for final offline investigations and for pilot-in-the-loop simulation. Today typically two models are used: The actuator disc model for minimum frame time and the blade element model, which includes the rotor aerodynamics like stall and transonic effects.

At ECD all the described models were used for the offline design and test, and for the pilot-in-the-loop evaluations of the control laws on the DASA simulator (Reference10).

### 3.3 Flight Test Data Diagnostics

Flight test data diagnostics encompasses all aspects of consolidating measured signals with respect to data consistency and channel compatibility. Any redundancy in the measured variables can be evaluated via kinematics relationships provided by non-linear flight mechanic equations in order to verify or improve data quality (References 13, 14).

A more statistical evaluation option is given by spectral analysis procedures. Single input/single output (SISO) spectral analysis has been widely used during flight test experiments.

A more important piece of design information for the rotorcraft flying qualities or control systems engineer is to estimate how much of spectral output is due to the various possible control inputs and how they are built up at the output when the effect of each control input is included. This is illustrated by considering a typical flight manoeuvre of a BO 105 helicopter wherein all four of the four control inputs are excited (Figure 3.2).

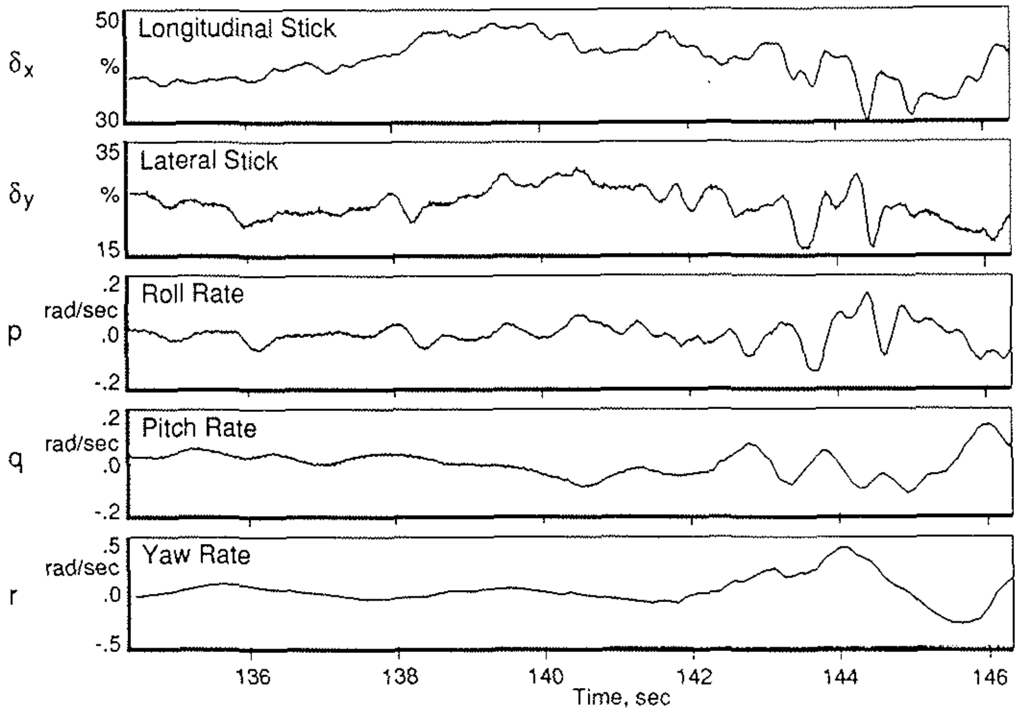



Figure 3.2: Flight Test Data Diagnostics

Treating the task as a multi-input/single-output (MISO) problem, the spectral output of roll rate p has been decomposed into four meaningful contributions from the control inputs $\delta_y$,.$\delta_x$,.$\delta_{TR}$.and $\delta_o$, and unknown extraneous noise. The control build-up at the output is shown in Figure 3.3 by the spectral output due to the primary control input $\delta_y$.alone, combined spectral output due to.$\delta_y$,.$\delta_x$; combined spectral output due to $\delta_y$, $\delta_x$ and $\delta_{TR}$; and combined spectral out put due to $\delta_y$, $\delta_x$, $\delta_{TR}$ and $\delta_o$. The figure shows that the major portion of the control build-up in the frequency regime 0.5 - 1.5 Hz comes from lateral stick $\delta_y$, whereas considerable control contributions at lower frequencies are also due to longitudinal stick $\delta_x$ and tail rotor $\delta_{TR}$ inputs (Reference 17).

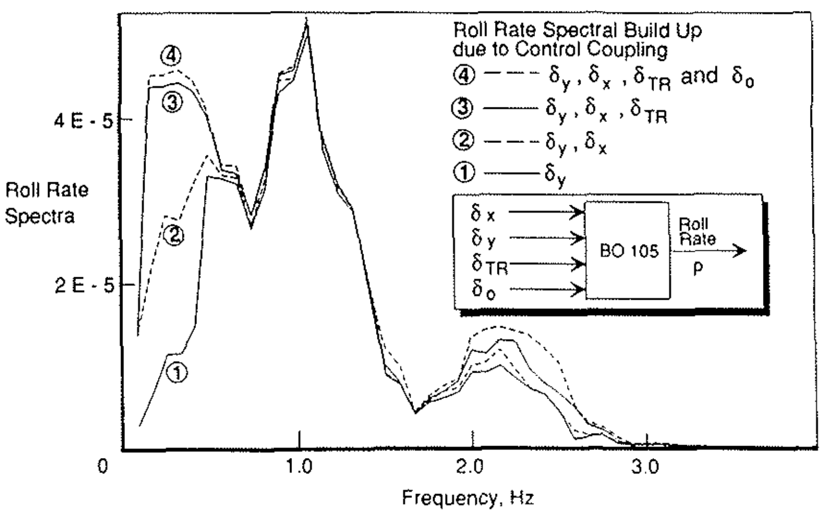



Figure 3.3: BO 105 MISO Decomposition of Roll Rate Spectrum

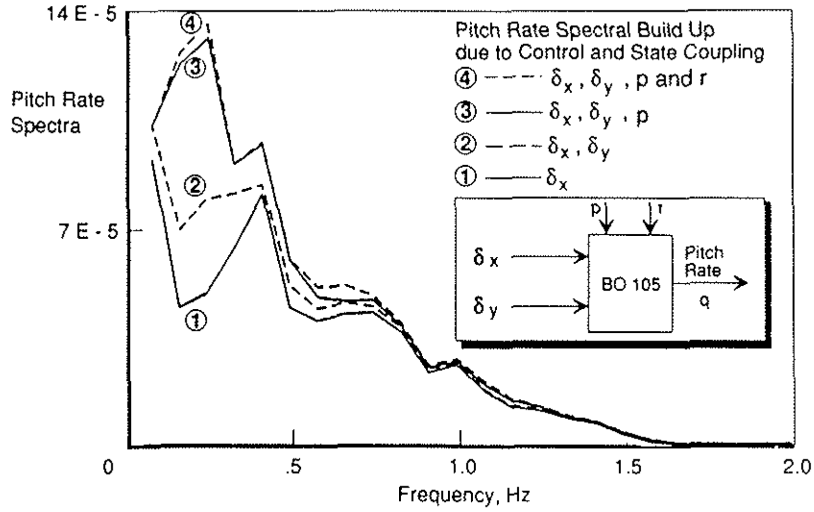



Figure 3.4: BO 105 MIMO Decomposition of Pitch Rate Spectrum

Iterative algorithms for the solution of multiple-input/multiple-output (MIMO) problems have been recently developed for the statistical analysis of flight test data (Reference 18). So-called joint multiple coherence functions have been derived to describe the combined effects of both controls and states on any selected response. The spectral decomposition of any flight state (response) can be calculated in order to illustrate explicitly the effect of each of the controls and states. Again, MIMO applications have been studied from measured BO 105 flight data (Figure 3.2) in order to predict the spectral effects of coupled controls and states on the pitch rate response. It can be observed from Figure 3.4 how the spectrum of pitch rate response is built up when progressively the effect of each control and state is added. Thus, the output spectral decomposition effectively indicates the significant influence of each of the parameters on the rotorcraft response. The strong pitch-to-roll state coupling effect due to the rigid rotor at lower frequencies is obvious.

In conclusion, with the development of advanced MIMO functions the frequency domain identification is becoming more attractive and powerful. Their main advantage is the provision of solutions which do not require any assumptions with respect to the model order or structure.

### 3.4 System Identification

Having consolidated flight test data available, (section 3.2) rotorcraft system identification plays the strongest part as a flight test validation tool for accurate modelling of rigid body and rotor coupling dynamics. The basics of system identification are depicted in Figure 3.5. System identification for fixed-wing MIMO aerospace flight vehicles have been thoroughly applied. Due to more complex aeromechanics and controls of rotorcraft special research and international collaborative work has been recently undertaken (References 13, 15).

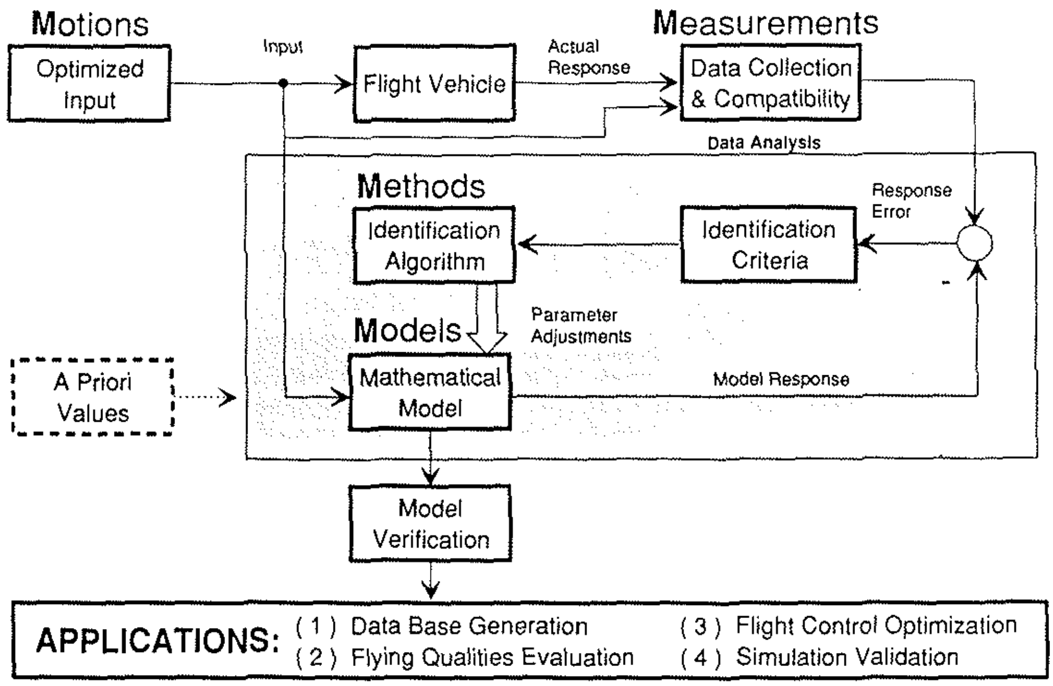



Figure 3.5: The Conceptual Framework of System Identification ("Quad M"-Basis)

Rotorcraft system identifications tools in the time and frequency domain have reached a maturity level that makes them a powerful tool to support not only research but industry activities in model validation, handling qualities evaluation, control law design, and flight vehicle design. They can potentially provide a major contribution to risk and cost reduction during the rotorcraft development and validation phase (Reference 15).

Referring to the future requirements for rotorcraft high bandwidth flight control systems extended mathematical models have to be structured to incorporate higher-order rotor dynamics which couple with the rigid body modes at higher frequencies (Figure 3.6, Reference 19).

