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EXPERIMENTAL INVESTIGATION OF CONTROL SYSTEM DESIGN METHODS FOR HELICOPTERS

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Abstract

Preliminary results of an experimental study which aims to evaluate a range of alternative control system design techniques for helicopters are presented. A 1.5m diameter, hingless model rotor dynamic rig is used to explore the performance and robustness of a range of body feedback control schemes. Classical, "one-loop-at-a-time" single input single output design methods are compared with a design based upon a classical multivariable method and one H^∞ method. Attitude demand, attitude hold control laws which have been designed for the hover case are evaluated and a preliminary assessment of robustness is made by testing the controllers off-design-point.

1 Introduction

The application of full-authority Active Control Technology to helicopters is lagging noticeably behind the technology exploitation on fixed wing programmes. Many alternative approaches to the design of full-authority helicopter flight control systems have been proposed, but real experience with implementation is scarce, despite the fact that numerous studies have shown that the potential benefits are highly significant. Previous designs have mainly been evaluated against mathematical models with known deficiencies in the region of the rotor dynamic response. A number of designs have progressed to piloted simulation but very few systems exist that have been subjected to rigorous experimental testing. This presents a real problem for the relatively few individuals in industry charged with the responsibility of designing control systems for the next generation of helicopters, since it is unreasonable to expect them to have expertise in all of the available techniques.

For a number of years, the University of Bristol, with support from the Defence Research Agency, Bedford have been developing an experimental rotor dynamic rig. The principal aim of this development has been to provide a facility which enables full-authority control system designs to be tested in a representative dynamic environment. The current research programme is being undertaken jointly by the UK Defence Research Agency, Westland Helicopters Ltd, and Bristol University and is funded via a LINK collaborative research programme with UK Department of Trade and Industry support. One of the major aims of this work is to bridge the confidence gap between theoretical development and final implementation by undertaking wind tunnel tests on a number of alternative control system designs. This paper describes the initial results of the first phase of this research, which has involved the design and evaluation of three alternative hover control system designs.

2 Experimental Rotor Rig

A comprehensive description of the rotor dynamic test facility is given by Brinson [Ref. 1] and is briefly summarised below. The research was carried out using a four bladed 1.5m diameter rotor with rigid hub and Gottingen 436 section, 60mm chord GRP rotor blades. All tests were conducted in the return section of the University large wind tunnel. The rotor operating condition for all tests was 1200 RPM, giving a tip speed of 93m/s. The datum collective setting was 11 degrees root pitch which corresponds to a rotor thrust of approximately 50lbs. A unique feature of the rotor rig is its high performance actuation system. This comprises brushless electric motors connected to a conventional swashplate arrangement, providing blade pitch slew rates in excess of 800 degrees/second at the blade root and a small signal bandwidth of well over 50 Hz. The control of the rig is fully computerized and the system contains extensive built in safety monitoring software. The complete rotor system is gimballed to provide pitch and roll freedoms up to approximately 40 degrees. The rig is not free to yaw or translate. Incremental shaft encoders provide accurate measurements of actuator positions, rotor blade azimuth position and pitch and roll attitude. The general arrangement of the dynamic assembly is shown in Fig. 1.

The rotor rig has been designed such that the ratio of hub moment produced per unit flapping, to rigid body inertia, is typical of an agile combat helicopter. This feature of the rig design ensures that the fundamental character of coupled rotor body behaviour for helicopters with high bandwidth rotors is reproduced by the dynamic rig.

The dynamic rig is under the control of a cluster of ten embedded computers. The real time software has all been developed in-house and provides a very flexible system which can be rapidly reconfigured to run a variety of test cases. Parameters such as rotor speed, control system phasing, actuation performance and authority and control law frame time can all be varied.

3 Mathematical Model

The mathematical description of the rotor rig is based upon an existing generic helicopter model developed by the DRA for helicopter flight mechanics research [Ref. 2]. Rotor, control system and rigid body data for the experimental rotor rig have been inserted into this model and the yaw and translational degrees of freedoms have been removed. The model contains a six state rotor model and first order actuator models. Thirteen state linear models are extracted from the non-linear model for the purpose of control system design. All of the results presented in this paper are for controllers designed for the hover.

4 Comparison of Analytical and Experimental Data

The open loop analytical and experimental frequency response data are given in Fig. 2. It can be seen that the on-axis response shapes are predicted reasonably well by the analytical model, especially in the vicinity of the gain crossover frequency. The gain deficit observed at low frequency is largely due to physical limits imposed upon the pitch and roll motion of the rotor rig during open-loop testing.

The off-axis response is less well captured by the analytical model and this is also a common and well recognised weakness of full scale helicopter models. The uncertain dynamics associated with the rotor model present a real challenge to designers of high performance high authority helicopter control systems and the lack of fidelity demonstrated in the rig dynamic model ensures that the control problem is representative.

5 Design Philosophy & Requirements

5.1 Controller Design Requirements

An attitude demand/attitude hold control scheme was specified and hence pitch attitude and roll attitude were the specified control variables. Performance requirements which reflect the rig scaling were chosen such that coupled rotor body modes and hence uncertain dynamics are excited. Accordingly, the cross-over frequencies of the open loop compensated system were chosen to be 16 rad/sec and 12 rad/sec in the roll and pitch axes respectively. The damping of the attitude responses was specified to be greater than 0.7 and off-axis coupling was to be minimised.

5.2 Controller Design Philosophy

5.2.1 SISO Controller

Westland Helicopters, under an Active Control Technology (ACT) programme has developed a series of controllers including rate command, attitude command and translational rate command. The attitude command control law designed for the Bristol rotor rig was based upon the ACT structure[Ref. 3].

The control system consists of individual pitch and roll attitude controllers, the two being connected by a matrix which converts the attitude information to body axis rate information. A decoupling matrix attempts to decouple the pitch and roll attitude responses. The controller includes a pair of forward loop filters surrounded by an inner rate feedback loop and an outer attitude feedback loop.

A single input single output (SISO) design approach was used, individually trimming gains and filters to achieve the desired responses.

For the purposes of the initial tests presented in this paper, the decoupling matrix elements are set to zero. The general controller structure is illustrated in Figure 3(a).

5.2.2 Classical Multivariable Controller

The Bristol University classical multivariable controller was designed using the pseudo-decoupling approach [Ref 4] of Ford and Daly.

A compensator of a specified order (controlled by the designer) is produced which attempts to minimise system cross couplings. The algorithm used [Ref 5] produces numerator terms only and hence the designer must insert the required number of poles to make the compensator realisable.

For simplicity of implementation, a first order non-diagonal structure was selected and a single pole was inserted to make the compensator realisable. The position of the pole was chosen in order to allow the numerator elements to act over the frequency range of interest whilst having due regard of the need to constrain high frequency gain.

Diagonal proportional plus integral (P+I) controllers were included to improve the low frequency properties of the system. The general compensator structure is shown in Fig. 3(b).

5.2.3 Classical Multivariable Plus H^∞ Controller

The Bristol University combined classical multivariable plus H^∞ controller uses the normalised coprime factor approach of Glover and McFarlane [Ref 6] to produce an H^∞ compensator which attempts to robustly stabilise the open loop system.

