SEVENTEENTH EUROPEAN

ROTORCRAFT

FORUM

Berlin

September 1991

EXPERIMENTAL INVESTIGATION OF HELICOPTER COUPLED ROTOR/BODY CONTROL

by

P.R.Brinson

Paper

91 - 79

UNIVERSITY OF BRISTOL

DEPARTMENT OF AEROSPACE ENGINEERING

Bristol, England

EXPERIMENTAL INVESTIGATION OF HELICOPTER COUPLED ROTOR/BODY CONTROL

Abstract

This paper describes a programme of research which aims to contribute to a better understanding of the crucial issues associated with the design of full authority control systems for high bandwidth helicopter applications. The status of an existing experimental programme is described and the design of an experimental test facility is discussed in detail. Preliminary test results and rig calibration data are presented.

Introduction

Tremendous progress has been made in the application of Active Control Technology (ACT) to fixed wing aircraft and its introduction on the Airbus Industries A320 aircraft is indicative of the maturity that has now been achieved in the fixed wing field. Sadly, the same level of maturity is not apparent in rotary wing applications even though the potential benefits have been shown to be at least as great. There are many reasons for the lag in the technology exploitation on rotary wing programmes, and not all of these are technical, but one of the major contributory factors is known to be the lack of fidelity in the mathematical representations used for control system design. This problem has received a large measure of attention over the last decade and significant progress has been reported in the literature (Ref 1,2,3). Mathematical models have improved, especially in the high frequency region where model uncertainty is greatest, but in addition to this, new design and synthesis tools have emerged that are sympathetic to the uncertainty inherent in the helicopter control problem. However, in spite of this progress, an inevitable consequence of the uncertainty in the mathematical representation used for design, is conservatism in the final controller design. Of course, end users of agile combat helicopters are demanding all of the available rotor system bandwidth for high agility tasks such as nap-of-the-Earth and this is forcing the design engineer to move ever closer to the areas of greatest model uncertainty.

The debate regarding the level of modelling needed to capture relevant dynamics for helicopter ACT designs continues and it is believed that much remains to be done especially in the practical application of the technology.

Bristol University under funding from UK MOD have initiated a programme of research whose broad aim is to contribute to a better understanding of the fundamental issues associated with the design of helicopter flight control systems for full authority high bandwidth applications. It is believed that the crucial issues will only be properly understood when control system designs are tested in a realistic dynamic environment and to this end a model rotor dynamic rig complete with control and instrumentation system has been developed.

The main focus of the current work is an assessment of the likely benefits associated with the use of rotor dynamic state in primary flight control computations. Specifically, the project aims to identify the extent to which inner loop bandwidth may be increased if rotor dynamic state is included in the primary flight control calculations and to assess the sensitivity of any demonstrable improvements, to implementation factors such as actuation bandwidth, control system non-linearities, computational frame rate etc.

Results of a theoretical study based upon a full force non-linear nine-degree-of-freedom mathematical model (Ref 4) have shown that significant improvements to helicopter short period behaviour may be expected as a direct consequence of using rotor flapping states in the inner loop control law processing for a typical light battlefield helicopter. The predicted improvements have been derived from a model which incorporates three rotor degrees of freedom (two flapping plus coning) but this model is known to be deficient in its representation of rotor dynamics and in particular does not model rotor lagging freedoms.

A model rotor dynamic rig and associated control and instrumentation system has been designed in order to substantiate the results of the theoretical study. The experimental facility has freedoms in two body rotations, (pitch and roll) and has been designed to exhibit high frequency properties which are similar in terms of coupled rigid body fuselage/rotor dynamics to that of a typical agile light combat helicopter.

Research Programme Objectives and Timescale

The overall aims of the current research investigation have been stated above. The detailed objectives of the current phase of research are as follows:

> To develop a model rotor dynamic rig which will facilitate experimental investigations of coupled rotor/body behaviour for full authority/high bandwidth applications.
>
> To develop a mathematical model representing the two rigid body rotations and three rotor freedoms (flapping and coning only initially).
>
> To quantify any improvements to controlled response arising from the inclusion of rotor flapping dynamics in closed loop feedback algorithms and identify any shortfall between predicted closed loop performance and actual performance measured on the experimental rig.
>
> To determine the performance relationships between rotor/body dynamics and control system dynamics required for practical control system implementation.
>
> To examine the robustness properties of developed control algorithms and determine the sensitivity of the control system to changes in the dynamic system configuration.

Design, manufacture and integration of the experimental rig facility has been completed and the rig is currently undergoing commissioning trials. Some preliminary open and closed loop testing has taken place and the results of these tests are presented in a later section of this paper. The current funded programme is due to complete in the first quarter of 1993.