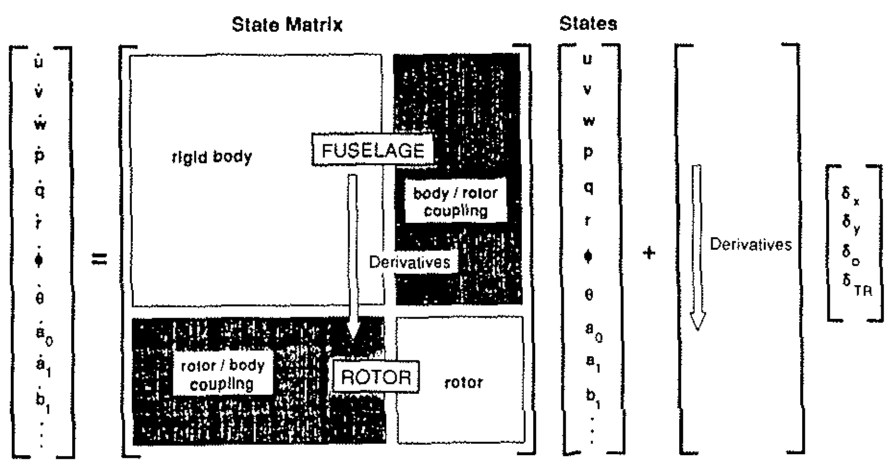



Figure 3.6: Higher Order Model Structure (Rigid Body / Rotor Coupling)

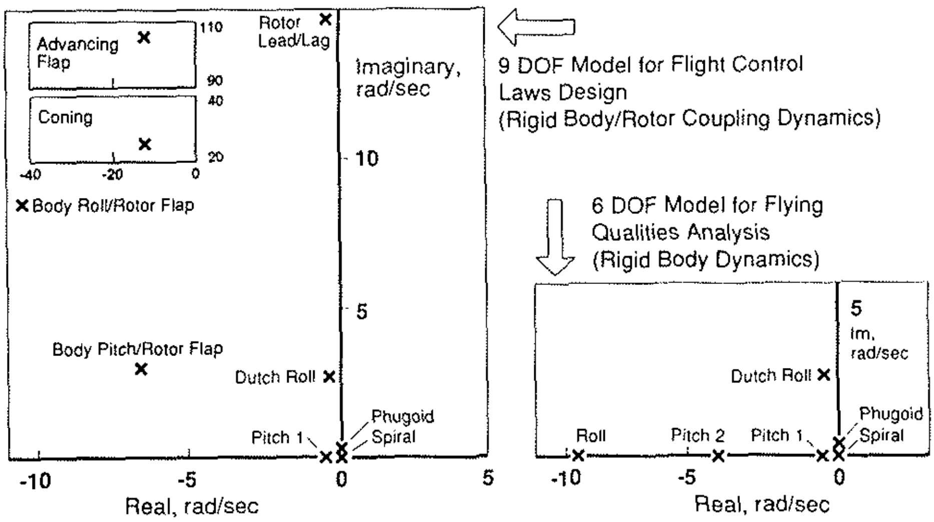



Figure 3.7: System Identification Results: BO 105 Eigenvalues of Different Model Structures

The effect of the rotorcraft model structure on the results of system identification are illustrated in Figure 3.7. Generally, 6 degree-of-freedom (6 DOF) rigid body dynamics will provide acceptable model quality for flying qualities investigations up to 1 Hz whereas 8 to 9 DOF model structures are indispensable for higher bandwidth rotorcraft flight control system design and evaluation (see chapter 4).

The detrimental effects of unmodelled rotor dynamics are clearly visible from the roll acceleration time histories in Figure 3.8. Taking rigid body-rotor coupling and rotor lead/lag model structure elements into account (see Figure 3.7, left side) provides almost perfect matching of the BO 105 flight test data and the identified 9 DOF model (Figure 3.8, bottom).

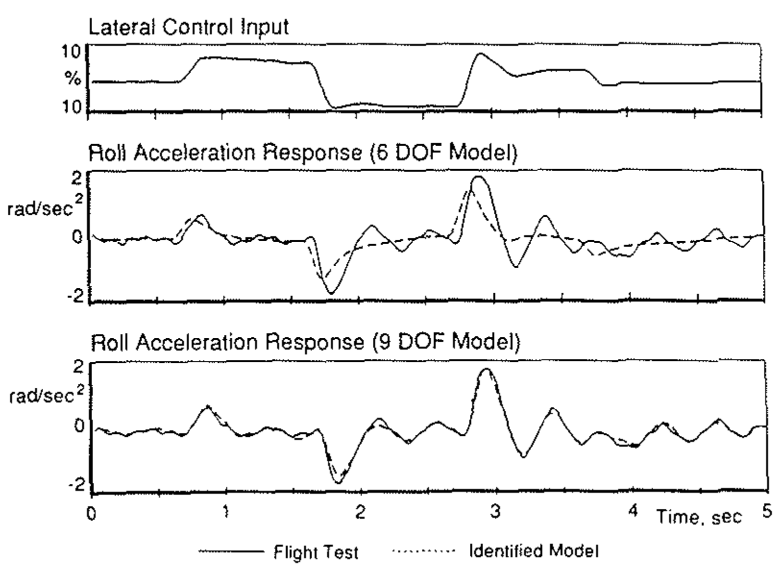



Figure 3.8: Effects of Unmodelled Dynamics

## 3.5 Inverse Simulation

The accuracy of complex non-linear rotorcraft simulation programs can generally only be evaluated by comparing flight test data and calculated responses due to given control inputs. In general, this comparison is only possible for short time histories, as inaccuracies in trim and mathematical modelling may lead to discrepancies in the long term behaviour and contradictory off-axis (coupling) responses.

The calculation of control inputs required to fly a predefined manoeuvre is described as inverse simulation. This is useful in the design phase of a new rotorcraft (Reference...). Further, inverse simulation can be used as a tool for improving the quality of simulation programs which are required for pilot-in-the-loop investigations and control law validation applications (Figure 3.1). In a further step to inverse simulation explicit model following control techniques have been successfully applied to the validation procedure of simulation programs. In conclusion, inverse simulation using model following control procedures is a suitable tool to evaluate the adequacy of models which shall be implemented in flight control law design and in pilot-in-the-loop simulators. The required "residual" controller outputs represent a quality criterion for the simulation fidelity. For a perfect simulation program these outputs should be equal to zero. This quality criterion can be used for further modelling improvements of the simulation program by systematically reducing the required outputs of the feedback controller to match measurement and simulation. For detailed results and discussions see Reference 22.

# 4. Flight Control System Design

## 4.1 General

With Fly-by-Wire/Light flight control systems becoming matured (see chapter 6), modern and future generations of rotorcraft are no longer constrained to mechanical flight controls and rely increasingly on computer systems to interpret the pilot's intentions and then to decide how the rotorcraft should react (Figure 2.1). Such sensor-based integrated flight control systems are more precisely responsive than direct mechanical links requiring skillful and coordinated pilot control mixing in all axes yielding potential high workload conditions (Reference 23).

The rotorcraft flight control system must exhibit performance robustness to a variety of disturbances and uncertainties. Selected problem areas are how to

- control an infinite dimensional rotorcraft with a four dimensional rotorcraft controller
- select and locate sensors and effectors (actuators)
- assess the effect of unmodelled dynamics and uncertain parameters (see chapter 3) and
- reject internal and external disturbances

In the following classical and modern flight control law design procedures will be shortly reviewed (section 4.2) and the most promising techniques discussed in more detail (section 4.3)

## 4.2 Flight Control Law Design

The roots of classical control law design, stability analysis methods devised by Nyquist, Bode, Nichols, lie in the solving of the single-input single output (SISO) servo problem. All the methods use a graphical pictorial representation which has ensured their continued popularity by engineers. Figure 4.1 depicts the solution to the classic problem of

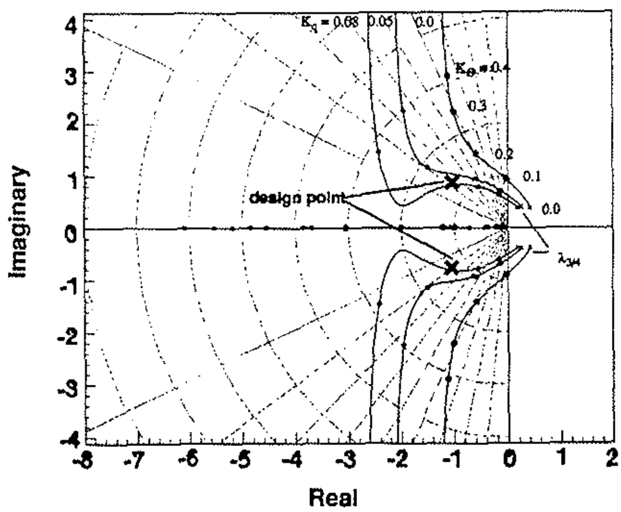



Figure 4.1: Root Locus Technique

designing a suitable feedback stabilisation for the pitch axis phygoid using the root-locus technique. The procedure is very simple, the engineer develops a carpet plot for suitable pitch attitude and pitch rate gains, optically identifying the best design point. Naturally the process can be repeated for different data sets, different speeds and a compromise gain found. Since conventional limited authority AFCS's are designed for hands-off IFR (adequate dynamic stability), the method has, in the past been adequate. Furthermore, the control, the control structure of attitude and rate feedback is very robust so that even significant differences between the simplified linear model and the real helicopter can be smoothed out in flight test.

The flight control system task of today can no longer be statisfied by the classical design methods. The objective of modern control systems has completely changed. The control response during hands-on flight must be influenced in order to eliminate all undesirable inter-axis cross-couplings, to change the basic response type (e.g. rate command plus attitude hold), and to make flying easier so that the pilot can concentrate on the primary mission task. In consequence, more complex structures are required than the single-input single-output /SISO) servo loop.

Since about two decades various design procedures for linear multivariable feedback systems have been established in order to formalize and generalize those time and frequency domain design methods for multi input / multi output /MIMO) flight control systems which were developed for classical single input/output /SISO) control systems.

One of the goals of multivariable control theory has been to capture major elements of the engineering process of SISO feedback design under a more procedural cover which allows an increasing rigorous and automated approach of MIMO feedback control system design with respect to the three basic requirements of stability, performance and robustness. An excellent survey about the useful techniques for the design of multivariable feedback systems such as the singular value loop shaping process is given in the textbook of Maciejowski (Reference 24).

Some generalized multivariable control design methods can be grouped into (1) time response methods such as Linear Quadratic Gaussion/Loop Transfer Recovery (LQG/LTR), (Reference 25), and (2) frequency response methods such as H-Infinity and Quantitative Feedback Theory (QFT), (Reference 26), have been applied to rotorcraft flight control law design although they mostly assume mathematical models with unstructured or structured uncertainties as they have not been validated by flight tests. Also, the quality of the designed feedback control laws with respect to stability, performance and robustness is generally validated only by ground based simulations and rarely by dedicated flight test experiments (Reference 16).

In conclusion, considerable progress has been made in the development of design techniques for multivariable feedback control laws of rotorcraft systems. But critical issues have to be addressed concerning real flight conditions. Modelling errors arising from high-order rotor dynamics plus interaxis aerodynamic and control coupling can seriously degrade flight control performance. Insufficient attention paid to modelling of flight control component dynamics such as actuators, sensors and filter can lead to excessive time delays, non-realizable feedback gains, and, in further consequence, to flight critical pilot-vehicle instabilities.

## 4.3 Model Following Flight Control Laws

Another multivariable control design method is concerned with so-called explicit model following control. It is probably the most promising and flexible technique which is especially attractive for task-tailored flight control modes and reconfigurable flight control laws.

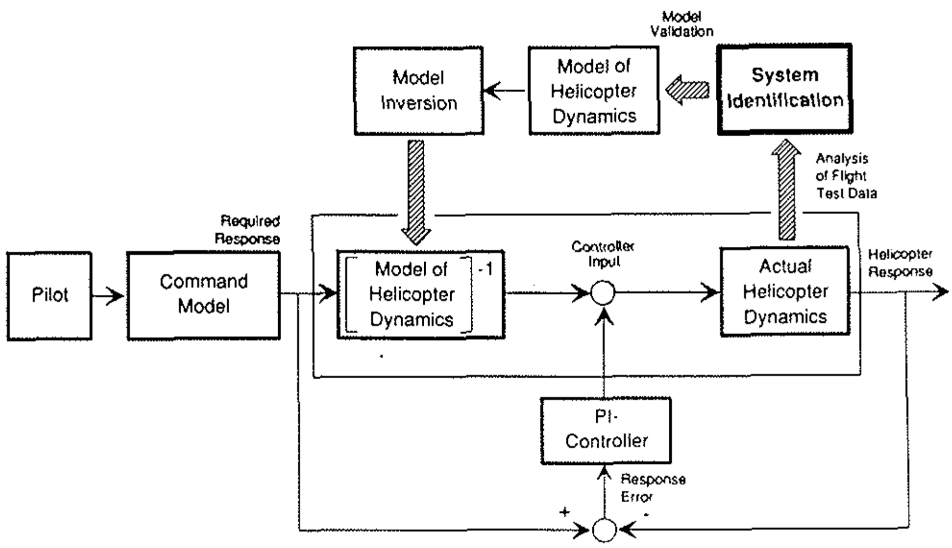



Figure 4.2: Principles of Explicit Model Following Control

Figure 4.2 shows the principle of explicit model following control. The pilot inputs are fed into command model which calculates in real-time the required helicopter response. A feedforward, which is the inverse of the identified host helicopter dynamics, generates control inputs for the actual (host) helicopter, An additional proportional / integral feedback controller (PI) is required to suppress errors between the actual and desired helicopter responses, caused by gusts and modelling inaccuracies.

The actual development of multivariable explicit model following flight control systems for rotorcraft began on the NASA VMS simulator (see section 5.1) as part of a joint transatlantic research program of the US Army and DLR (References 12, 27). The first results of ground-based simulations indicated a strong despendance of the model-following performance on the dynamics of the model to be followed, Increases in model bandwidth placed higher demands on the control system. Therefore, the control laws had to account for position - and / or rate - limited actuators (Reference 12).

When this model following control principle was implemented and evaluated on the variable stability CH-47 research helicopter of NASA (see section 5.2) and to the BO 105 ATTHeS (see section 5.2) in-flight simulator, it became clear that improvements to the initial design were needed to compensate for large time delays caused by higher-order effects such as rotor flapping dynamics, sensor filter dynamics, and computational time delays. The final flight tests of the Army / NASA CH-47 and DLR BO105 control systems achieved excellent model following performance (References 28, 29).

In conclusion, the basic model-following philosophy should place most emphasis on the definition and calculation of the feedforward gain matrices. The more is known about the basic flight vehicle and system dynamics, the more exact these gains can be calculated. The effect of unmodelled rotor dynamics can be seen in Figure 4.3. The top diagram shows the desired and actual roll response due to lateral stick inputs, for the ATTHeS helicopter with a six degree of freedom (6 DOF) host helicopter (BO105) model. When an eight degree of freedom (8 DOF) model is used (Figure 4.3, bottom), the errors between desired and actual responses are significantly reduced.