The application of this method to VSTOL aircraft control is detailed in references 7 and 8 and an example of the application to the helicopter can be found in reference 9. The approach proposed here differs very slightly in that pre compensation is achieved using the classical multivariable approach described above before constructing an H^∞ filter to robustly stabilise the whole system.

Such an approach is particularly well suited to the helicopter problem because of the rapid changes in control cross coupling which occur in the intermediate frequency region due to the rotor dynamic response. These dynamics are uncertain but the fundamental character of the coupling is understood and can be used to improve the loop shapes before submitting them to the H^∞ optimisation procedure. In the hands of a skilful designer, this can lead to an H^∞ filter which exhibits less rapid changes in gain and phase. It can also help the designer to retain greater physical insight into the overall control system behaviour.

A sub-optimal H^∞ controller is chosen because of its superior high frequency properties [Ref. 9]. The general controller structure is as shown in Figure 3(c).

For the purposes of the initial study, the H^∞ controller was placed in the forward path. Since the H^∞ compensator is designed for robustness, and not for time domain performance, significant overshoots in the command response are to be expected [Ref. 7]. Project constraints have so far prevented any comparison tests with the filter in the feedback path.

6 Preliminary Results

Closed loop frequency response and step response tests were used to evaluate the three controllers. For reasons of expediency, frequency response tests were conducted at twelve discrete frequencies in the range 0.5 Hz to 12 Hz. The input demand size for the frequency response testing was approximately four degrees peak-to-peak in both axes. The input demand size for the closed loop step response testing was approximately 7 degrees peak-to-peak in all cases. Repeatability of the test data was found to be excellent.

6.1 Results On Design Point

The closed loop frequency responses for all three control schemes are overplotted in Fig 4. Fig. 4(a) shows the results predicted by the analytical model and Fig 4(b) shows the measured closed loop frequency responses. It is apparent from Fig 4(a) that the rapid increase in off-axis response close to the desired crossover frequencies present an interesting design challenge.

The H^∞ scheme produces the best on design point closed loop response shape (Fig. $4_{(a)}$). Only marginal differences exist between the classical multivariable design and the SISO design. This is largely to be expected since the coupled rotor body modes are not significantly affected by rigid body and first rate of change of rigid body data. The analytical model predicts the H^∞ scheme to provide better suppression of the coupled rigid body/rotor modes and better off-axis performance than both of the other controllers. Again, this is to be expected since the loop shape of the H^∞ filter reveals more aggressive changes in gain and phase in the vicinity of the coupled rotor body mode than that provided by both the SISO and classical multivariable schemes.

In the measured responses shown in Fig. 4(b), the H^∞ controller can be seen to retain more of its off-axis performance. Interestingly, the off-axis roll coupling which is the most troublesome due to higher pitch rigid body inertia is improved in the intermediate frequency region at the expense of higher levels of cross coupling in the low frequency region. All three controllers exhibit less damping than that predicted by the model and the H^∞ controller stimulates a coupled rotor body mode in roll (see Fig. $4_{(b)}$). The degradation in damping apparent in the frequency response data is confirmed in Fig. 5 which shows the on-axis and off-axis responses to step inputs in pitch and roll. Overall, it can be seen that at the design point closed loop performance improves with controller complexity although as expected the increment in improvement obtained by the classical multivariable scheme is somewhat marginal.

Throughout all of the testing, instantaneous blade flapping was recorded but because of intermittent problems with the rotor instrumentation, these data are not presented. Interestingly, the H^∞ controller achieves better suppression of cross coupling with substantially less rotor flapping and substantially less actuator activity than both of the other controllers. In fact, both the SISO and classical multivariable controllers penetrate a six degree cyclic pitch software authority limit in the intermediate frequency region of the closed loop frequency sweep in both axes.

6.2 Results Off Design Point

Figures 6 - 8 show the performance of all three control schemes as advance ratio is increased. Wind tunnel testing was restricted to 8m/s maximum which represented an advance ratio of approximately 0.09.

A deterioration in the roll on-axis and off-axis response can be seen at 8m/s for the SISO scheme and both SISO off-axis frequency responses reach 0dB in the vicinity of 4Hz. The classical multivariable off-axis roll response degrades immediately away from the design point and the H^∞ controller degrades progressively as the tunnel speed is increased. Overall, the H^∞ controller out performs the other two controllers and provides superior decoupling of the more troublesome roll off-axis response.

Interestingly, the lightly damped mode apparent on design point in the experimental data in roll, improves its character as the H^∞ controller moves off design point. In contrast, the SISO controller stimulates a coupled rotor body mode as the controller moves off design point.

Figure 9 shows on-axis and off-axis step responses for the case of a forty percent increase in pitch inertia with zero tunnel velocity. Once again, the H^∞ controller produces the best overall response shape. Testing of this case was restricted because of time limitations and it is less easy to make absolute judgements of controller performance.

7 Implementation Issues

Issues relating to practical implementation of the control laws were also considered. All of the control laws tested were implemented using an embedded fourth generation floating point Digital Signal Processor. All software was written in the high level language C and the software development environment included a C source level debugger which considerably eased software verification.

All of the designs were created using continuous domain methods and subsequently discretised using a trapezoidal integration scheme. An automatic code generator was not used to target the control law filters. The thirteen state H^∞ filter executed in just over 400 micro-seconds allowing a frame time of 1 milli-second to be used with ample spare capacity in the frame. No serious problems were experienced when targeting the control law for real time execution.

The implementation of SISO and Classical Multivariable control law filters was considerably simpler than for the H^∞ filter.

8 Conclusions

A control system problem which is representative of the challenge of the helicopter problem has been studied and three control system solutions have been evaluated.

The results show, that overall, the H^∞ based control scheme provides the best on-design point and off-design point performance. It should be borne in mind however that the results presented here are preliminary and represent only the first iteration of control law design. Further refinement and testing of all three existing control schemes is planned and an eigenstructure assignment based control scheme is also being developed.

The classical multivariable control scheme offered little real benefit over the SISO scheme and the small improvement in off-axis roll observed on the design point disappeared as soon as the controller was moved off design point. The H^∞ based controller degraded progressively as it was moved off design point.

The classical multivariable and SISO controllers required considerably more actuator authority than the H^∞ based design and caused excessive cyclic rotor flapping in the intermediate frequency region.

Implementation and verification of the chosen control schemes presented no real technical difficulties and computational requirements fall well within the capability of current generation microprocessor systems.

References

1 P.R. Brinson 1991
Experimental Investigation of Coupled Helicopter Rotor/Body Control
17th European Rotorcraft Forum

2 G.D.Padfield. 1981
A Theoretical Model of Helicopter Flight Mechanics for Application to Piloted Simulation
TR 81048 DRA Bedford

3 M.T. Charlton, C. Guyomard, R. Lane et al 1993
European ACT Programme - A Collaborative Approach to Handling Qualities and Control Law Design.
49th AHS Forum, St. Louis

4 J.M. Maciejowski 1989
Multivariable Feedback Design Addison Wesley Publishing Company

5 M.P. Ford , J.M. Maciejowski & J.M. Boyle 1990
Multivariable Frequency Domain Toolbox User's Guide
Cambridge Control Ltd.