Experimental Facility

Detailed design requirements were established using the high level objectives listed above and the salient characteristics of the resulting design are described below. The general arrangement of the dynamic assembly is shown in Fig 1. The rig is currently being operated in a specially prepared laboratory area but will be moved to a wind tunnel once the integrity of the dynamic arrangement has been fully established. The rig is mounted on a test pedestal some eight feet above the ground.

Mechanical/Dynamic System

Rotor System The rotor system design is based upon an existing GRP rotor blade with Göttingen 436 section and 60mm chord. The four bladed single rotor diameter is 1.54m with an essentially rigid rotor hub. The rotor blades have constant spanwise section and zero twist. The rotor dynamic arrangement is located within a gimbal which provides free motion in pitch and roll. Maximum possible roll angle is approximately 50 degrees and maximum pitch angle is limited to approximately 70 degrees. The rotor is not free to yaw or translate.

Although the majority of the work will be carried out using the rigid hub arrangement described above, an alternative existing four bladed rotor which is articulated in flap will be used for comparative purposes.

Actuation System Actuation of the main rotor is provided through a conventional swashplate system with high performance brushless electrical rotary actuators producing the basic drive. The three swashplate actuators are coupled to the lower swashplate assembly using planetary roller screws and the combination of actuator and roller screw provide blade root slew rates in excess of 500 degrees/second. The actuation system has a theoretical small signal bandwidth in excess of twice the maximum rotor shaft design limit speed of 1800 rpm (30 Hz). The blade pitch control range is approximately 30 degrees and cyclic phasing is accomplished electronically.

Rotor Drive and Gimbal Arrangement The rotor drive is provided by a 10KW hydraulic vane pump servo motor. Hydraulic fluid is supplied to the motor via an electro-hydraulic servo valve using rotary hydraulic unions to interface with the moving gimbal platform.

A cable tensioned using a dead weight is attached (via a suitable rotating to non-rotating interface) to the main rotor hub to provide vertical stability during the rotor start-up phase. The dead weight is lifted, using an actuator, when a satisfactory trim has been established. In addition to providing a programmable limit on the platform attitude range, the dead weight and actuator have been used as part of a fail safe strategy which in the case of actuator or power failure will return the rig to the vertical state.

Control and Instrumentation System

The electronic sub system is assembled in a floor standing standard rack system which houses all of the control and instrumentation hardware in addition to the amplifiers and associated control electronics for the motor drives. A separate control console comprising a two axis stick for pitch/roll control and single axis stick for collective control is also provided.

Hardware Architecture The architecture of the control and instrumentation system is shown in Fig. 2. A commercially available single board computer based upon a 32 bit Motorola processor forms the heart of the data processing arrangement and this board is supported by a 40 Mbyte hard disk, floppy disk and runs a multitasking operating system. The board interfaces to two backplane bus systems which allows a wide choice of standard input output interface boards to be readily incorporated. The host processor is master to eight slave processors which undertake all of the rig real time control and instrumentation functions. The eight slave processors are based upon second generation Digital Signal Processing (DSP) devices and the DSP's each communicate with the host processor using a 1K word dual ported RAM. The combined processor throughput exceeds 90 MIPS. The boards containing the slave processors have all been purpose designed in-house.

Language tools for the DSP devices are not available for use with the chosen host system arrangement so a personal computer is interfaced to the host system using a 1 Megabit/second serial link. In addition to the language tools, the personal computer has a tape streamer which is used to archive run-time data.

Instrumentation Incremental shaft encoders have been used for all positional instrumentation. Swashplate data is available to an accuracy of 0.001 millimetres which corresponds to 0.0015 degrees at the blade root.

Pitch and roll attitude data are provided to an accuracy of 0.005 degrees and rotor azimuth/blade azimuth position is provided to an accuracy of approximately 0.04 degrees. The encoder mounted on the hydraulic motor main shaft is also used to calculate rotor speed.

Strain gauges are used to measure instantaneous blade bending which is processed to provide estimates of rotor flapping and coning angles. The strain gauge signals are passed through a twenty way slip ring assembly prior to being conditioned using an eight channel amplifier. A DSP board performs the real-time multiblade coordinate transformation to provide the required instantaneous rotor flapping signals.

Software The use of DSP processors which have very high throughput in numerically intensive applications has meant that it has been possible to code most of the real time software using the language "C", thus minimising software design/development times.

The chosen software configuration is totally asynchronous with separate free running clocks on each of the processor boards. The control loops implemented for the swashplate actuation system run at a frame rate of 500 microseconds whilst the frame rate for the pitch and roll controllers is 1.2 milliseconds. The operational software for the DSP boards is loaded by the host as part of the normal startup procedures.

Once the rig is operational the host processor is largely redundant but it does provide the operating executive and off-line development environment for the system. Additionally, the host processor manages a 4 Megabyte circular buffer into which all relevant run-time data is dumped for subsequent off-line analysis.