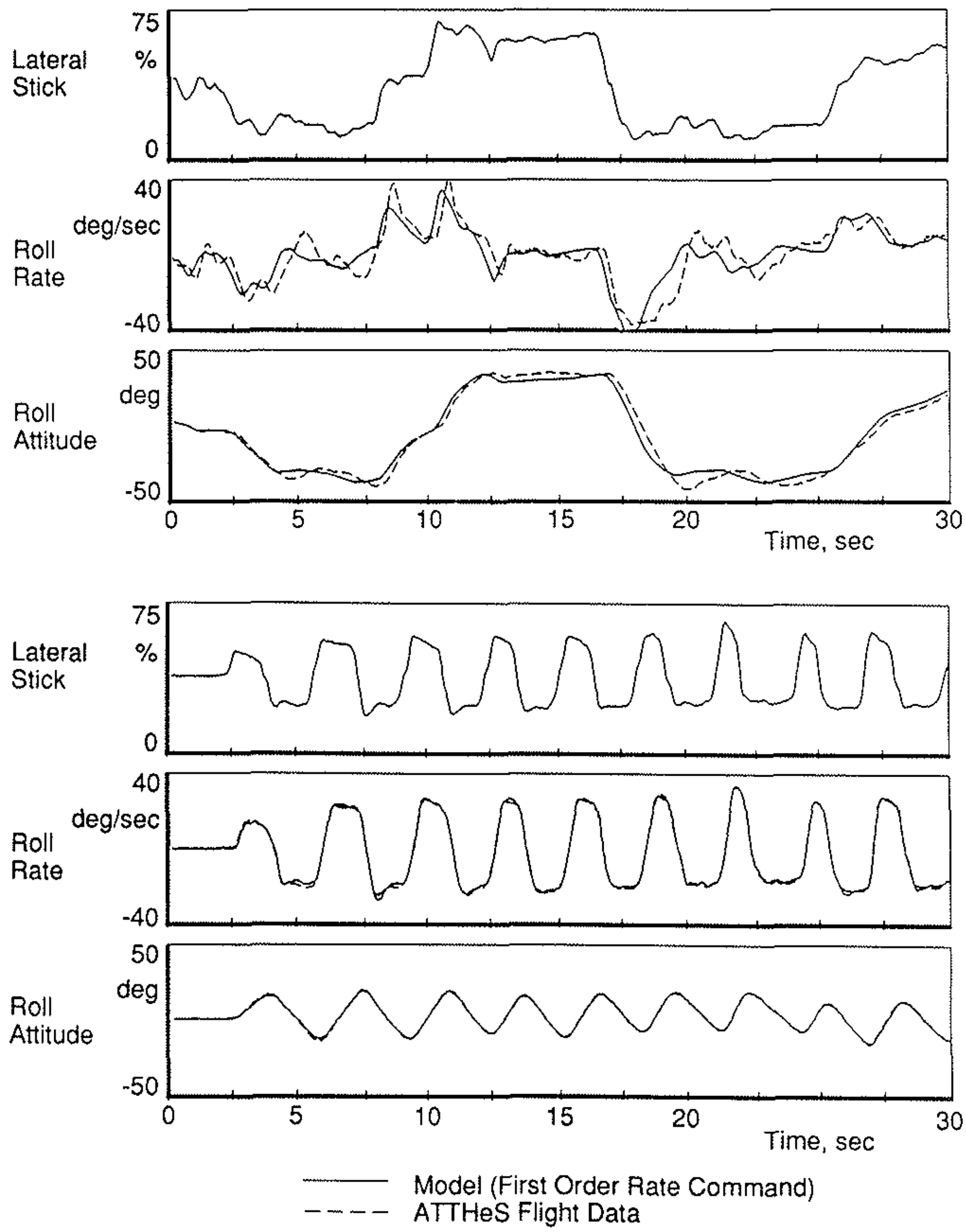



Figure 4.3: Effect of Rotor Dynamics Modelling on Simulation Fidelity
(Top: 6 DOF BO 105 Rigid Body Model
Bottom: 8 DOF BO 105 Rigid Body/Rotor Coupling Model)

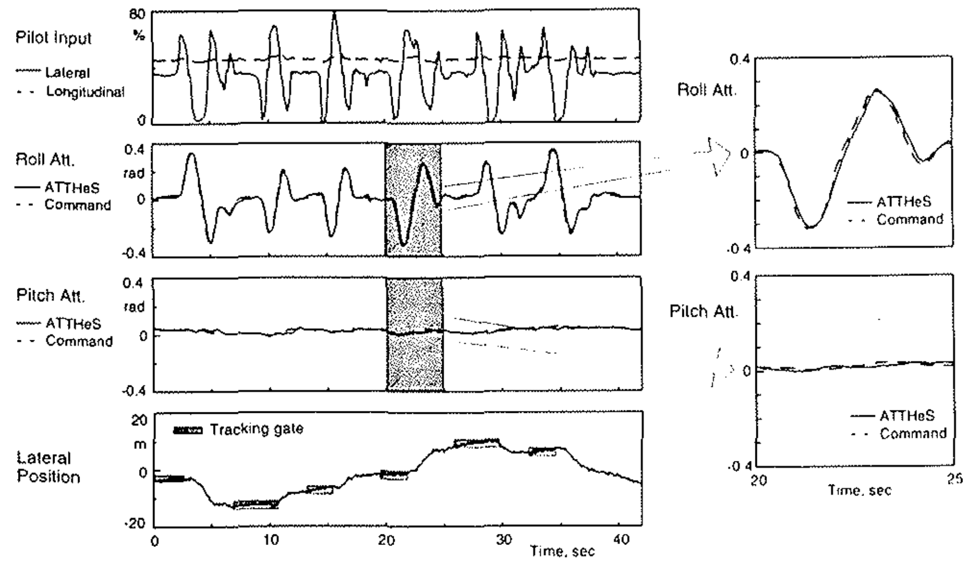



Figure 4.4: Control Model Performance for a Slalom Tracking Task

Figure 4.4 shows the performance of the control model for a slalom tracking task. Decoupling of pitch and roll motions allows the pilot to achieve excellent tracking performance in the slalom task with only a minimum of longitudinal control inputs. The enlargements show the high quality operational performance of the ATTHes model following controller for a decoupled rate command system (Reference 30).

Explicit model following flight control laws have also been successfully flight tested during the experimental ADOCS program (see section 6.3.4), and they play also an indispensable role during the flight control law design for the RAH-66 Comanche project (References 31, 32).

Nevertheless, explicit model following control is not yet realized over the full flight envelope. *A practical compromise recently developed at ECD is shown in Figure 4.5. It uses* the feedforward structure only for the most important axes decouplings and for an optimized primary response.

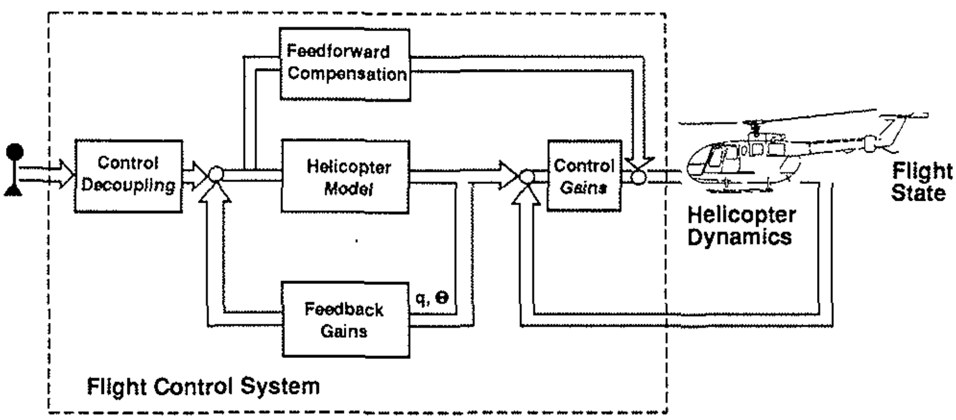



Figure 4.5: "Compromise" Structure for Model Following Control

As an example, Figure 4.6 describes the main features of a control law, which was designed by ECD under the European ACT-programme (Reference 10). According to the structure shown, a compromise was found between the pure feedback design, which is not quick enough for high bandwidth requirements and an explicit model following structure. The main elements are:

- Dynamic feedforward for the primary response characteristic about the pitch, roll and yaw axis
- Concentration on the most important decouplings for the feedforward compensation
- Robust feedback design for the stabilization and the compensation of the offset from the ideal feedforward control strategy.

Further improvements of this control law will include the implementation of the collective axis and the optimization of the command model for the yaw axis.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="4">Speed Range</td></tr>
<tr><td colspan="2">Hover/Low Speed<br>(IAS < 40 kts)</td><td colspan="2">Forward Flight<br>(IAS > 40 kts)</td></tr>
<tr><td rowspan="6">Pilot Control</td><td>Collective</td><td colspan="4">Direct Link</td></tr>
<tr><td>Longitudinal</td><td colspan="4">Pitch - RCAH<br>Pitch-to-Roll-Decoupling<br>Direct Feedforward Control</td></tr>
<tr><td rowspan="2">Lateral</td><td>Roll - RCAH</td><td colspan="2">Roll - RCAH<br>for<br>t (±5° bank) < 1 sec</td><td>Turn Coordination<br>for<br>t (±5° bank) > 1 sec</td></tr>
<tr><td colspan="4">Roll-to-Pitch Decoupling<br>Direct Feedforward Control</td></tr>
<tr><td rowspan="2">Pedals</td><td colspan="2">Yaw - RCDH</td><td colspan="2">Yaw - RCDH (RC short term only)</td></tr>
<tr><td colspan="4">Yaw to Collective Decoupling<br>Direct Feedforward Control</td></tr>
</table>

Figure 4.6: Advanced Control Law Desgin

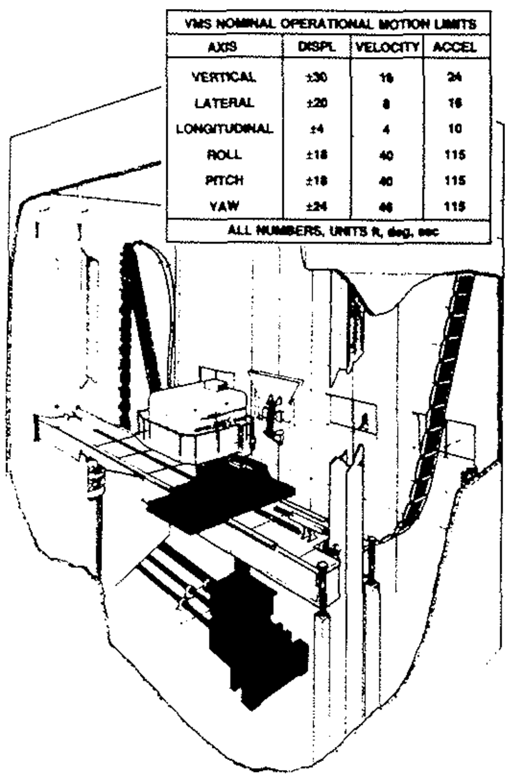
## 5. Simulation Facilities

### 5.1 Ground Based Facilities

With the availability of very large and fast computers for the realization of high bandwidth characteristics of the rotorcraft and high resolution visual scenes ground-based simulators became a powerful tool for generic handling qualities studies, advanced control system design and development, and man-machine integration.

It was often discussed whether or not the motion cues are necessary for a realistic evaluation of the helicopter's characteristics. While simulators without motion system are very useful and effective for a great number of research and development tasks, it is generally agreed that motion simulation is required to obtain full pilot performance in high bandwidth tracking and aggressive mission tasks. The following section shortly describes some moving and fixed base simulators operated by research establishments and industry.

NASA Ames VMS: The NASA Ames 6-degree-of-freedom Vertical Motion Simulator is illustrated in Figure 5.1 with a list of the operational limits of the motion system (Reference 34). The cockpit cab is interchangeable, four image presentation "windows" provide the outside imagery generated by a Singer Link DIG-1 Computer Image Generator. The CIG data base contains adequate macro-texture for the determination of the rotorcraft position and heading with a reasonable precision. A seat shaker provides vibration cueing to the pilot, with frequency and amplitude programmed as function of airspeed, collective position, and lateral acceleration. Aural cueing is provided by a sound generator and cab-mounted speakers. Airspeed and rotor thrust are used to model aural fluctuations. Different helicopter instruments and controls may be installed in the cockpit depending on the actual investigation.



| VMS NOMINAL OPERATIONAL MOTION LIMITS | | | |
|---|---|---|---|
| AXIS | DISPL | VELOCITY | ACCEL |
| VERTICAL | ±30 | 16 | 24 |
| LATERAL | ±20 | 8 | 16 |
| LONGITUDINAL | ±4 | 4 | 10 |
| ROLL | ±18 | 40 | 115 |
| PITCH | ±18 | 40 | 115 |
| YAW | ±24 | 46 | 115 |
| ALL NUMBERS, UNITS ft, deg, sec | | | |

Figure 5.1: NASA Ames Research Centre Vertical Motion Simulator (VMS)

DRA - AFS - Facility: Figure 5.2 shows a general view of the Advanced Flight Simulator (AFS) facility at DRA Bedford. The facility was recently enhanced by the addition of the Large Motion System (LMS). Platform motion in 5 axes is provided, with roll, pitch, yaw, heave and sway or surge, depending on the orientation of the cockpit when mounted into the motion system. The LMS has large linear displacements (± 5 m), and high velocity (3 m/sec) and acceleration (10 m/sec$^2$ ) capabilities (Reference 35).