6 K. Glover & D. McFarlane 1989
Robust Stabilization of Normalized Coprime Factor Plant Descriptions with H∞ - Bounded Uncertainty
IEEE Trans. AC-34(8), 821-830

7 R.A. Hyde 1991
The Application of Robust Control to VSTOL Aircraft
Phd Thesis University of Cambridge

8 R.A. Hyde , K. Glover & G.T. Shanks 1995
VSTOL First Flight of an H∞ Control Law
IEE Computing & Control Engineering Journal

9 I. Postlethwaite & D. Walker
Full Authority Active Control System Design For A High Performance Helicopter
19th European Rotorcraft Forum

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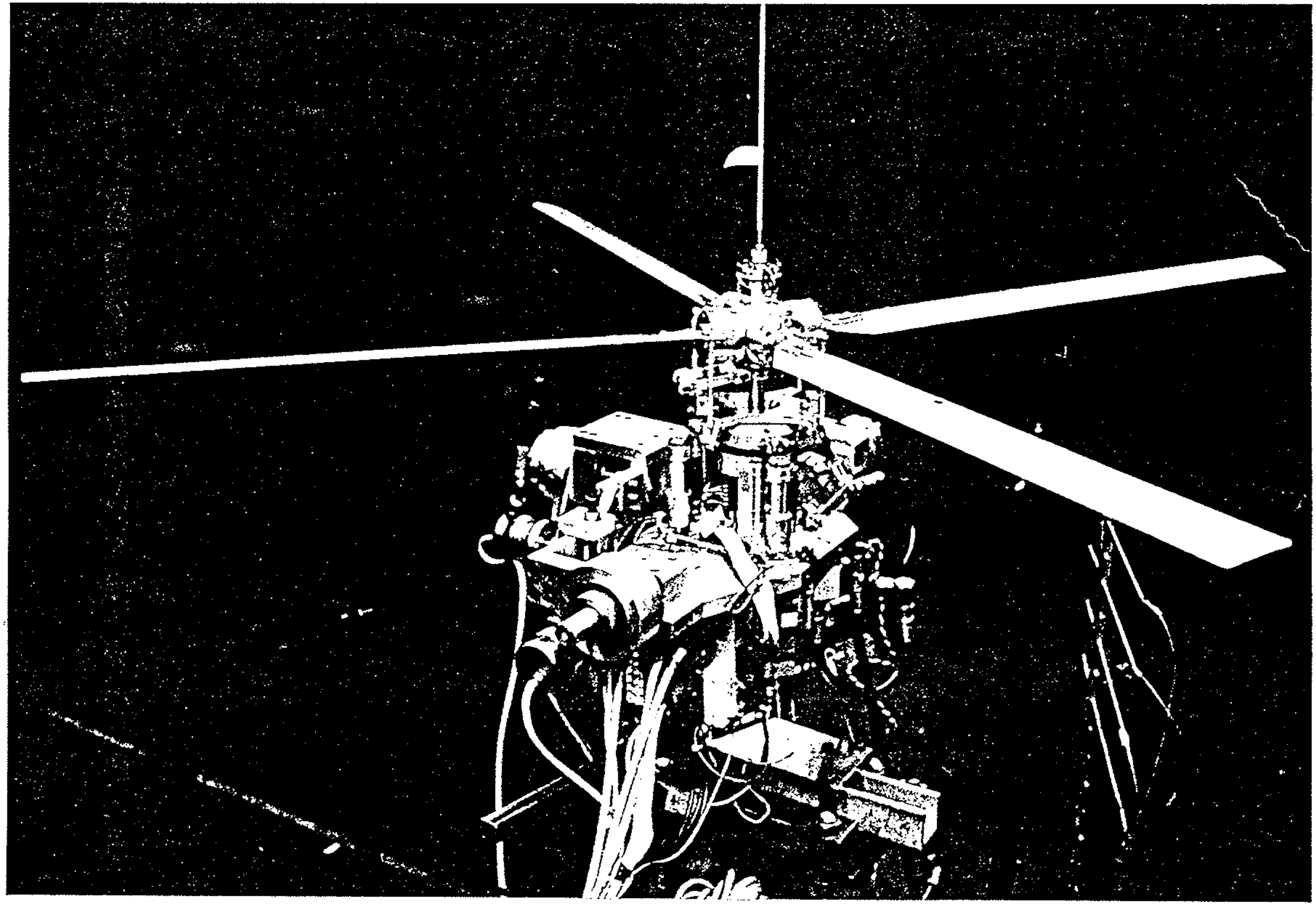