Monitoring and Built in Test A large proportion of the software development effort has been associated with the design of an active failure monitoring scheme. The requirement for a system capable of bringing the rig quickly to a safe state following malfunction/failure arises as a consequence of the bandwidth and control authority vested in the swashplate actuation arrangement. Although control authority is currently restricted to approximately +/- 4 degrees about a nominal collective setting of 10 degrees, it is anticipated that control authority will be increased to at least +/- 10 degrees for much of the dynamic testing. With this much authority, a hardover condition of 10 degrees cyclic can be reached in approximately 20 milliseconds with rather dramatic consequences.

Exhaustive dedicated self-test on all of the DSP processor boards is initiated on startup immediately after the program load phase is complete and a status report is issued to the user prior to enabling all of the motion control circuits. All of the boards contain on-line built in test algorithms comprising a suite of reasonableness tests on incoming and outgoing data. Watch-dog timers are also used on all of the DSP boards and these are monitored by the host processor.

In addition to on-line built-in-test algorithms in each of the processor boards, a separate board is used to monitor the behaviour of the rig system as a whole and this board can initiate a rapid orderly shut-down in the event that its monitoring algorithm detects conditions exceeding pre-specified limits.

Preliminary Test Results

All of the test data presented herein has been taken without any attempt to optimise the servo loops controlling the swashplate system or main rotor drive system. Indeed, current limits and servo loop gains have been set deliberately low to reduce the risk of accidental damage during the commissioning phase.

Data has been collected with the rotor in a simulated hover state with a rotor shaft speed of 1200 rpm and collective setting of 10 degrees geometric blade pitch measured at the blade root. The calculated rotor thrust for this condition is 225 N. Sinusoidal inputs of amplitude 3 degrees peak to peak were used for all of the open loop testing. During the active period, the gimbal platform is free to rotate unrestrained to approximately 10 degrees in both pitch and roll axes.

Open Loop Results

Open loop frequency response data for the above conditions are shown in Fig. 3 and selected time response waveforms are shown in Figs. 4 and 5 for pitch channel and roll channel excitation respectively. The data presented in Figs. 4 and 5 represent selected two second time slices of the pitch and roll channel responses. There is evidence of small amounts of once per revolution motion on the roll axis data and the drifts in attitude apparent in all of the traces are due to recirculation of the rotor wake.

Data repeatability across a large number of runs with identical starting conditions has been observed to be excellent and although insufficient data has been collected todate to allow sensible comparisons to be made with full scale, these early results are very encouraging and do clearly demonstrate operation of the facility as an integrated system.

A number of points regarding the data presented are worthy of brief discussion:

(i) Because of the lack of translational freedoms the low frequency behaviour will clearly not reproduce the low frequency properties of a fully dynamically free rotor.

(ii) The asymmetry apparent in the low frequency on-axis phase characteristics is almost certainly due to recirculation/ground effect. The current test site side wall (roll axis) clearance is less than one rotor diameter whereas the test site is effectively open at both ends.

(iii) The characteristic increase in off-axis response at approximately one third shaft speed due to the existence of the rotor flapping regressing mode can be clearly seen in the roll attitude response to longitudinal cyclic control.

Closed Loop Results

Very simple attitude demand/attitude hold controllers with proportional plus integral structure have been designed for both the roll and pitch channels using the open loop test data given above to guide the design. Step responses for the pitch and roll channels are given in Figs. 6 and 7 respectively. The step inputs were applied 10 milliseconds from time zero in both pitch and roll axes. It should be emphasised that these results have been taken very recently and no serious attempt has been made to optimise the control system gains.

The data presented in Figs. 6b and 7b have been derived from applying an inverse rotor phasing algorithm to actual swashplate position measurements obtained at the three swashplate actuation locations. The initial application of control can be seen to be very rapid with the first peak in cyclic actuator position occurring only a few milliseconds after the demand is applied. It should be noted that the excursions seen in collective do not result from intended changes but rather as a result of skew in the swashplate actuation computational frames.

Future Programme

The next major phase of the current programme involves the development and validation of a mathematical model of the rig dynamics. This will allow more sophisticated controllers with feedback loops closed on rotor dynamic state to be designed and evaluated which in turn will facilitate the testing required to complete the planned programme.

In addition to this, the University of Bristol is working with the UK Defence Research Agency, Westland Helicopters and other UK Universities and industrial organisations to define a new programme of research to evaluate a range of control system design methodologies. It is anticipated that the Bristol rig will be used as the host facility for controller evaluation.

Conclusions

High frequency dynamics associated with the rotor system, actuation system and computing system will place fundamental restrictions on the bandwidth of control for the next generation of highly augmented agile combat helicopter.