The cockpit is a hybrid helicopter/fast jet facility and while some of its features are representative of those found in rotary wing aircraft, e.g. rudder pedals and collective control, others are not. The pilot's seat and seating position are more typical of fixed-wing aircraft, although it does provide both normal, 'g' onset cueing and vibration cueing and has provision for the installation of sidearm controllers. Visual cueing is provided by a 3-channel Link-Miles CGI Image IV graphics system through collimated CRT monitors mounted symmetrically in the cockpit to give a centre window and two side windows. The FOV is ± 63 deg in azimuth and up to ± 24 deg in vertical plane.

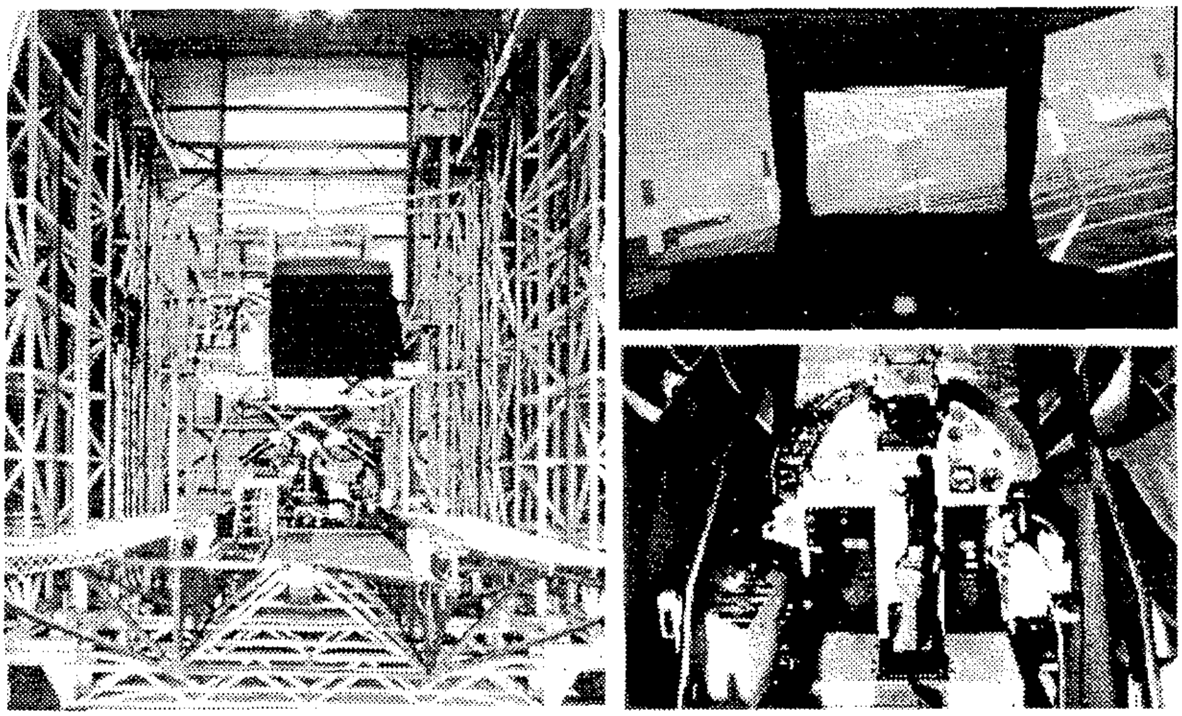


Figure 5.2: DRA's Advanced Flight Simulator (AFS)

ECF's Simulation Centre: This is a new research and development facility specifically for helicopter piloted simulation (Figure 5.3). It's characteristics are still being improved (e.g. improved field of view and equipment), Reference 33. The visual system consists of a 8 m diameter dome screen on which is projected a computer generated imagery. The global field of view presently available is 120 deg in azimuth and 80 deg in the vertical plane. Two databases are available: the first one has been specially developed for helicopter piloted simulations to allow a better realism of NOE flight. The cockpit has been designed for Man Machine Interface studies for 7/9 tonne helicopters. It has side by side seating and is equipped with conventional collective and pedal controls, and a two axis sidestick controller. Head down, there are two CRT displays. A HUD will be available later.

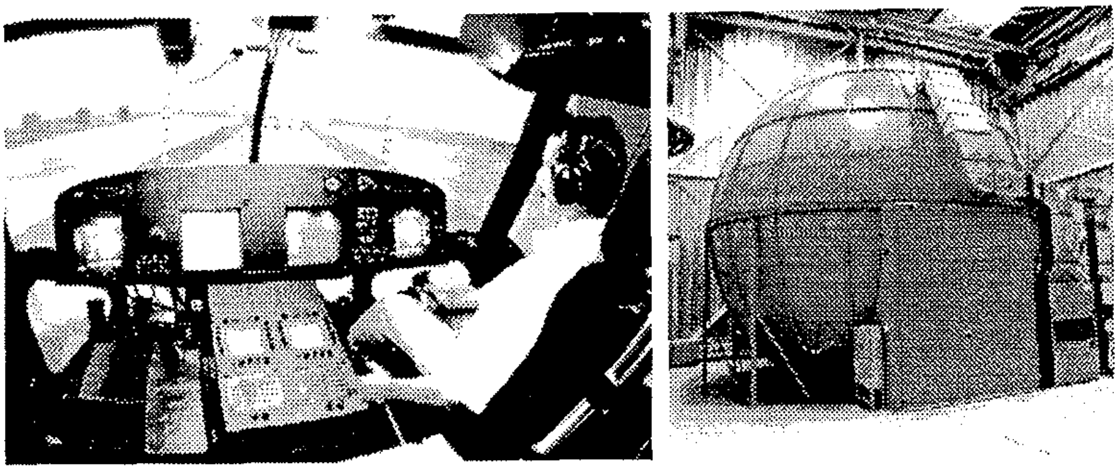


Figure 5.3: ECF, Sphere Simulation Centre

DASA/ECD Simulation Centre: The dome simulation facility (Figure 5.4) is shared between the Military Aircraft and Helicopter Division. It features interchangeable cockpits with a large field-of-view from the computer generated imagery. Specific high resolution scenery has been developed for Nap of the Earth simulations with a field of view of ± 70° in azimuth and +70° / -40° in elevation. It is fixed based with provisions for buffeting and g-seat vibration and noise generation (Reference 36).

The heart of the facility is the General Electric COMPU-SCENE IV visual system. This consists of a 10 metre spherical dome, a six channel projection system, a computer image generator using the photo mapping method, a HARRIS Nighthawk simulation computer, three exchangeable helicopter simulation cockpits, and an interface computer. The cockpit shown is equipped with conventional controls for the left hand seat and an adjustable mounting for sidestick controllers for the right hand seat.

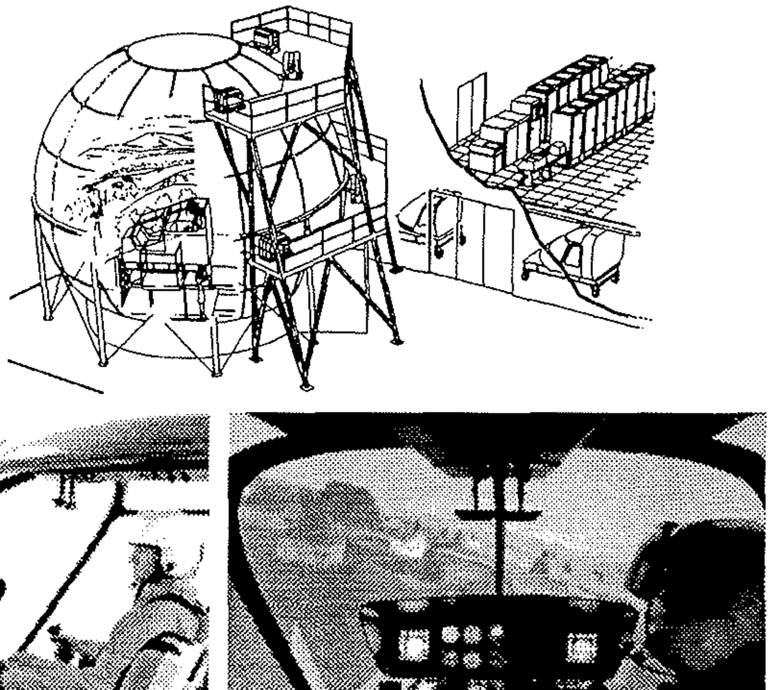


Figure 5.4: DASA / ECD Dome Simulation Facility

## 5.2 Helicopter In-Flight Simulators

In spite of or sometimes because of the sophistication of ground-based simulators there are numerous applications where unrestricted motion, three-dimensional visual information and the real operational environment are crucial to the success of the simulation. In those cases, where the ground-based flight simulator has inherent limitations the airborne in-flight simulator offers the only alternative. In this view, the ground-based simulator and the in-flight simulator are complementary facilities, both indispensable for advanced helicopter flight control system research and development.

Extensive experience with the development and operation of in-flight helicopter simulators have particularly been made in Canada, in the United States, in Germany, and recently also in France. To give an overview, the variable-stability helicopters, which are currently used are briefly characterized. Excellent survey papers describing the present status and future plannings of helicopter in-flight simulators can be found in (Ref. 37, 38).

For over 20 years, the Canadian Flight Research Laboratory of the NRC has operated a Bell 205-A1 helicopter, the civil equivalent of the UH-1H, as a fly-by-wire research aircraft (Figure 5.5). The aircraft is equipped with full authority dual-mode hydraulic actuators, which provide full-authority electrical fly-by-wire control from the simulation pilot's seat. The rotor stabilizer bar is removed, to improve the rotor cyclic input response. This testbed has been used as a fundamental research tool for flight mechanics research, simulating a wide range of vehicle types but specialising in advanced rotorcraft topics. In cooperation with the US Army AVSCOM and NASA the aircraft has been involved in the process to generate data for supporting the development of the ADS-33C (Reference 3). In parallel of the ongoing use of the NRC 205-A1 a new in-flight simulator is under development which is based on a Bell 422 helicopter.

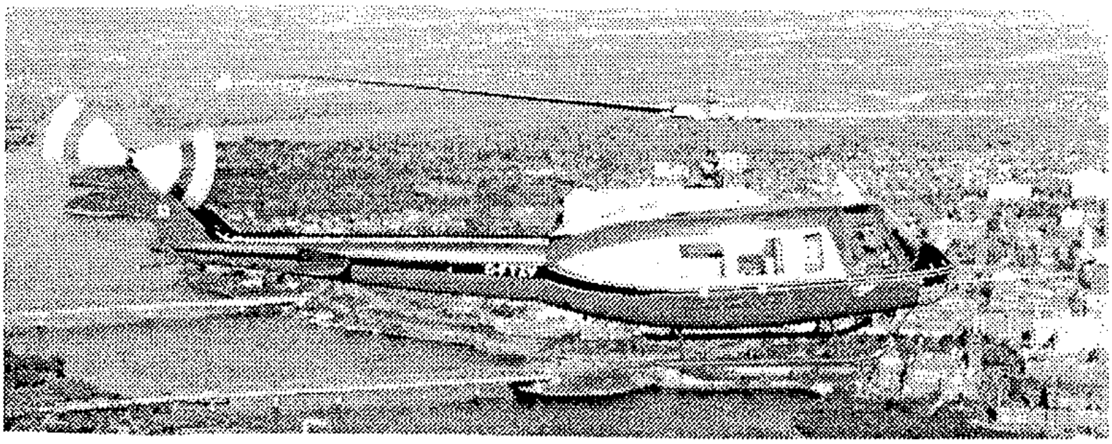


Figure 5.5: NAE Bell 205A-1 Airborne Simulator

The NASA / Army CH-47B variable stability helicopter, originally developed at NASA Langley, was operated at Ames Research Centre from 1979 to 1989. The CH-47B is a twin-engine tandem-rotor cargo helicopter, capable of lifting a 10.000 pound payload. The large speed range (up to 160 kts) of this aircraft is particularly attractive, and the fairly high control authorities in pitch and roll implies the capability of simulating the trim characteristics of a wide range of helicopters. Within the over 450 research flight hours the testbed was used in a wide variety of experiments providing data in many flight control and handling qualities areas.

The BO 105 FbW helicopter (Figure 5.6) was originally developed at MBB and operated since 1975 as a variable stability helicopter for flight control and guidance system design (Reference 39). The aircraft was put into service at DLR Braunschweig in 1982 and has been developed into an in-flight simulator BO 105 ATTHeS (Advanced Technology

Testing Helicopter System) (Reference 40). The simplex fly-by-wire control system includes full-authority, non-redundant fly-by-wire (FbW) control system and a Fly-by-Light /FbL) control system for the tail rotor which was integrated in 1988. The safety pilot is provided with a mechanical link to the rotor controls. The inherently high control power and damping of the "hingeless" rotor allow simulations of a uniquely broad range of helicopter characteristics including high bandwidth system capabilities.

Within the last ten years of operation, ATTHeS was used in various research and development programs during which is accumulated over 1100 flight hours (Figure 5.6). ATTHeS was used for fundamental handling qualities research, control law optimization, response system evaluation, and 6 DOF helicopter simulation. In addition, the testbed has been involved in the European ACT program and in programs of European test pilot schools.