Fig 1 Dynamic Helicopter Research Rig

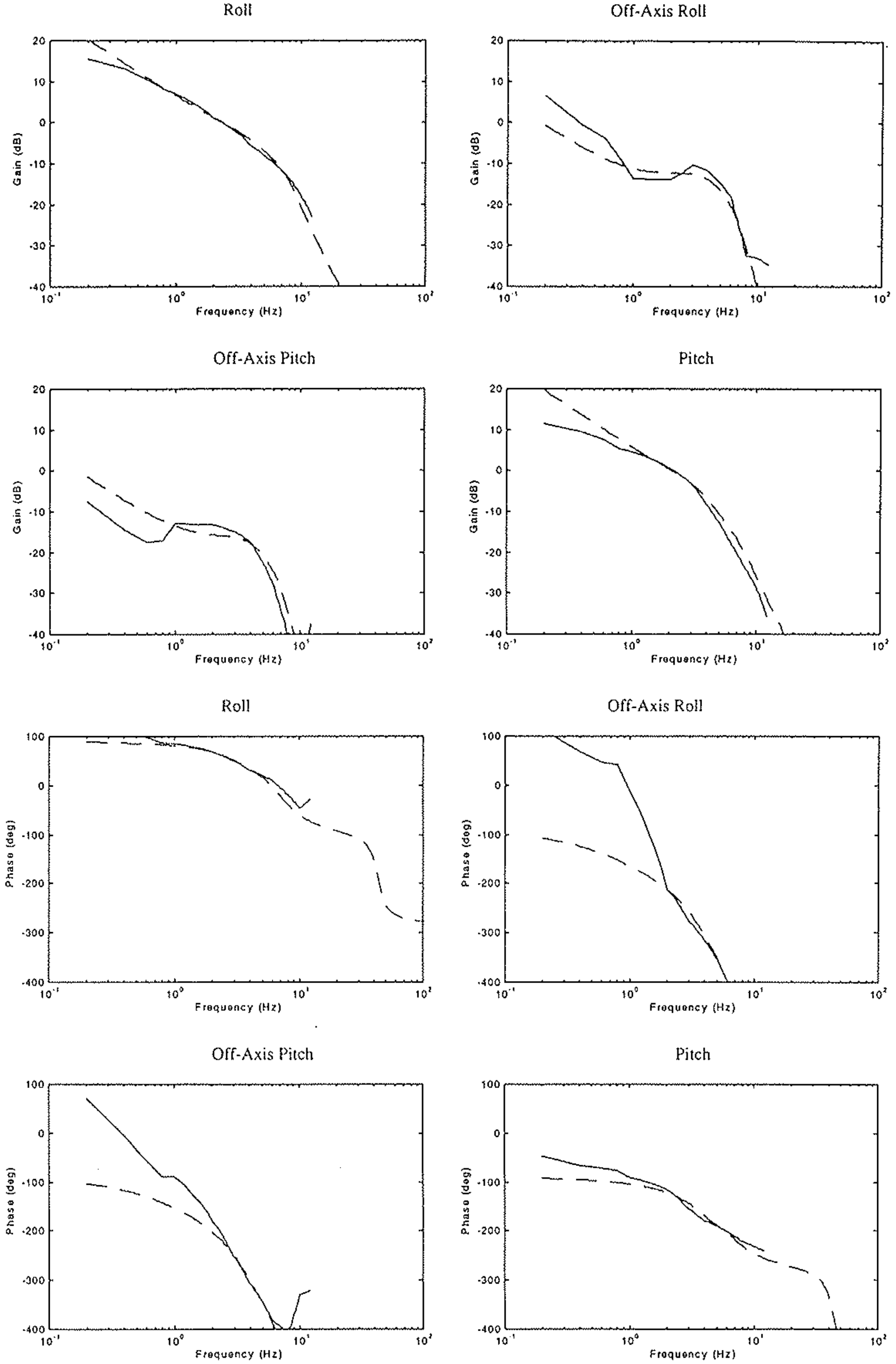


Fig. 2 Analytical and Experimental Frequency Response Data

-- Analytical , - Experimental

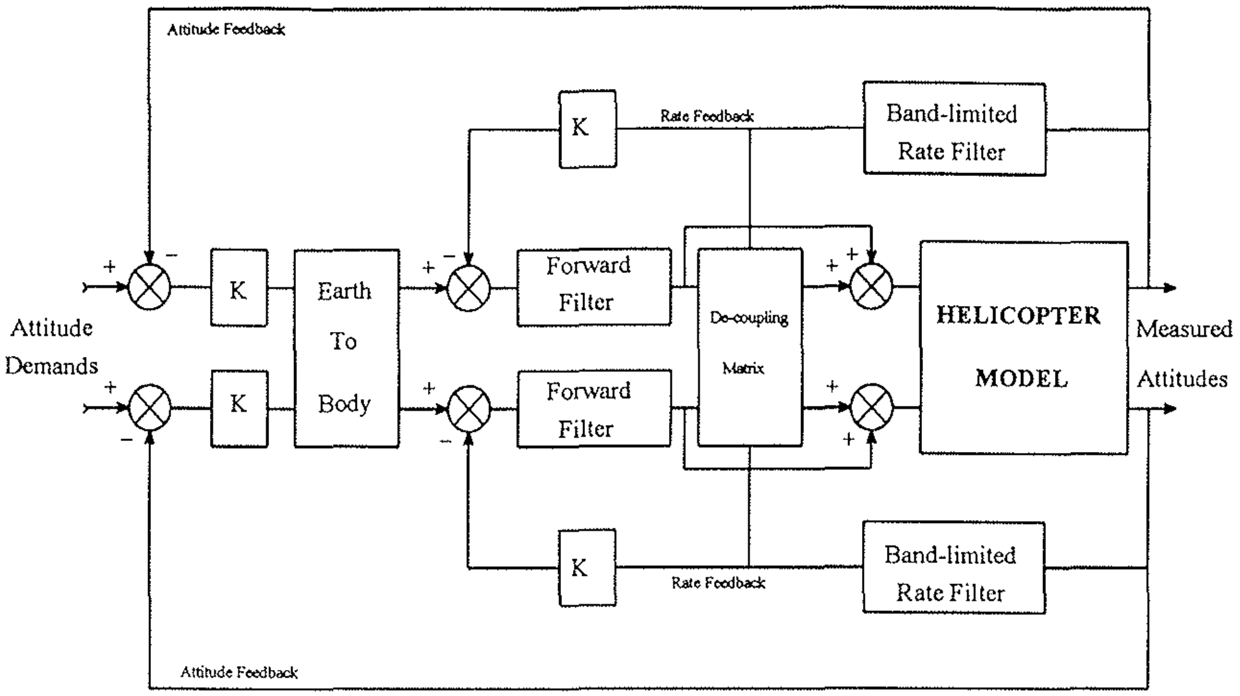