The stated aim of the programme described in this paper is to contribute to a better understanding of the issues associated with effective implementation of high bandwidth helicopter ACT systems. The results of this study are very encouraging and shown every sign that the stated aim will be met. Considerably more testing will be required especially in the forward/simulated forward flight regime where the effects of rotor dynamics are most pronounced before the scope of any such contribution can be assessed.

References

1. J.C.Doyle, Analysis of Feedback Systems with Structured Uncertainties, Proc. IEEE, part D, 129, pp 242-251, 1982.

2. A.Yue, I.Postlethwaite, G.D.Padfield, H^8 Design and the Improvement of Helicopter Handling Qualities, Thirteenth European Rotorcraft Forum, Paper No 7.2, Sept. 1987.

3. A.Simpson, The use of Stodola Modes in Rotor-Blade Aeroelastic Studies, Sixteenth European Rotorcraft Forum, Paper No 3.4, Sept 1990.

4. P.R.Brinson, Towards Higher Bandwidth in Helicopter Flight Control Systems, Royal Aeronautical Society Conference on Helicopter Handling Qualities and Control, Paper No 18, Nov. 1988.

Acknowledgements

This work is supported by the U.K. Defence Research Agency (Bedford) and their technical and financial support is gratefully acknowledged. The author would also like to acknowledge the contribution made by Bristol Polytechnic who initiated the research programme and undertook a significant proportion of the detailed design and manufacturing work. Thanks are also due to Keith Firks for his enthusiasm and attention to detail in the final phases of rig design and assembly.