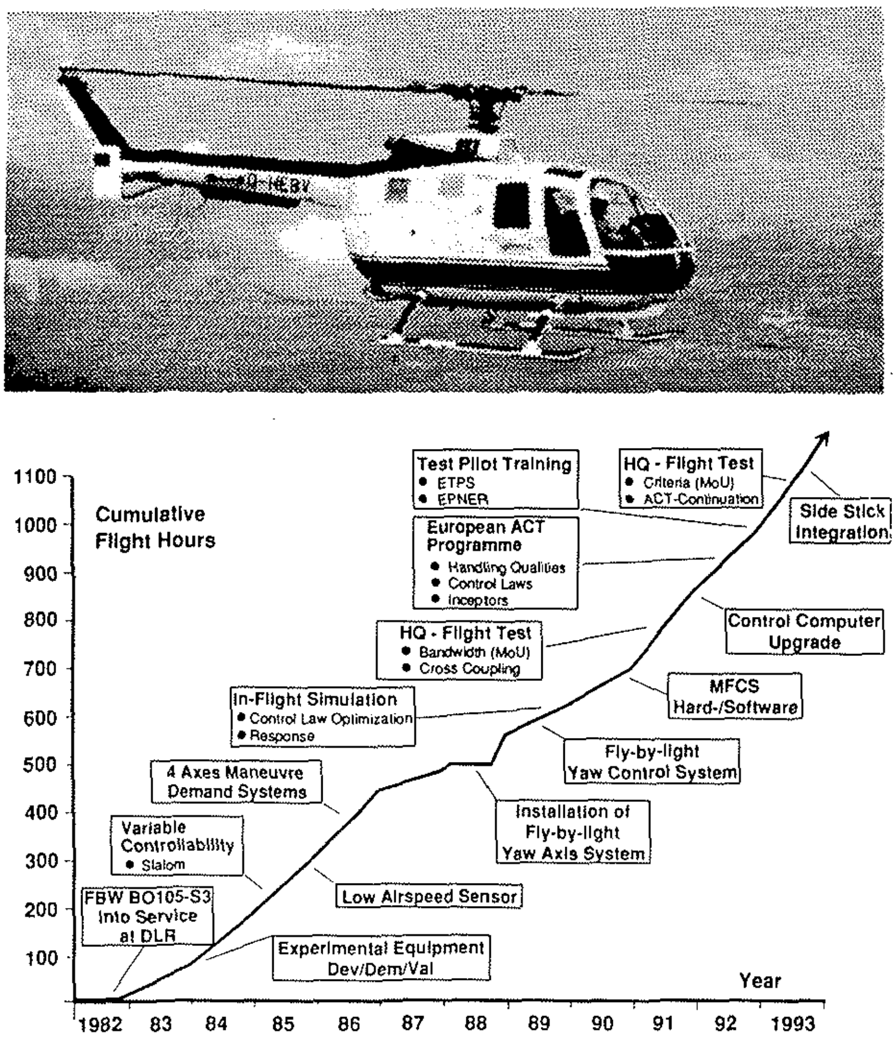



Figure 5.6: BO 105 - FBW/L In-Flight Simulator ATTHeS and its Flight Test Statistics

The Sikorsky S-76B SHADOW (Figure 5.7) was designed by Boeing Sikorsky in order to become the primary testbed in the development of many of the RAH-66 Comanches's subsystems such as displays, inceptors and flight control concepts and algorithms. Equipped with a fly-by-wire (FBW) control system, the SHADOW also carries conventional controls, plus safety precautions that allow instant transfer from the FBW system if needed. Another safety aspect is a second pilot in a conventional cockpit behind the single-seat station. These features have been comforting, particularly during some of the nap-of-the-earth (NOE) flight experiments the aircraft routinely performs.

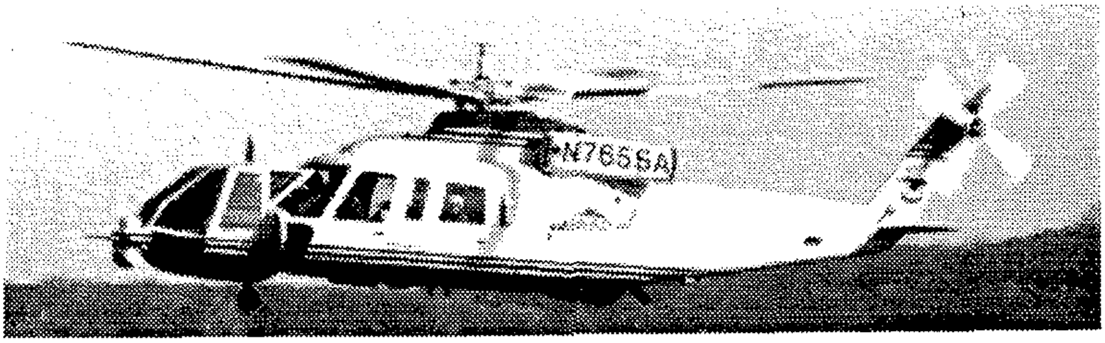



Figure 5.7: SHADOW In-Flight Simulator

The Dauphin 6001, developed and operated by Eurocopter France is primarily used as an experimental aircraft for active control technologies. The aircraft has a duplex fly-by-wire with a mechanical back-up (Figure 5.8). The evaluation pilot has right-hand side-stick controls, while the safety-pilot keeps conventional mechanical controls. Electrical control commands are generated by two synchronous FbW computers that monitor each other, and are programmed in two different languages (Reference 41).

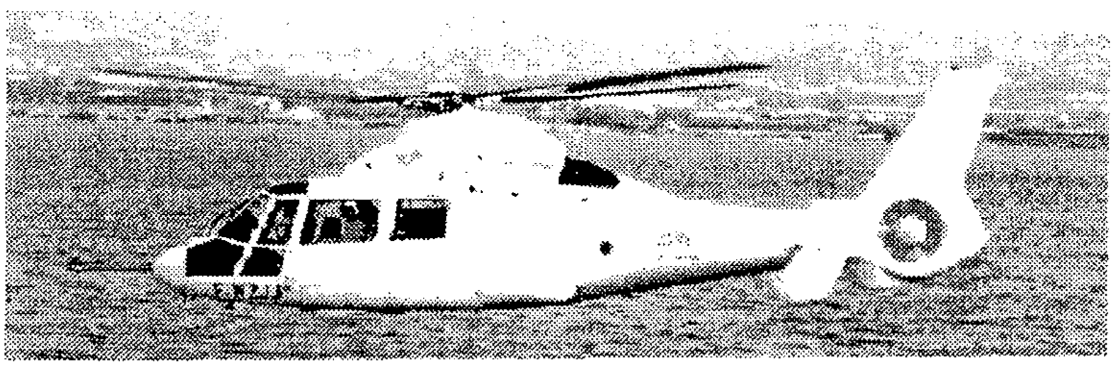


Figure 5.8: ECF Dauphin 6001 FbW System Demonstrator

In Japan, Kawasaki Heavy Industries has designed and flight tested a FbW research helicopter, based on the BK 117 (Figure 5.9). The 4-axis full authority digital FbW is basically a triplex redundant system. It employs smart actuators and (3 + 1) C axis side stick controllers and provides the pilot with significant workload reduction by axis decoupling, automatic flight path management and automatic flight envelope management (Reference 42). First flight took place in 1992, and was proceeding with full-authority FbW-mode investigations.


Figure 5.9: KHI BK 117 FbW Experimental Helicopter

## 6. Technology Development and Implementation

### 6.1 Historical Trends

An attempt is made in Figure 6.1 to give an overview about the history of development in helicopter flight controls technology and to illustrate how the evolution in electronics and computers has influenced this development. Helicopter Flight Control Systems have been, until recently, mechanical systems. Their development was dominated by mechanical engineers, struggling for simple and robust designs, accepting hydraulic actuators when necessary. There have been good reasons for doing so. The understanding of the very complex flight mechanics of helicopters was generally poor, and the prediction of helicopter dynamics from analytical models or wind-tunnel tests was rather vague. With analog computers it was purely impossible to model the complex behaviour of a helicopter.

With the advent of fast digital computers, able to solve the very complex high order equations within reasonable time and cost, the situation has changed drastically. Stability Augmentation Systems (SAS) and control laws, which were up to this time empirically adapted to helicopters in very intensive flight tests, could now be developed with the aid of computers, thus reducing the costly flight tests. Simulation today serves a highly useful role during the design phase up to the pilots training, and for type certification.

Today we are at the edge of a phase which will permit to utilize in future production helicopters fly-through-computer techniques in which computers and electronic circuits replace mechanical rods as the link between the pilot controls and the rotors. This allows to tailor the helicopter mission performance without limits imposed by the inherent inflexibility and complexity of mechanical controls, or by the performance limits set by superimposing Auto Pilots or Stability Augmentation Systems (SAS) with limited authority. One can already imagine "fly by" - systems with so powerful computers that in-flight real-time parameter identification and fuzzy logic application will permit self optimizing control laws. This is supported by "explosive" hardware developments in the area of digital electronics with steadily decreasing size, weight, power consumption and cost, and increasing reliability.

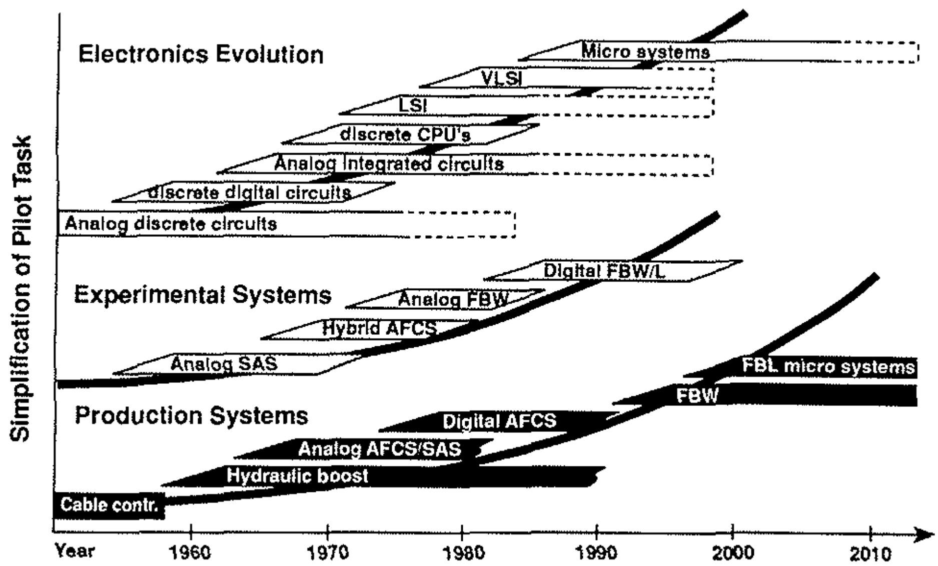



Figure 6.1: Historical Trends of Helicopter Flight Controls

But there are still hurdles to be taken: One of the main problems is the absence of helicopter inherent redundancies as can be used by the fixed wing engineer. There we have the possibility to reconfigure the control system, should a control surface fail. There is no substitute for a failed control to any one rotor blade on a helicopter. Therefore, actuators are required with a very high safety level converting the fly by signal to an actual force at the root of the blade. These signals need to be very safe as well. And again, due to the peculiar situation, we cannot rely on natural dissimilarities to protect from design deficiencies specifically within the software of digital systems.

### 6.2 Limits of Mechanical Systems

As mentioned above, the classical approach is a mechanical control system (Figure 6.2). This technology has reached a very high degree of maturity. As long as we are dealing with light helicopters designed for VFR operation, the mechanical solution will be, for a considerable time to come, the most economical solution. This is particularly right for civil applications which usually do not require the pilot to fly in ground proximity at adverse weather conditions and be on steady look-out for adversaries. This type of operation, however, is one of the limiting factors for a broader and more regular utilisation of helicopters.

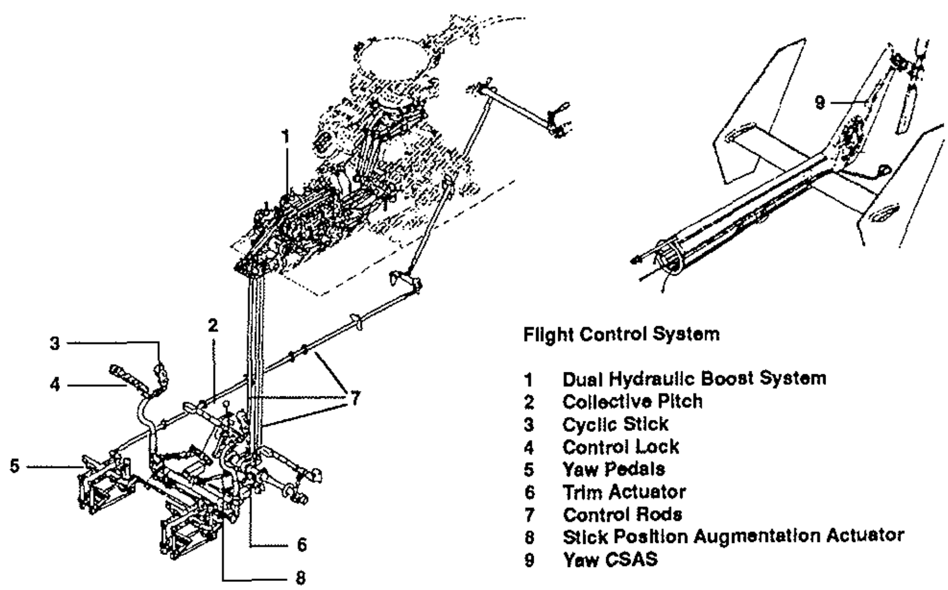



Figure 6.2: Conventional Mechanical Flight Control System

Furthermore, with growing aircraft size, say beyond the 3 ton class, pure VFR utilisation is a rare role and IFR capabilities with a certain level of automatic stability augmentation and autopilot functions is mandatory. Presently, the usual practice is to introduce the autopilot demands by means of secondary parallel actuators, either electro-mechnical or electro-hydraulic, driving the normal mechanical controls. The dynamic requirements to stabilize a helicopter usually requires faster inputs into the rotor system. Parallel actuators are therefore complemented with series actuators but with limited authority to prevent excessive inputs in case of an actuator input failure. Since such actuators are directly driving the mechanical controls, it is a matter of the mechanical impedance of the control system, whether the motion is fed only into the rotor or partially also into the stick and pilots hands.