Figure 3(a) Single Input Single Output Controller

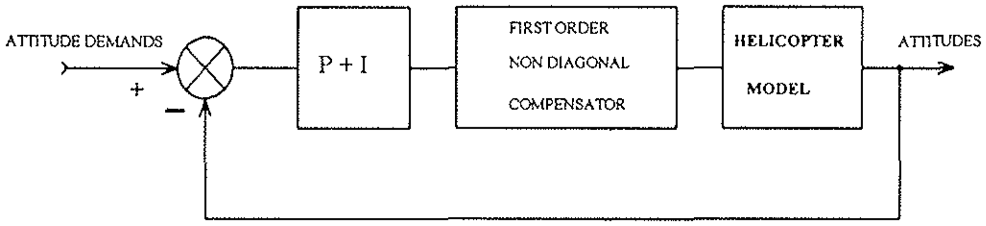


Figure 3(b) Classical Multivariable Controller

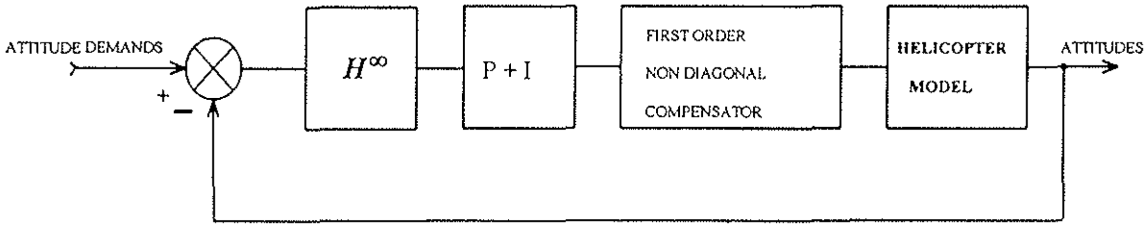
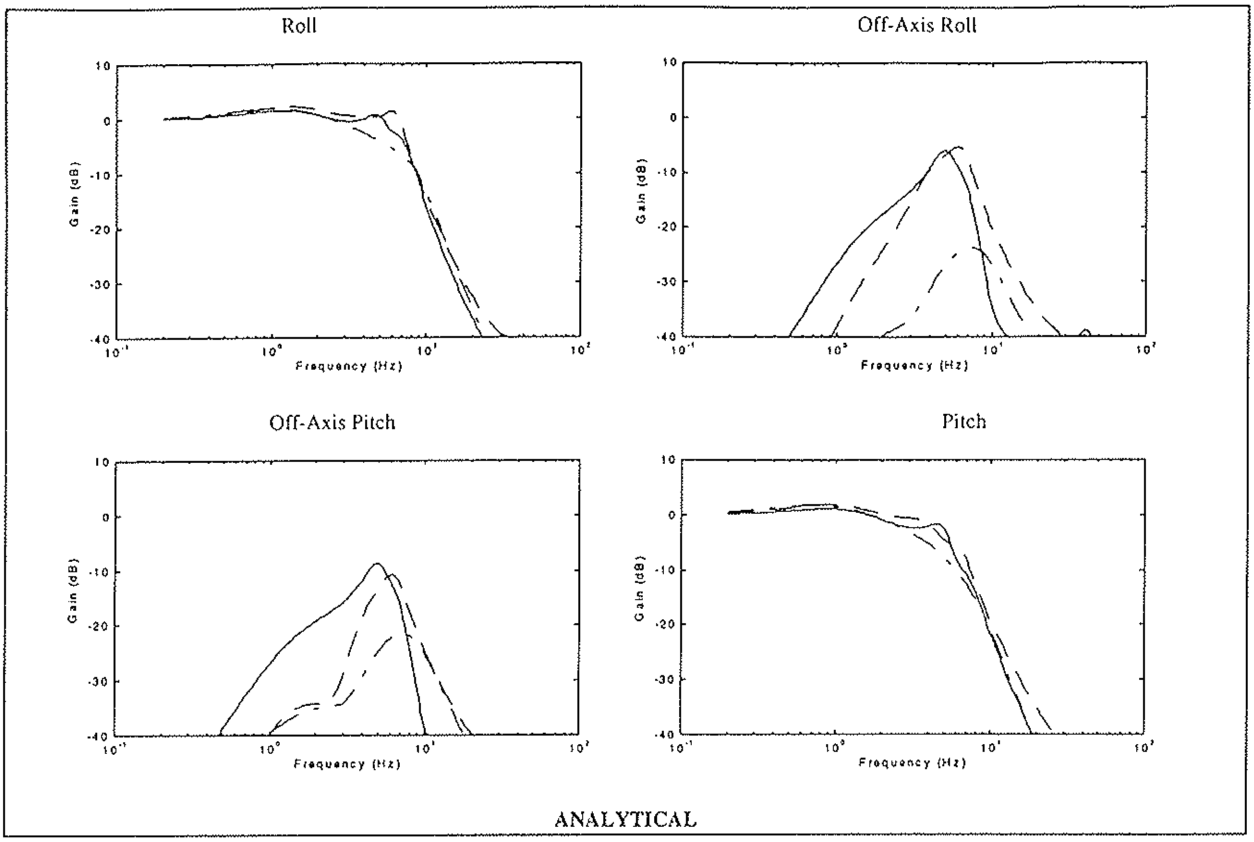
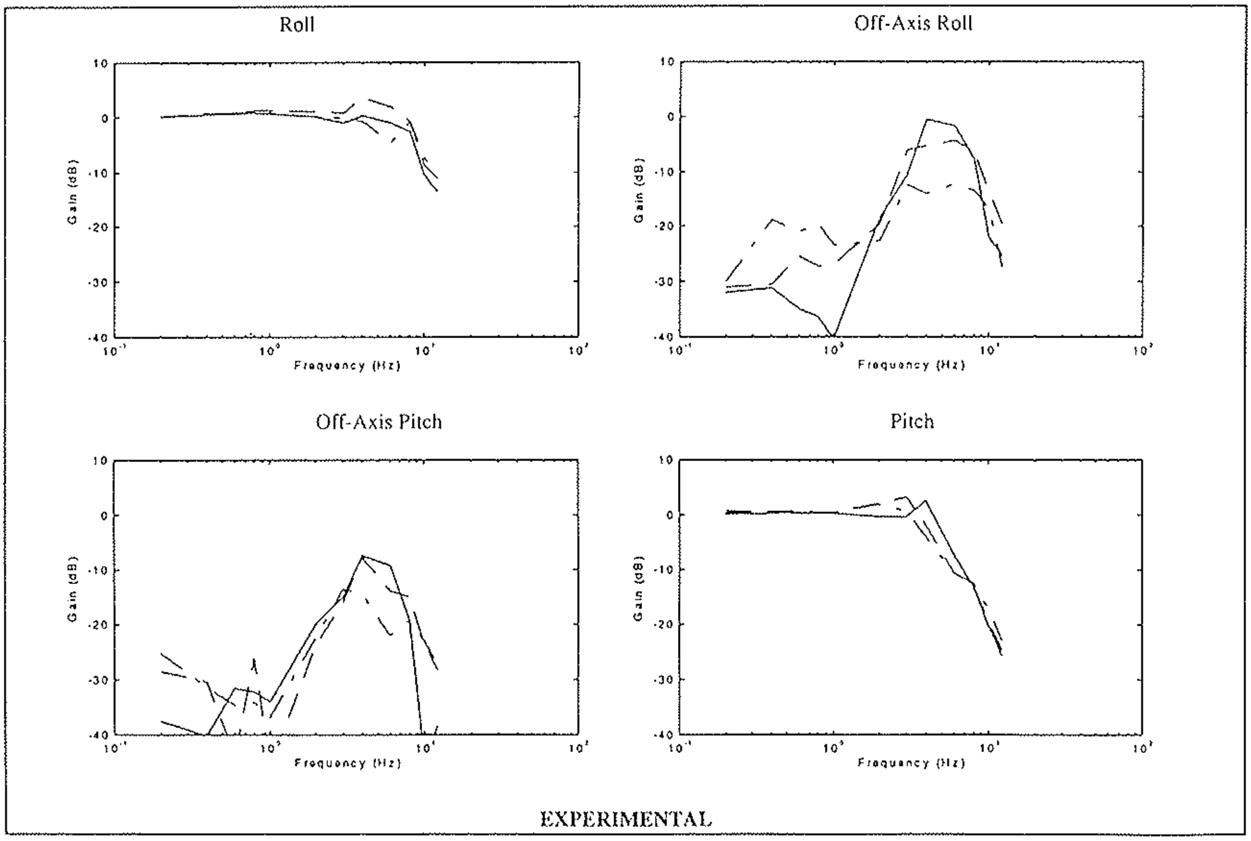