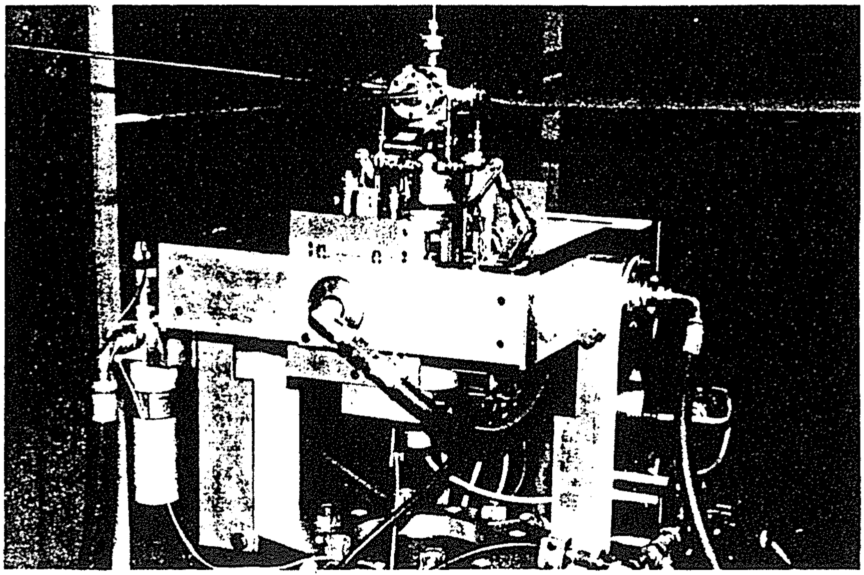

Fig. 1 Experimental Rotor Rig

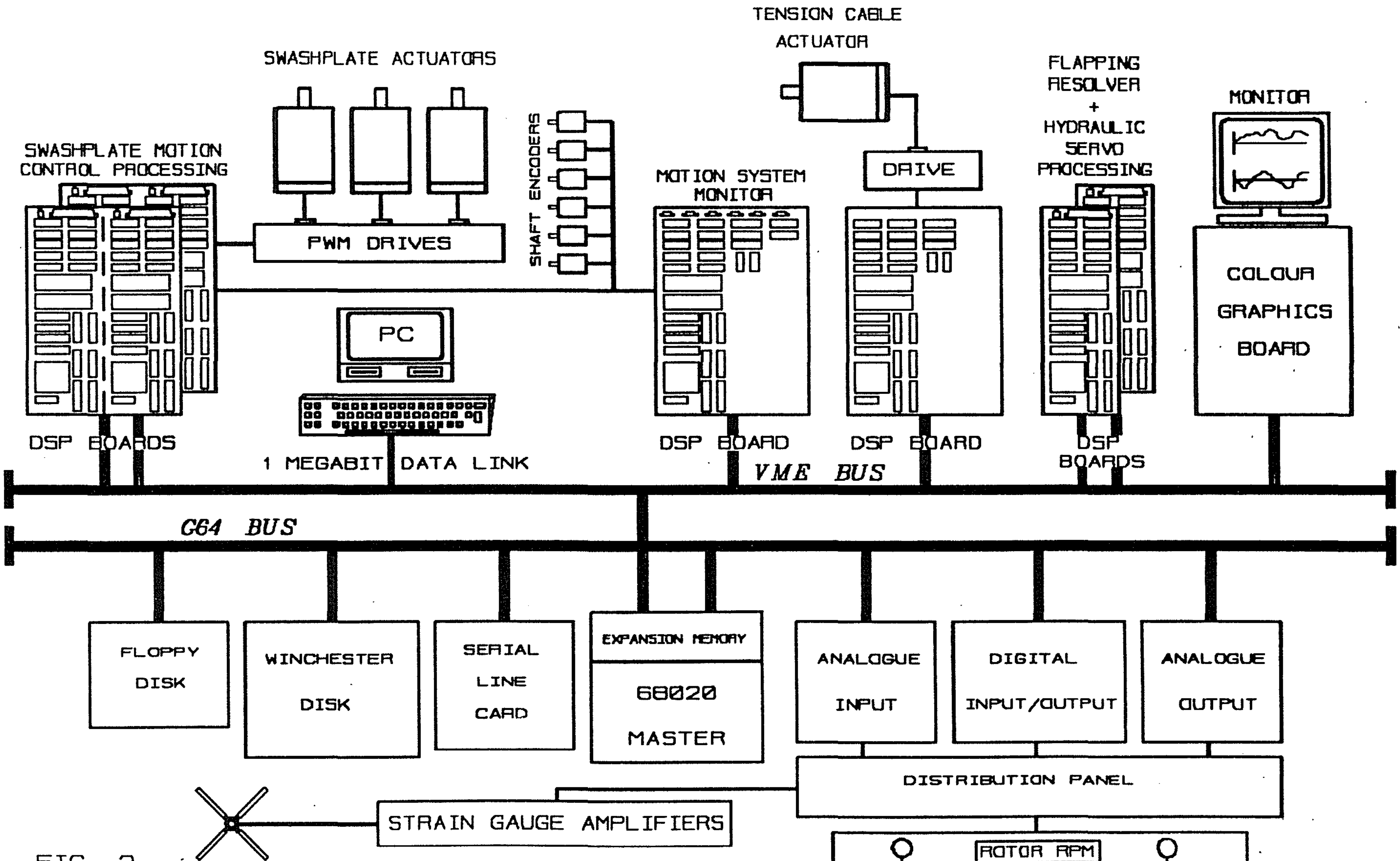

FIG. 2

ELECTRONIC HARDWARE CONFIGURATION

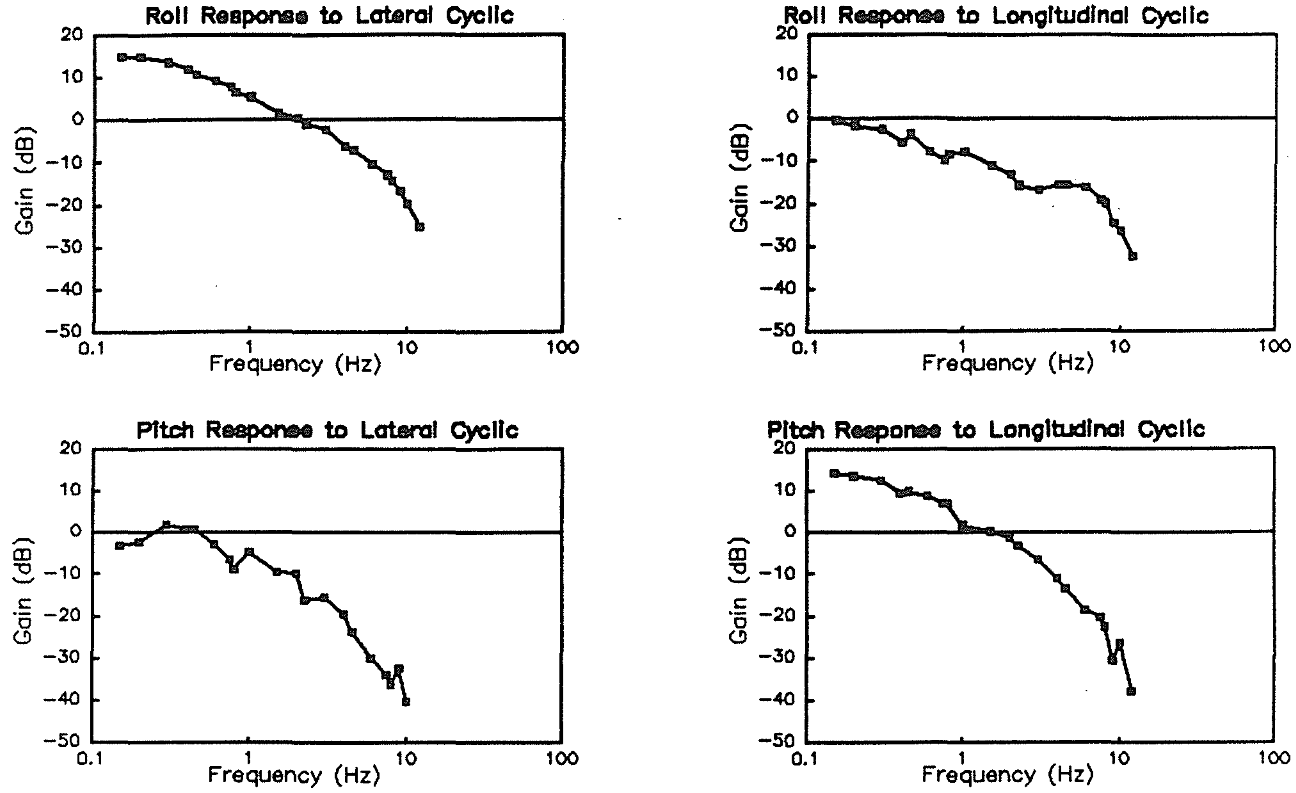

Fig. 3a Open Loop Frequency Response Magnitude Plots