On larger helicopters control runs get longer, with more hinges, attachments, and bearings which require very careful design of the mechanical parts in order to bring friction and backlash to a minimum. In case of military helicopters the vulnerability requirements will most likely lead to a duplication of the entire system. Furthermore, operational criteria like performance accuracy and mission success are becoming dominating factors. By that, the advantages of the originally lightweight, highly reliable, low cost mechanical control system can turn into the opposite. Considering such limiting factors of mechanical systems, a promising technology which is offered today lies in full-authority fly-by-computer systems.

### 6.3 Fly-Through-Computer Systems

Fly-by-wire controls have since long been used in military fighter aircraft and in civil aviation applications, the supersonic Concorde has been flying with an early analog fly-by-wire controls since 1969. The early '70s also saw the first application of FbW technology to helicopters at ECD, in their BO 105-S3 In-Flight Simulator Program (Reference 39). ECD at that time could draw most of the expertise from the fixed-wing fraternity. Boeing-Vertol followed the FbW technology in their TAGS-Program for the HLH-Demonstrator (Reference 43). So, fly-by-wire has been around for a long time, and it is worthwhile to review briefly its major components.

A fly by system is made up of 4 major categories of components or subfunctions (Figure 6.3). Firstly, there are the sensing elements providing the aircraft states angular rates, angular and linear accelerations, aircraft attitude and orientation in space, altitude and velocities and further specific mission parameters. There are, secondly, the pilots inceptors, which provide the pilot demands to the system and the state selectors in form of either mode selectors or guidance inputs from mission computers. All this information is transmitted to the digital flight control computer, which computes the demands to the actuators, that now drive the angle of attack of the blades. The picture gets more complicated as we have to regard not only the pilots efforts but also the effects of potential failures of components, transmission lines or power provisions.

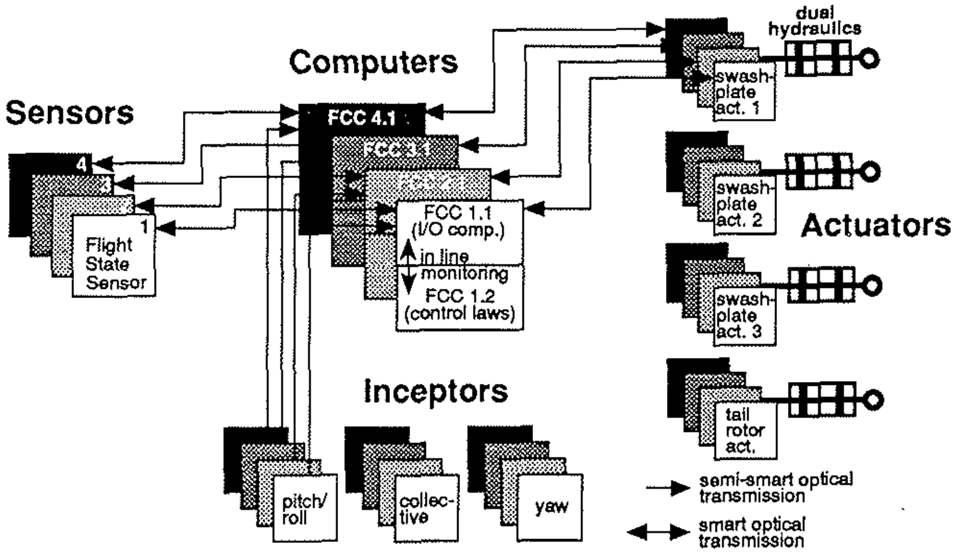



Figure 6.3: Digital Flight Control System Layout

#### 6.3.1 Pilots Inceptors

From today's point-of-view, the pilot's station will see quite a revolution in the next generation of helicopters. With regard to the inceptors there is a great variety of different

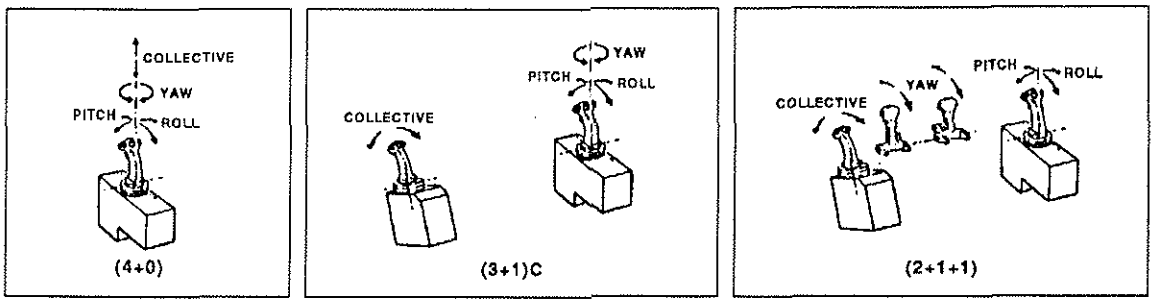



Figure 6.4: Controller Configurations

approaches to the problem. There are the traditional solution with passive centerstick, collective lever and pedals and there is very advanced concepts of concentrating these functions in one 4-axis stick controller.

Helicopter engineers have been very imaginative in their designs of such controllers. Figure 6.4 shows various types of side-stick pilot controller configurations investigated, including different levels of integration, i.e. number of axes to be controlled. There is certainly a definitive advantage for the sidearm controllers: The limited space for displaying essential mission information in front of the pilot is cleared from the hands of the pilot, obstructing his vision. An armrest for pilots comfort can easily be provided. In search of the best suited inceptor configuration, many dedicated research activities and extensive simulation work was conducted by a number of research institutions and industry (References 44 to 47, for example).

There were some lessons learned from these studies: The original concepts of combining all 4 control axes into one inceptor have not proved satisfactory to the pilots, and required too complex control laws. Current trend is to be cautious with the selection of side-arm inceptors and retaining separate vertical and directional axes with a combined longitudinal/lateral right-hand controller, or at most combining longitudinal/lateral/ directional in a right hand controller, with a classical left hand collective/power control.

In addition to these findings, recent studies indicate that a variation of the stick characteristics (in terms of force gradient, amount of displacement and damping) on one and the same helicopter from one mission segment to the other leads to a substantial improvement to the piloting task. A number of institutions has been concentrating on the use of so-called active controllers (References 48, 49, 50). Active within this context means that the various stick characteristics can be varied in flight by the flight control computer and tactile information is provided to the pilot.

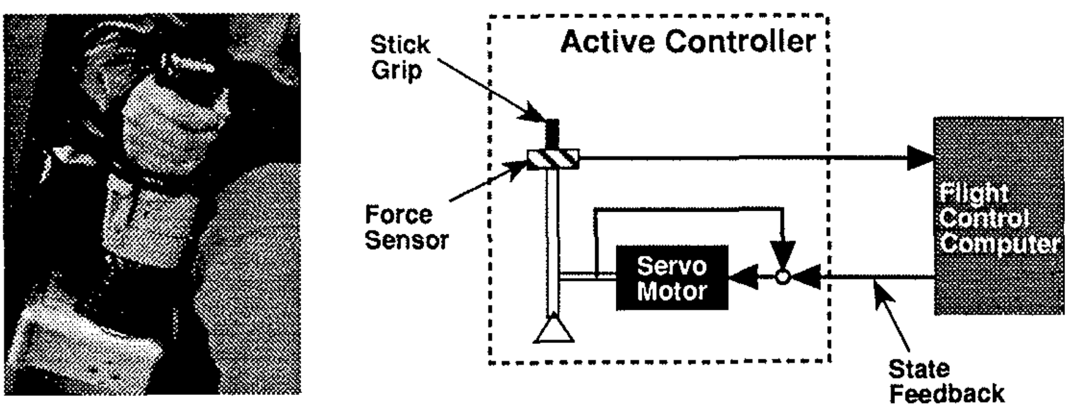



Figure 6.5: Active Side-Arm Controller

One of these stick concepts, pursued by Eurocopter Deutschland, is presented in Figure 6.5. It has undergone intensive simulator evaluations and is presently being prepared for flight trials (Reference 50). One very important feature of this concept is that it has been designed as a smart element, i.e. it does not require participation of the flight control computer to perform its function. It requires only parameters which have been established by the computer. Should this information fail, the stick can continue to operate with a predetermined standard set of parameters. Synchronization of pilot and copilot controls as well as force summing is performed electronically. Furthermore, position trimming of the sticks is being performed ensuring that the pilot retains information about the actual flight state and the remaining control authority.

### 6.3.2 Smart Actuation

The same smart principle can be applied to the actuation subsystem, as was done in ECD's OPST-Programme. The actuators, built by Liebherr-Aero-Technik (LAT), were designed as "smart" devices with optical interfaces for digital information transmission (Figure 6.6). The actuator servo loop closure, the in-flight monitoring, reconfiguration upon

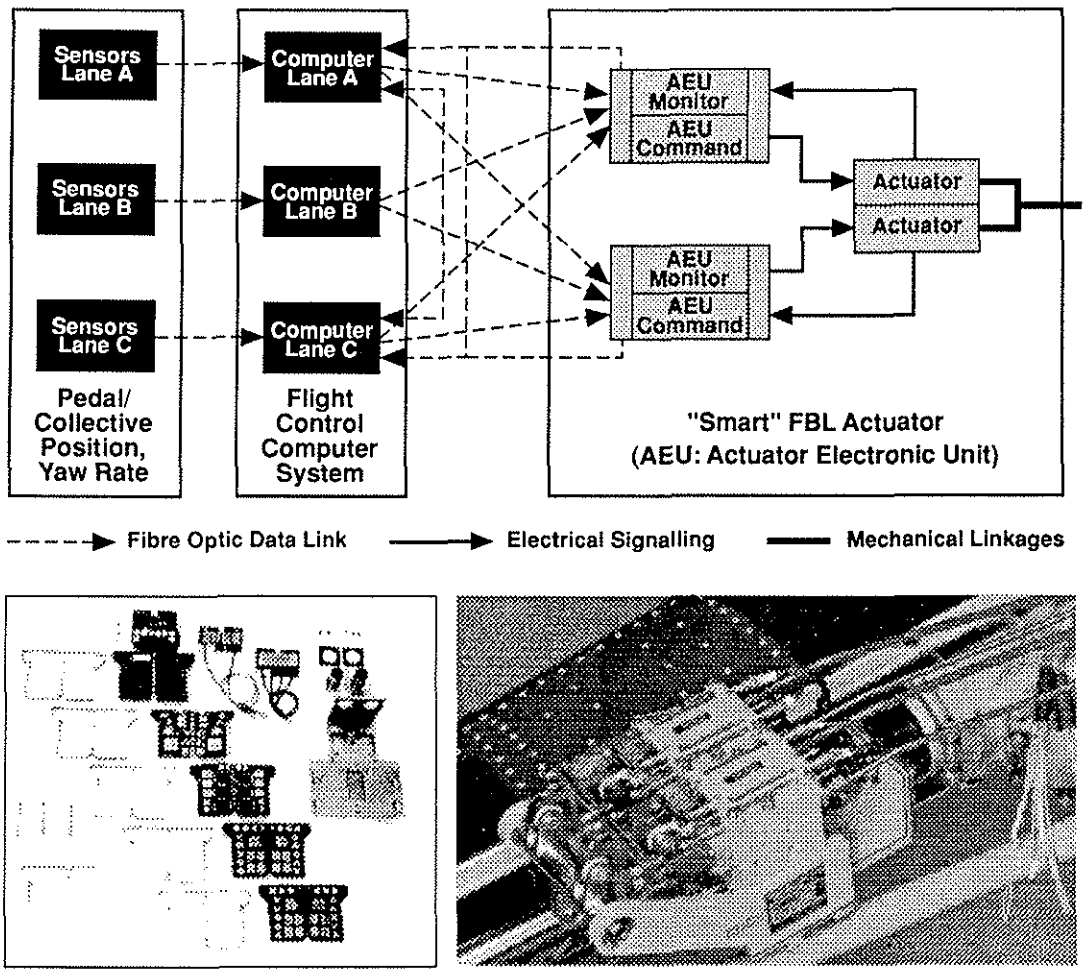



Figure 6.6: Structure of a "Smart" Yaw Actuator with Electro-Optical Interfaces

malfunction, and pre-flight build-in test equipment are contained in the actuator housing. Only the demand signals are received from and the status information is provided to the flight control computer. This concept leads to an essential reduction of adjusting and tuning requirements upon installation, and a reduction of maintenance efforts due to more precise failure location information. Due to the physical identity, the history of the actuator can be stored, failure information can be retrieved without relying on log card information (Reference 53).