Figure 3(c) Classical Multivariable plus H^∞ Controller



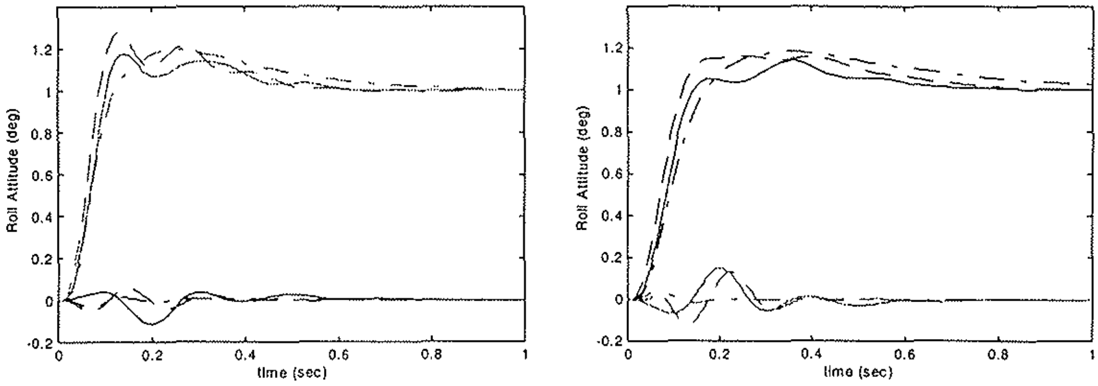
ANALYTICAL



EXPERIMENTAL

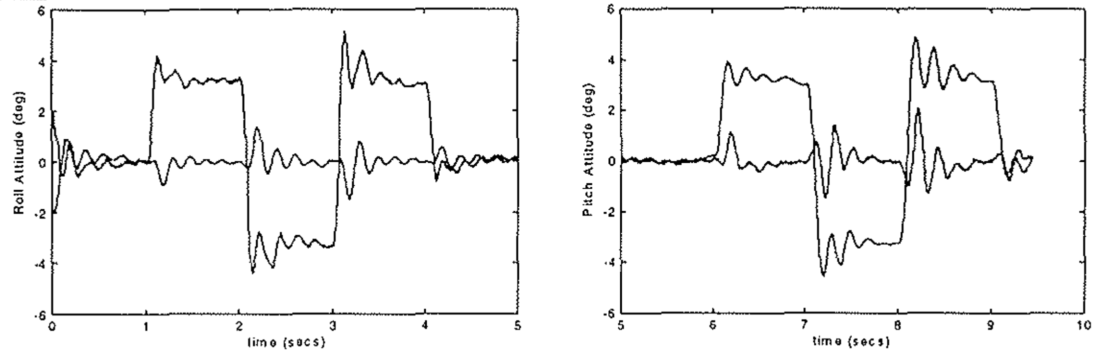
— Single Input Single Output Controller   – – Classical Multivariable Controller   – • – Classical Multivariable plus H∞ Controller

Fig.4 On Design Point Closed Loop Frequency Response Data

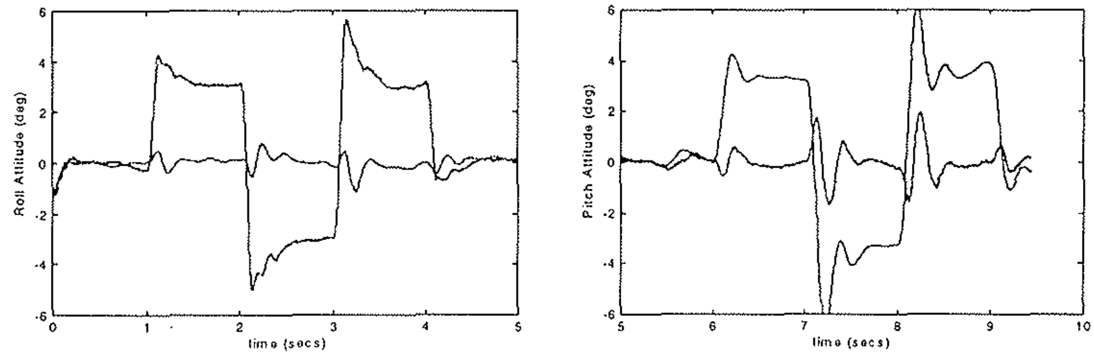


ANALYTICAL

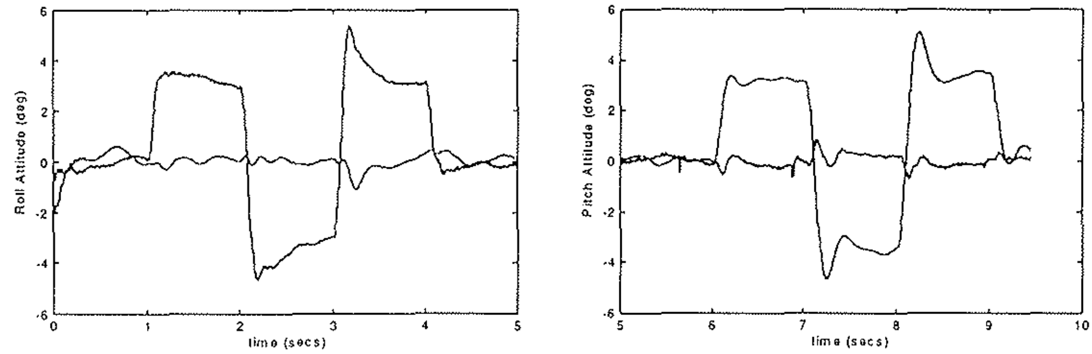
—Single Input Single Output – –Classical Multivariable –•–Classical Multivariable Plus H∞