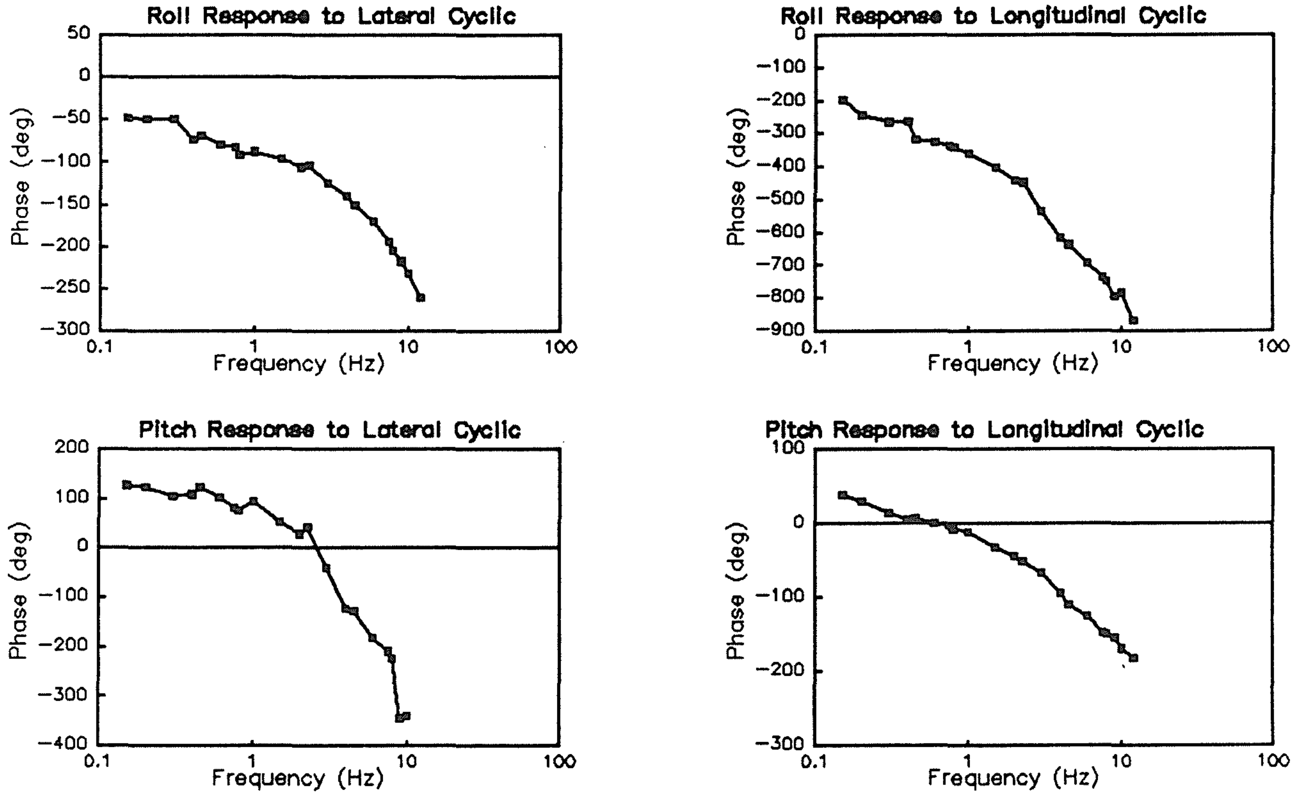

Fig. 3b Open Loop Frequency Response Phase Plots

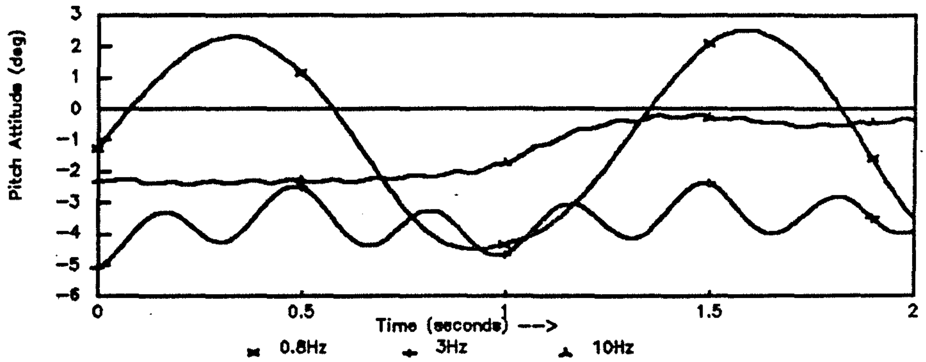

Fig. 4a Pitch Axis Open Loop Response

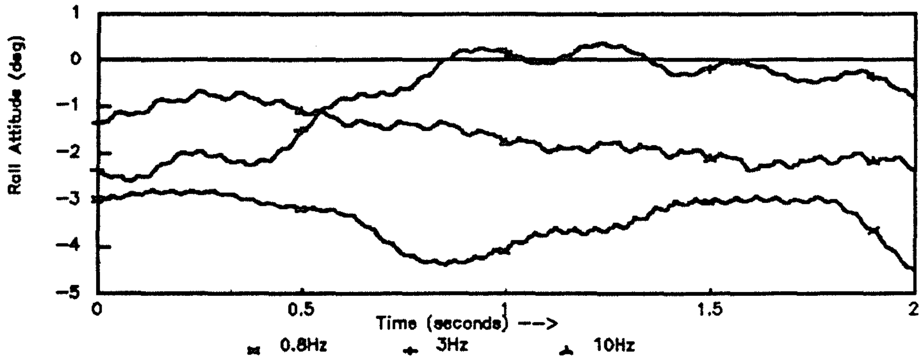

Fig. 4b Roll Response to Pitch Channel Excitation