### 6.3.3 Digital Micro-Electronic and Computing Technology

No doubt, one of the biggest technological advances which has aided the flight controls engineer is the rapid development which we have seen, particularly in the '80s, of micro-electronics. This has helped the engineer twofold: Firstly in pure performance (increases in processor speed, reduction in size, power consumption and cost) and secondly in application flexibility.

It was impossible, 10 years ago, to have predicted the current situation. However, if one analyses the electronic history since the early '60's when computers became a viable commercial proposition, there has been a steady performance factor increase of around 40 every 5 years (Table 6.I). In fact the developments in computing power and levels of integration are currently out pacing our ability to make use of them and where as in the '70's, the processing aspect was a factor limiting the complexity of flight control systems this is not so today. It is difficult to predict the component technology of the next 10 years hence, and even 3 years is a problem, but there is one certainty that component prices fall at around 100 % per year until they become a virtual negligible cost.

| | COMPUTER HARDWARE | | | MEMORY | |
|---|---|---|---|---|---|
| | Cost ECU/MIPS | Size $m^3$/MIPS | MTBF [hrs.] | Cost ECU/MByte | Size $m^3$/MByte |
| 1965 | 3.000.000 | 90 | 40 | 2.000.000 | 3 |
| 1975 | 80.000 | 0,9 | 800 | 100.000 | 0,009 |
| 1985 | 2.000 | 0,006 | 10.000 | 1.000 | 0,0002 |
| 1990 | 50 | 0,00002 | ? | 80 | 0,000002 |

Table 6.I: Trends of Cost and Performance of Computers

The cost and performance advantages are, however, not the whole story. Aviation flight control suffers the problem of relatively small production runs when compared with industrial computing. To take the advantage of the electronic compactness, customised chips need to be developed which can not be amortised at a reasonable cost. Until recently the answer was the customer definable ASIC, a device containing many standard logic components, which are fused only when delivery occurs. The penalty is, however, in getting the software specification right "first time" since each rework encounters non-recurring costs at the chip manufacturer. The flexibility of the recently developed Electrically Programmable Logic Devices (EPLD) technology (Table 6.II) is ideal for development work since the user can reconfigure the chip himself, as easily as changing EPROM software, virtually an unlimited number of times. The small additional component cost is easily offset by the development savings.

| | ASIC (Application Specific Integrated Circuit) | EPLD (Electrically Programmable Logic Device) |
|---|---|---|
| **Performance** | | |
| Logic Element Capacity | 6 000 -> 100 000 | ≅ 3 000 |
| Clock Frequency | > 100 Mhz | up to 90 Mhz |
| **Unit Cost** | | |
| Chip Development Cost (assuming 3x design loops) | 80 000 $ (Payable to subcontractor) | 300 $ (In-house material cost) |
| Recurring Cost | 300 $ (1 000 + quantities) | 500 $ (1 + quantities) |
| **Investment** | | |
| Design Tools Investment | 70 000 $ (Proprietary; Workstation Platform) | 10 000 $ (PC Platform) |
| **Design Restraints** | | |
| Pin Layout Compatibilities | Pin Position User Defined | Dependent on EPLD Type |
| **Redesign** | | |
| Turn-Around Time | 1 month | 1 hour |
| Rework Cost | 20 000 $ | 10 $ |

Table 6.II: Digital Micro-Electronic Technology

### 6.3.4 Control Signalling Technology ("wire or light"?)

As mentioned earlier, control signal transfer by wires has been around for a long time. The Fly-by-Light technology was taken up later: The Advanced Digital/Optical Control System (ADOCS) Demonstrator program began in 1980. It was conducted by the Boeing Vertol Company on a modified UH-60 A Black Hawk helicopter ("Light Hawk", Figure 6.7), under a US-Army contract. Distinct technology elements of the program included a complete fly-by-light system for communication between system elements, multi-axis side-stick controllers, and specific flight control law developments. The first "fly-by-light" manoeuvring was accomplished in 1985 (References 51, 52).

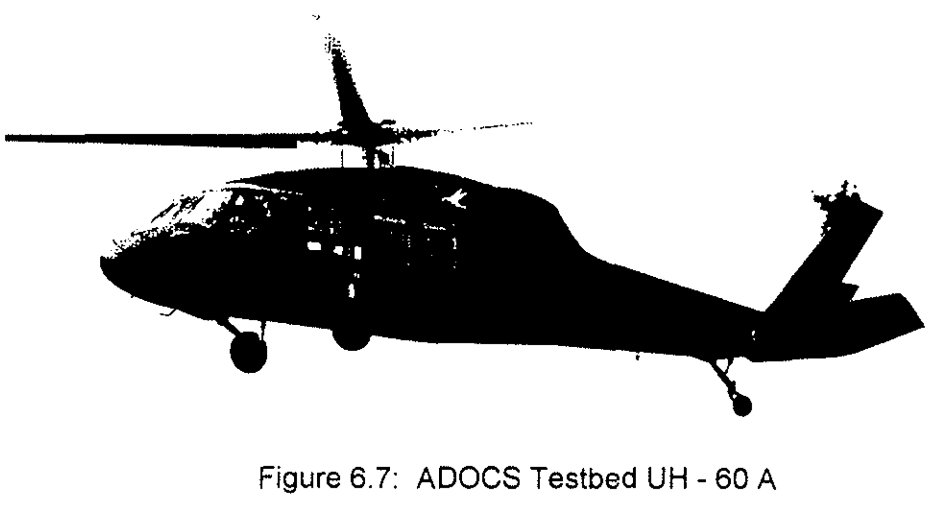


Figure 6.7: ADOCS Testbed UH - 60 A

In Germany, a Fly-by-Light technology program (OPST1) was started in 1986, in cooperation between Eurocopter Deutschland, LAT and DLR. The program included a digital, fault tolerant yaw axis control system on the FbL-basis installed on the FbW BO 105. The motivation was to investigate the technological advantages and cost effectiveness of this technology (References 53 to 55). First flight was in 1988 (Figure 6.8), the programme proved very successful, and provided highly valuable information about the case of applying FbL to helicopter flight controls.

Figure 6.8: BO 105 Digital Fly-by-Light Yaw Control System in Flight

Table 6.III compares wire and light transmission technologies with respect to 3 key parameters. There is, firstly, the data transfer rate, which is rather limited on an electrical system, leaving no growth potential in signalling for more sophisticated monitoring or synchronizing systems. Secondly, though not the single largest item in a FbW/L primary flight control system, the interconnecting signal lines do contribute a significant factor in weight. Studies into a 9 to-class helicopter indicate that around 30 percent could be saved off the interconnection cable mass of a FbW solution by applying FbL technology instead.

| Characteristic | FbW | FbL |
|---|---|---|
| Data Transfer Rate (effective) [MBit/s] | 1 - 2 | > 20 |
| Transmission Line Mass [gm/m] | 27 | 4 |
| Economic EMC/EMI Level [V/m] | ~200 | >>200 |

Table 6.III: Key Parameter Comparison

Finally, with the steady increase in the requirements for both radiation and susceptibility of electrical equipment to electromagnetic influences, the question of EMI/EMC gets a high priority. Military specifications have always been severe, and it is not surprising that the civil authorities revised their specification standards asking now for testing under much higher field strength values (average up to 600 V/m, peak values up to 6000 V/m, depending on frequency).

In the OPST-Programme, the FbL-control system was subjected to EMC testing (Figure 6.9) to evaluate EMI resistance, and to gain more experience in this area. As a result, for frequencies between 14 kHz to 2 GHz tested, no performance impact was noticed at field strengths in excess of 220 V/m. It could be demonstrated, that optical data transmission is completely EMI free and shielding and filtering are unnecessary (Reference 55). In the meantime, there is more than 600 flight hours practical FbL-experience on the BO 105-FbW/L (ATTHeS)-aircraft, without any hardware malfunction, see Figure 5.6.

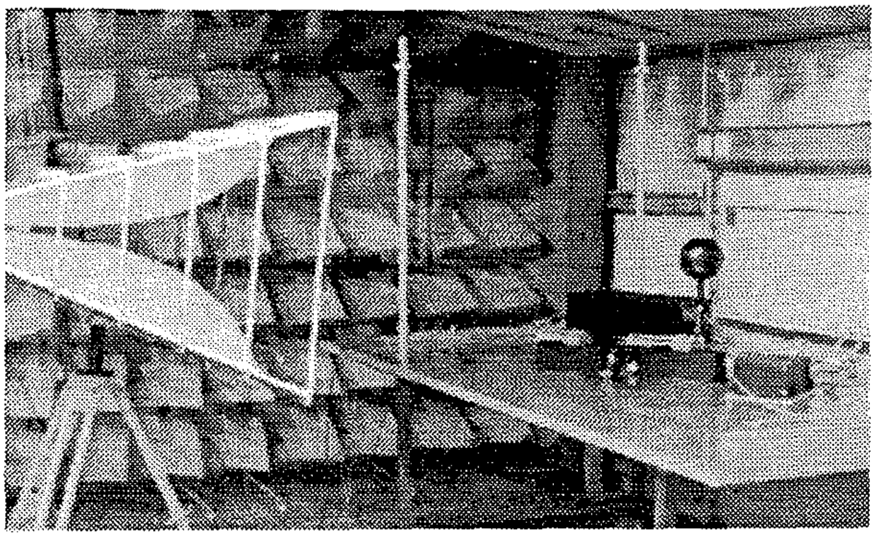


Figure 6.9: EMI Testing of FbL-System

### 6.3.5 The Smart System

Applying the smart principles to the sensors it becomes evident that a control system based on this smart hardware architecture does not only offer the prospect of improved flight safety but also will reduce the cost of maintenance and ownership. In the design phase such system provides the system engineer and the certification authorities with more transparent interfaces then today's centralized systems. Failure mode and affect analyses are more transparent since failure propagation from one subsystem to the other is restricted to very few signals. During manufacturing, the system harness is considerably simplified and do to the modular approach no harmonisation (rigging) is required. Automatic testing reduces both man hours and human errors.

Looking into the future there is an immense potential in this approach. Principally the sensors are not type specific as they can be used for many projects, the same applies to the sidestick controller and the flight control computer. The only elements specific to a project is the actuator which have to be physically sized to meet the force and velocity requirements and also the control laws to be loaded into the flight control computer. There is great potential for standardisation and with this, higher quantity production and again shorter development cycles. Technological advances can much easier be incorporated during the manufacture of smart subsystems at much lower cost then today.

## 6.4 Advanced Systems Payoffs

The benefits of the technology advances in flight controls as described before will have a considerable impact on future helicopters, particularly when considering the integrated effect in the design process and in the aircraft's on-board systems. A summary of these aspects is given in Table 6.IV, showing the payoffs of advanced digital FbW/L control systems over conventional mechanical systems in terms of safety, mission performance and life-cycle-costs.

Enhancements in safety are mainly due to increased redundancy of multiple signalling paths and data processing, with inherent EMI immunity when FbL-technology is used. Advanced control laws allow significant reduction in pilot workload, with main benefits in safety and system performance. Modularity of the design provides more transparent interfaces and easy fault location testing which leads to a reduction in costs. Finally, changes of software and electronic devices is much simpler than reconfiguring mechanical arrangements which gives a substantial flexibility in design.

| | | |
|---|---|---|
| EMI Immunity | when using FBL-Technology | |
| Increased Redundancy | due to multiple signalling paths | SAFETY |
| Reduced Pilot Workload | due to improved handling qualities | |
| Significant Weight Advantage | especially for military aircraft requiring ballistic damage tolerances | PERFORMANCE |
| Improved Maintainibility | due to modular design and increased fault location BIT | LIFE CYCLE COSTS |
| Design Flexibility of Control Functions | due to software changes instead of mechanical reconfigurations | |

Table 6.IV: Digital FbW/L Systems Payoffs Compared to Mechanical Systems

## 7. Aircraft Application and Developments

The current helicopter projects under development include a wide spectrum of technologies in their flight control system designs. The anglo-italian EH-101 helicopter and the franco-german TIGER / GERFAUT antitank / escort helicopter both apply systems based on mechanical controls. In addition, digital duplex flight control systems with limited authority (AFCS) are available, which provide - apart from basic stabilization and command augmentation functions (CSAS) - a variety of higher (autopilot) modes (References 56, 57).

On three other new helicopter developments (V-22, RAH-66 Comanche, NH-90) the flight control system is based on fly-by-wire technology: The V22 was forced to take this route due to the complexity of flight control associated with convertible rotorcraft.