SINGLE INPUT SINGLE OUTPUT



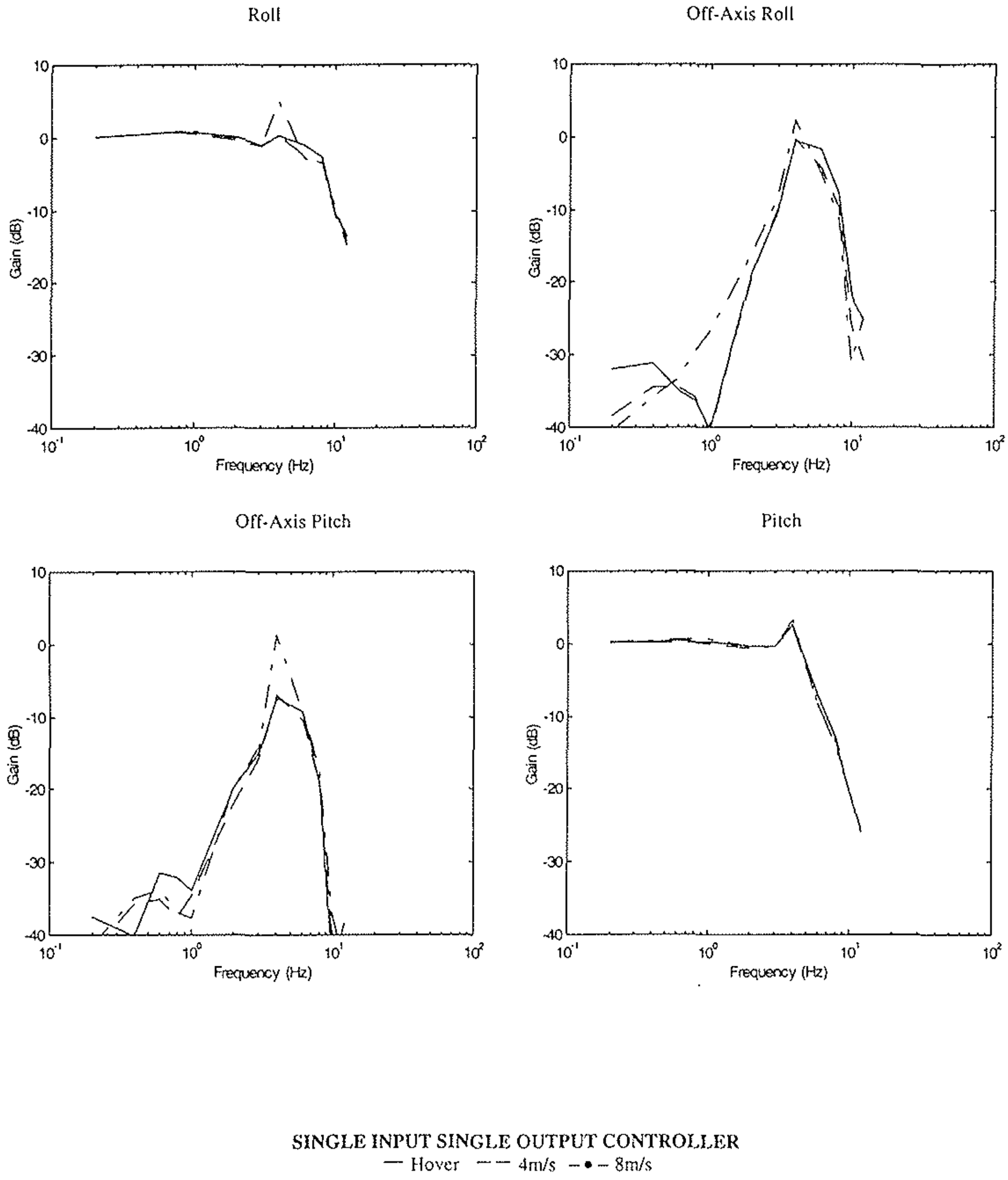
CLASSICAL MULTIVARIABLE



CLASSICAL MULTIVARIABLE PLUS H∞

EXPERIMENTAL

Fig.5 On Design Point Step Response Tests



Roll

Off-Axis Roll

Off-Axis Pitch

Pitch

Fig. 6 Off Design Point Closed Loop Frequency Response Data

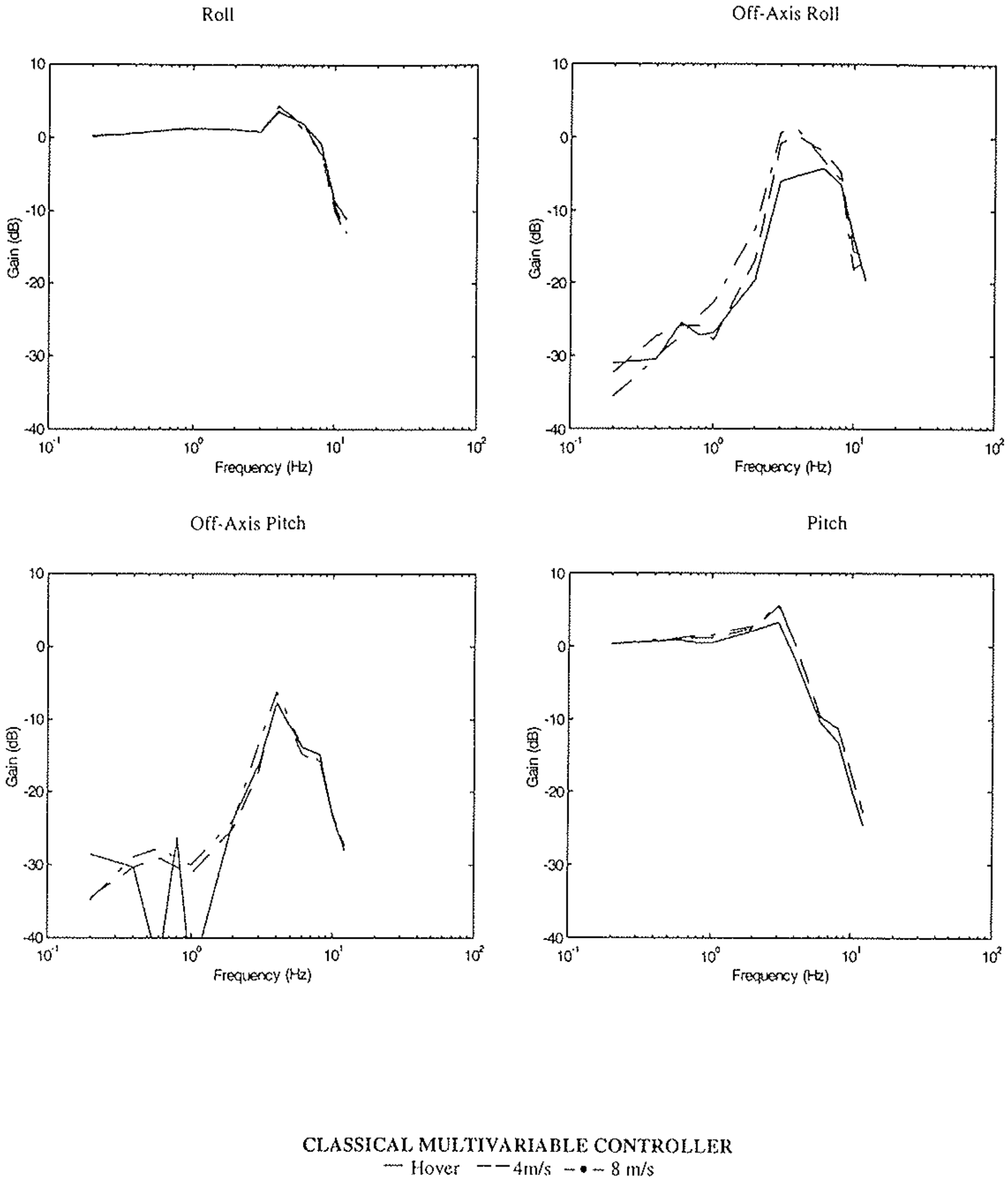
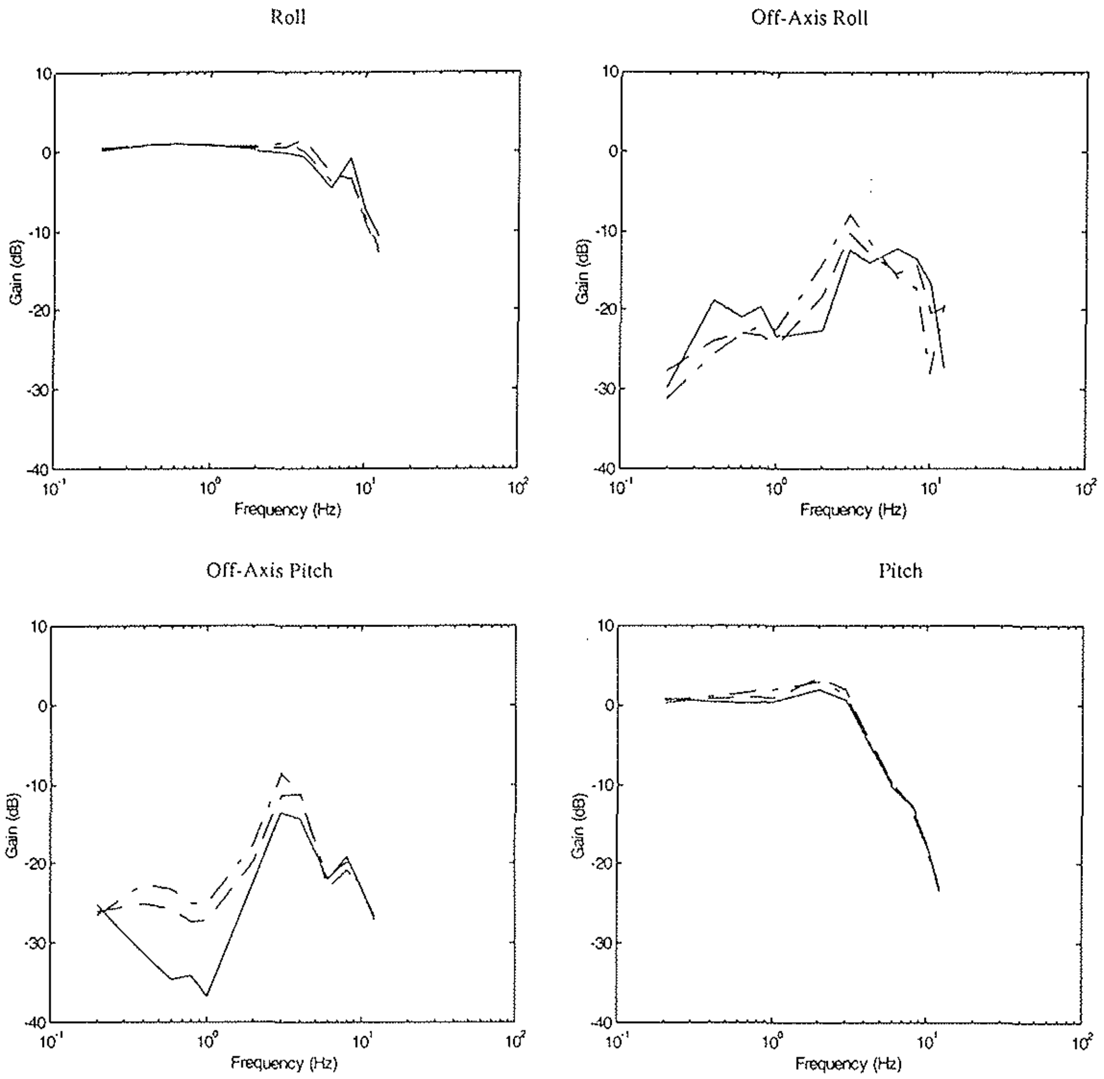
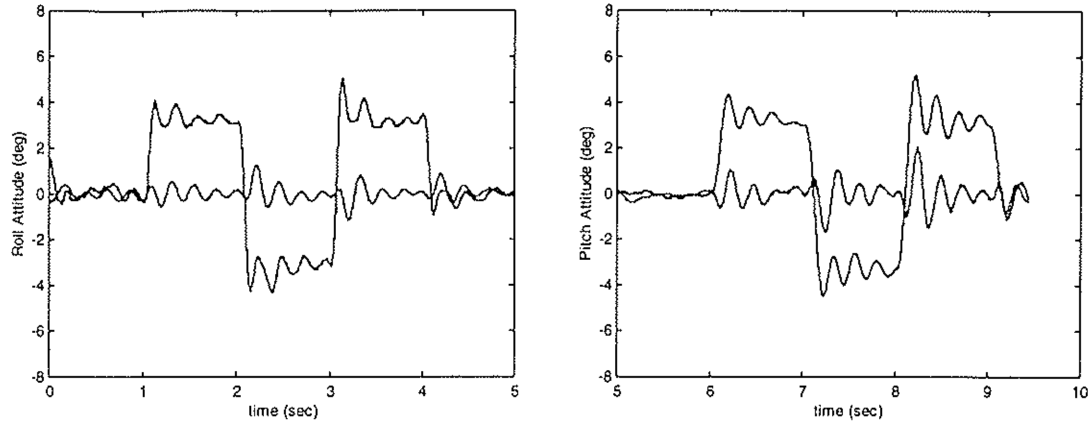