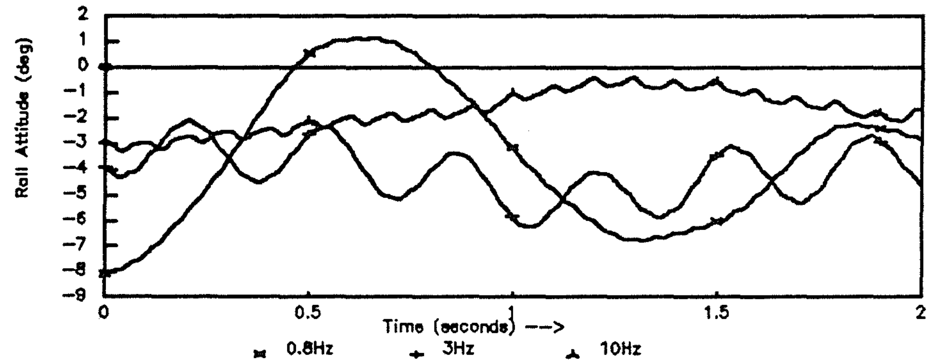

Fig. 5a Roll Axis Open Loop Response

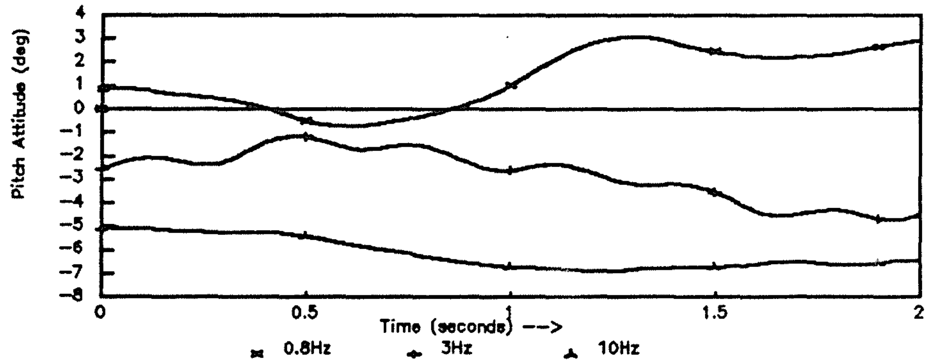

Fig. 5b Pitch Response to Roll Channel Excitation

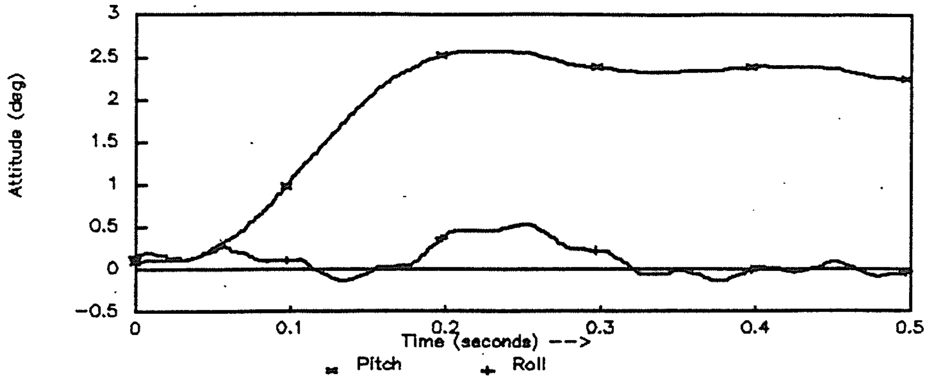

Fig. 6a Pitch Axis Step Response