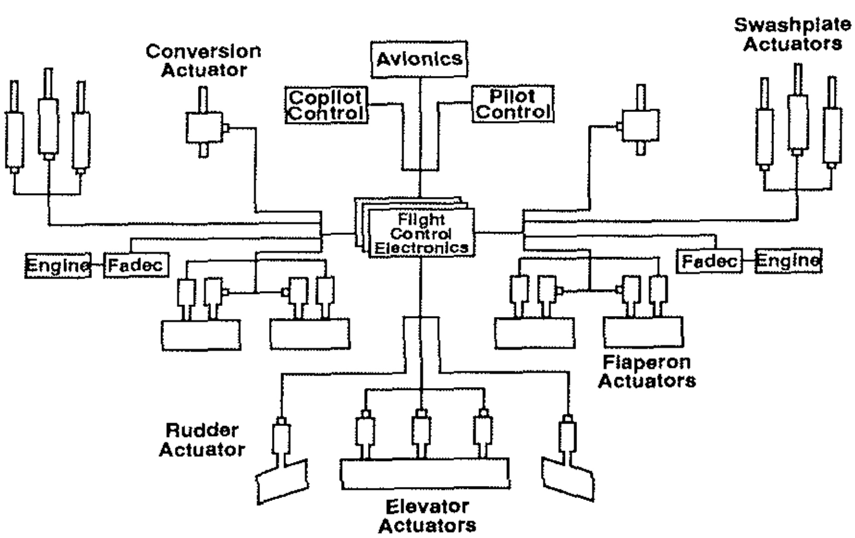



Figure 7.1: V-22 Flight Control System Installation

The experimental forerunner (XV-15) flight control system is a good illustration of this complexity. The V22 initial studies baselined a distributed, optically-signalled digital fly by light system. Due to the unavailability of advanced components at the time of the detailed design, studies showed that the distributed approach resulted in cost, reliability and installation penalties. A centralized configuration in triplex arrangement was therefore selected (Reference 58). Figure 7.1 shows the operational elements, which are integrated by the flight control electronics. This development was made possible due to the technology programs, such as ADOCS, and HLH, sponsored by the US Army over a period of 15 years.

The RAH-66 Comanche armed reconnaissance helicopter also applies fly-by-wire technology in its flight control system design, as the solution to a complex flight control task. The control system arrangement is shown in Figure 7.2. Here the high workload and need for very rapid and precise manoeuvring was the primary driver together with vulnerability considerations. The flight control system is partitioned into a primary flight control system (PFCS) and an automatic flight control system (AFCS). Control laws are based on explicit model - following structure. To achieve targeting effectiveness improvements, a functional integration of the flight control system with the fire control system was conducted which results in a very effective Integrated Fire Flight Control System (IFFC), Reference 59.

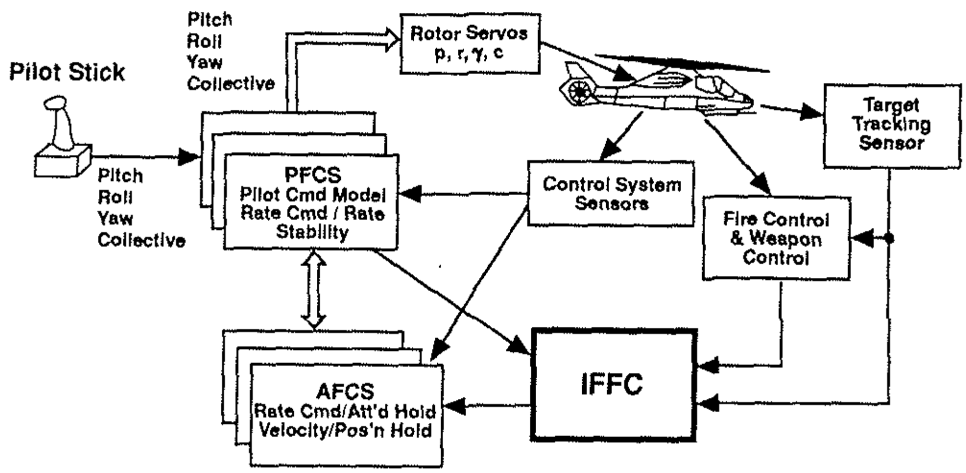



Figure 7.2: RAH-66 Comanche IFFC System Arrangement

In the common European 4-Nations Programme, the NH-90, the selection of the basic flight controls and augmentation system was based on the fulfilment of the relevant requirements. The driving factors, besides handling qualities improvement, was the clear demonstration of weight advantages for a FbW system over a mechanical system, when taking into account the severe vulnerability requirements (Figure 7.3). The system employs distributed quadruplex flight control computers (duplex for AFCS), distributed cable routing, duplex sensors and 2+1+1 axis side-stick controllers (Reference 60). This decision was based on the experience gained at ECD and ECF with this type of system on the BO 105 and Dauphin flying demonstrators. A FbL-System, technically the superior solution owing to its inherent EMC/LEMP immunity, was studied for the NH-90, but was not selected due to the (then defined) programme time scale and associated time risk.

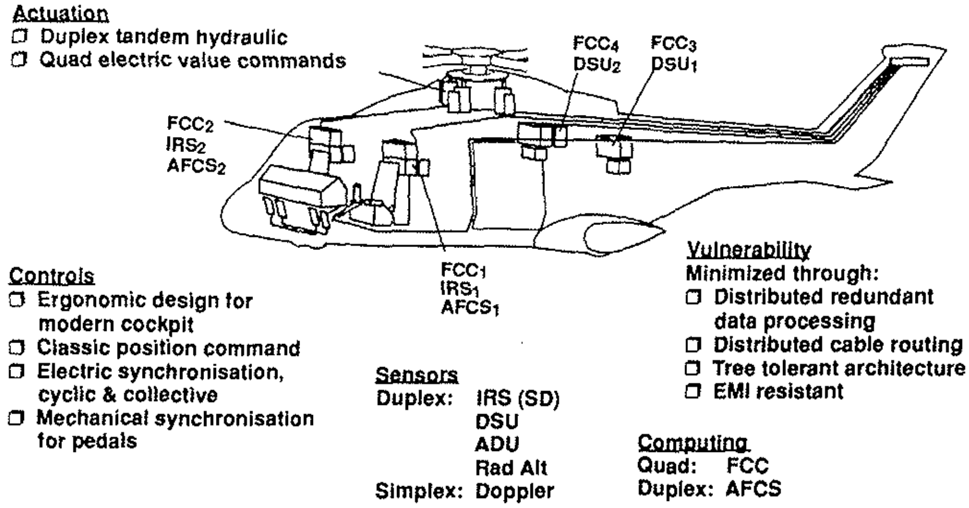



Figure 7.3: NH90 Flight Control System

## 8. Need for the Future

This short overview illustrates one important point: It takes 10 years and more of in flight experience to mature new flight control technologies to a point were they can be introduced into a project specifically when fixed price developments are contracted. This again means that in fast revolving technical areas like electronics and computing the hardware introduced into a production aircraft is well matured (if not to say of age) by that time. The only method to circumvent this dilemma is to use, with some lead-time to the development, flying testbeds for the promotion of such vital technologies.

In the US, the NASA-Ames research centre has just taken a big step in this direction with its new RASCAL (Rotorcraft / Aircrew Systems Concepts Airborne Laboratory) helicopter, Figure 8.1. Focusing on Comanche development, three main research programs crucial to developing effective nap-of-the-earth flight have been identified: SCAMP to develop advanced helicopter flight controls, NOE aimed at defining sensor-processing requirements and RAPID, which to combine these into a demonstration program. The goal is to integrate image processing interactive displays, global positioning system (GPS), ring laser gyros, propulsion transducers, rotor state and body state sensors, sidearm controller, color helmet-mounted displays and head trackers. All this will be tied together by a programmable fly-by-wire system (Reference 61).

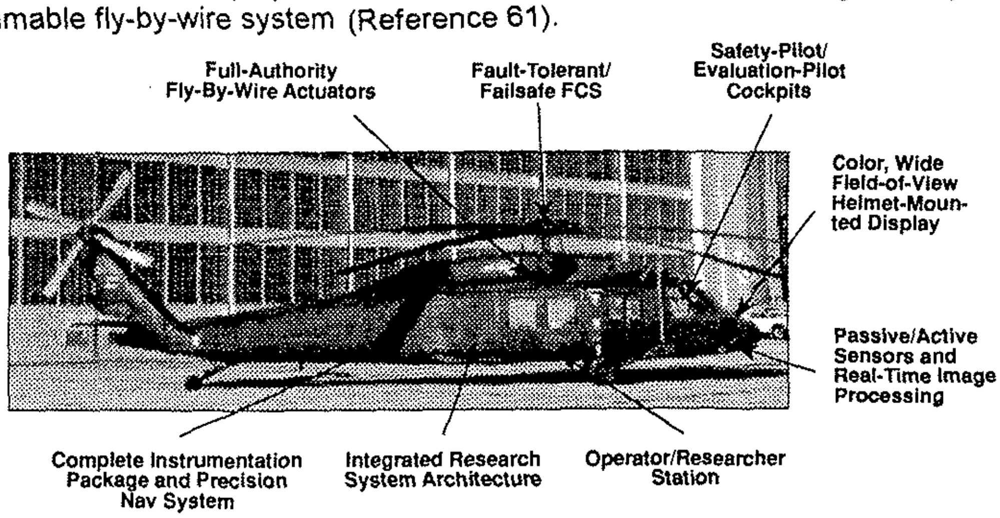



Figure 8.1: NASA RASCAL Research Aircraft

On the basis of the experience accumulated with the BO 105 FbW/L and FbW/Dauphin helicopters, DLR and Eurocopter intend to realize a new ACT Demonstrator and Flying Helicopter Simulator (FHS) (Reference 62). The utilization of modern technologies including a Fly-by-Light control system with variable redundancy levels, a proven smart actuator concept, and an integrated sensor unit, will result in a flexible and highly efficient test facility for technology development, for research purposes, for the support of future rotocraft development programs and for specific investigations for government agencies. Main application potential of the flight vehicle will include technology integration, demonstration and evaluation, demonstration of operational reliability, and development of criteria for qualification and certification purposes. DLR and Eurocopter are prepared to develop and operate this test facility (Figure 8.2) on the basis of a BK 117 helicopter, in order to promote the application of advanced technologies and extension of rotorcraft utilization. The broad range of different uses represents a particularly economic solution in terms of cost/benefit.

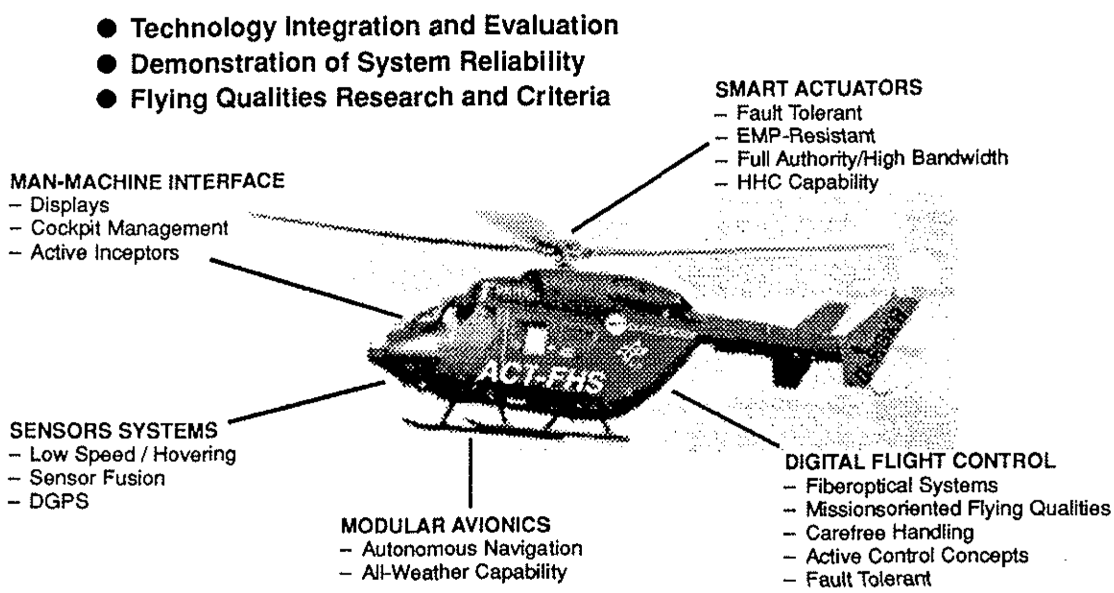



Figure 8.2: ACT Demonstrator / Flying Helicopter Simulator (FHS)

## 9. Conclusions and Recommendations

This paper reviews the current status of helicopter flight control including the handling qualities criteria, the flight mechanics models and analysis techniques, the flight control system design methods, the ground-based and airborne simulation facilities, and the technology development and implementation in actual rotorcraft development programs. The following conclusion can be drawn from the overview:

- The application of advanced flight control systems offers substantial improvements in safety, mission performance, and cost effectiveness for future helicopters.
- Advances in flight controls technology, evaluation criteria, mathematical modelling techniques, real-time-simulation, and flight control design methods allow for realization of operational systems providing substantial benefits, if the experience and the tools available are used adequately.

However, some critical issues should be raised concerning human limitations and aspects of affordability:

- What is the pilot's role in a highly augmented, partly automatic helicopter flight control system?
- Are there technical or training options available to increase pilot acceptance of helicopters with complex flight control systems, flying close to the ground and in adverse weather conditions?
- What are the minimum requirements for future helicopter flight control system? Are these helicopters affordable for military and civil operators?

The following recommendations are based on the experience available and reflect the lessons learned during relevant rotorcraft development and testing programs:

- Detailed, proven and credible, handling qualities criteria are indispensable as a design guide during the development of advanced flight control systems.
- High bandwidth mathematical models, carefully validated by flight test data, together with flexible, interactive computational tools are needed for design and analysis, regardless of the method of control system design.
- Ground-based and in-flight simulation play a dominant role and are becoming indispensable in the development and evaluation of modern integrated rotorcraft flight control systems.
- In spite of the progress made in the new flight control technologies, there are some remaining problems to be solved before they are fully matured and their risks are identified.
- In order to introduce advanced, enabling and fast processing technologies into a specific helicopter project, flying testbeds are needed for the early promotion, qualification, and demonstration of such technologies.

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