Fig.7 Off Design Point Closed Loop Frequency Response

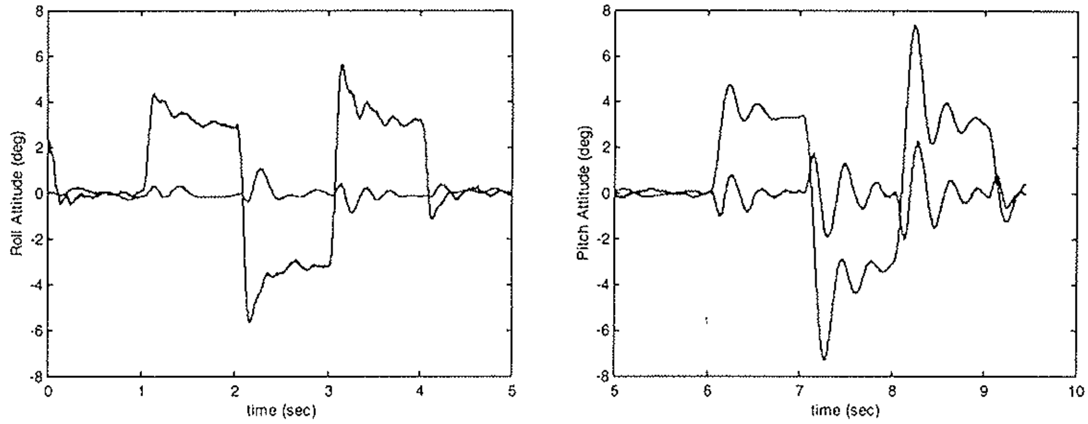


CLASSICAL MULTIVARIABLE PLUS H∞ CONTROLLER
— Hover ——4m/s —•— 8 m/s

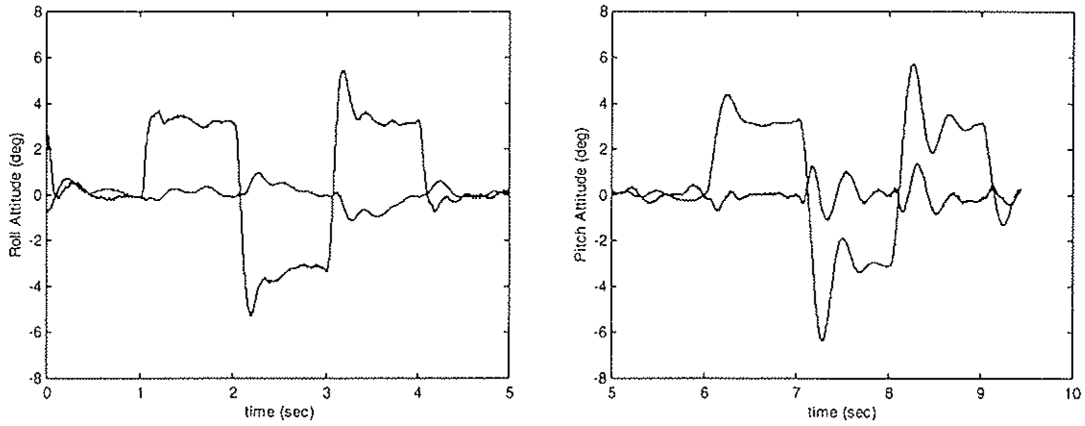
Fig.8 Off Design Point Closed Loop Frequency Response



SINGLE INPUT SINGLE OUTPUT CONTROLLER



CLASSICAL MULTIVARIABLE CONTROLLER



CLASSICAL MULTIVARIABLE PLUS H∞ CONTROLLER

Fig.9 Off Design Point Closed Loop Step Responses
40% Increase in Pitch Inertia