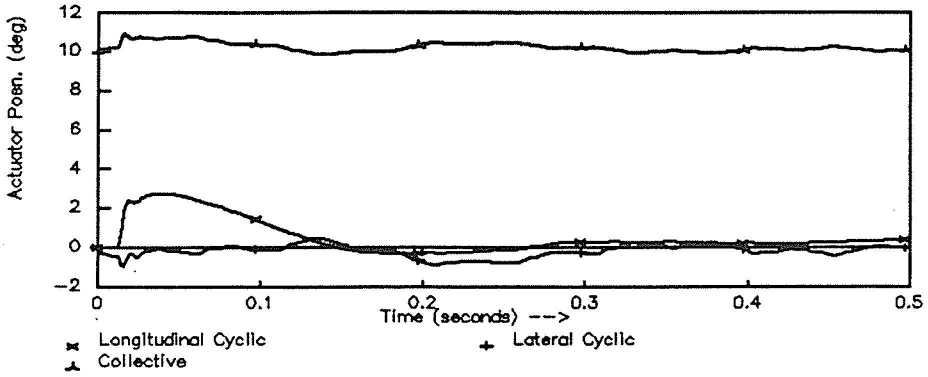

Fig. 6b Actuator Activity

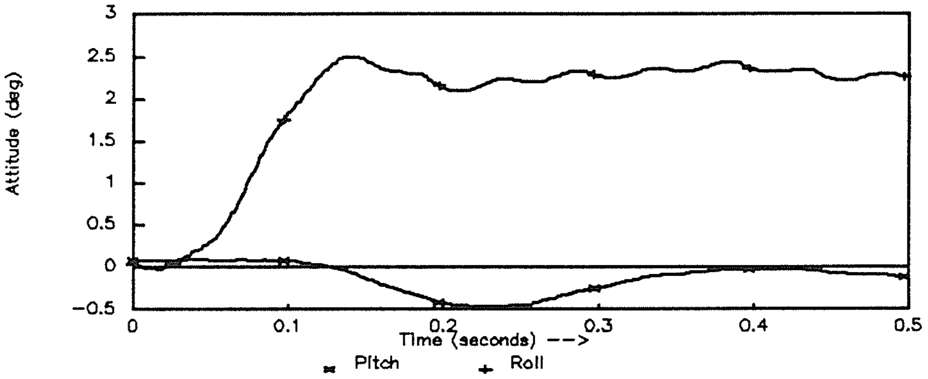

Fig. 7a Roll Axis Step Response

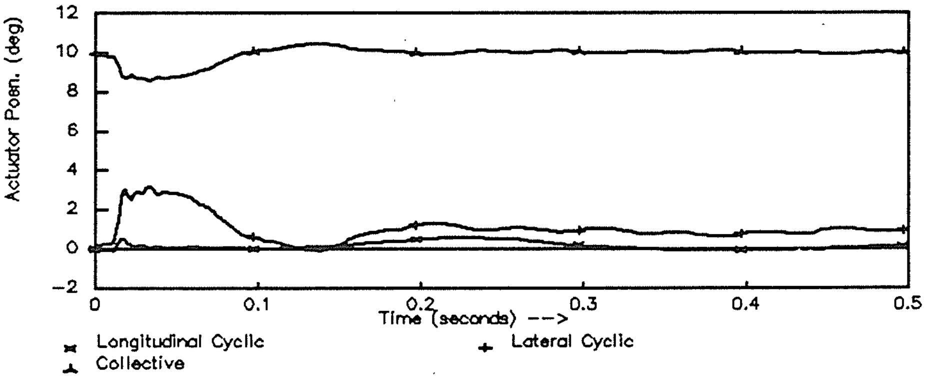

Fig. 7b Actuator Activity

Printed by the University of Bristol Printing Unit