AN EVALUATION OF A SIMPLE PID CONTROLLER DESIGNED USING OPTIMAL CONTROL THEORY WHEN APPLIED TO HELICOPTER STABILISATION.

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Abstract

Smiths Industries Aerospace and Defence Systems Ltd and Agusta S.p.A are developing an all digital Automatic Flight Control System, AFCS, for the EH101 helicopter. The system comprises an autostabiliser and an autopilot. The autostabiliser drives fast acting limited authority series actuators to suppress disturbances to a datum trim position and slow acting full authority parallel actuators to retrim the aircraft. The autopilot provides commands to the autostabiliser when a mode is engaged.
The autostabiliser control laws have been designed on a single axis basis using classical Root Locus techniques to derive the proportional plus derivative gains used in the series actuator control loop and the integral gain used primarily in the parallel actuator trim system.
A method is presented which uses optimal control theory to derive gain matrices for a multivariable PID controller which takes account of cross coupling effects. No state estimation or additional sensors are required to implement the control law which makes it potentially suitable for use in an AFCS. A comparison of the simulation results obtained using this method is made with those obtained from the current AFCS control laws.

Notation

u = control input
x = system state
y = system output
A = plant matrix
B = input matrix
C = output matrix
D = derivative gain matrix
E = unit matrix
F = partitioned matrix used in computation
G = optimal feedback gain matrix
I = integral gain matrix
M = partitioned matrix used in computation
P = proportional gain matrix
Q = state weighting matrix
R = control weighting matrix
T = desired plant matrix

Subscripts

i denotes output matrix of integral states
Italic type denotes vector quantity

Superscripts

T denotes matrix transpose
-1 denotes matrix inverse

Introduction

The SEP20 AFCS designed for the EH101 helicopter has an all digital dual duplex architecture to provide the most redundant and fault tolerant system within the specified weight, power, sensor and actuator constraints. A single Flight Control Computer is capable of driving the suite of actuators required to maintain aircraft control in all axes. The possibility of common mode failures has been minimised by using dissimilar microprocessors, two Motorola 68000 and two Intel 80286, per FCC, programmed with flight software developed by two teams in different geographical locations. Multiple sensor inputs are used to increase redundancy and each FCC has three power supplies driven from different sources to maximise the availability of the system. The autostabiliser software is verified to level one, flight critical, whilst the autopilot is level two, flight essential. The system configuration is shown in fig 1.

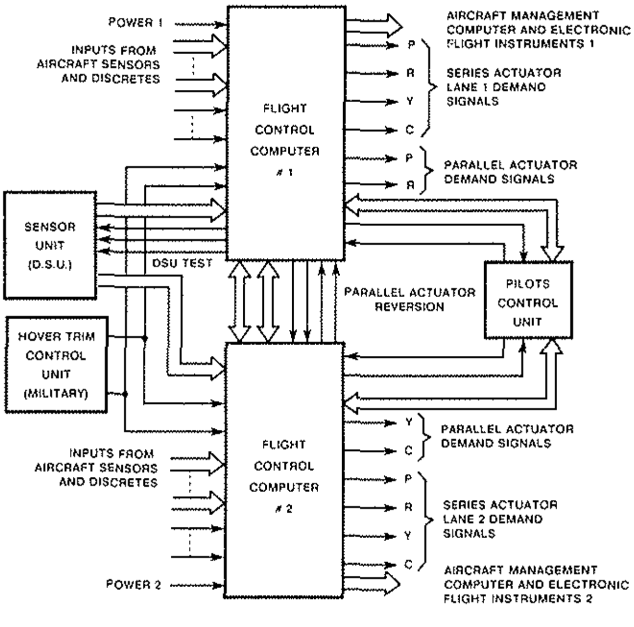

FIG 1. EH 101 AFCS SYSTEM CONFIGURATION

Development of the system is complex,expensive and fraught with all of the difficulties associated with software intensive systems, ie, data synchronisation, latency, processor throughput and memory constraints. Whilst the primary task of the AFCS is aircraft stabilisation, only 15% of processor throughput is dedicated to processing the control laws.The remainder is consumed by built-in test, sensor management, failure analysis, mode management, datum synchronisation and data output. The majority of this processing is concerned with identifying failures within and without the system in order to reconfigure sensor usage or internal processing.

References 1,2 and 3 are typical of methods that exist for enhancing the handling qualities of helicopters and probably will form the basis for control design in future systems. However, it has been recognised, ref 4, that rapid prototyping of the less deterministic elements of digital systems, as mentioned above, is one way to reduce the high risk inherent in large scale software development. Thus, as much importance must be placed on simulating the digital interactions of multi-processor, multi-unit systems as has previously been placed almost exclusively on control law development.

The EH101 AFCS control law development has included mainframe computer simulation, simulator activity with Test Pilots and finally flight trials. This considerable investment in effort has been rewarded by a system which has been largely unchanged in the area of control laws during the potentially expensive flight trials phase of the project. However, it is worth posing the question; is it possible for the designer to provide a more representative set of starting gains for his PID controller in keeping with the philosophy of rapid prototyping the entire system?

The PID controller chosen for the autostabiliser has the advantage of being well documented, easy to implement and relatively robust. The control law gains have been derived using the Root Locus technique on a separate axis by axis basis and proven as described above. While the use of Root Locus has proved satisfactory for this application, alternative techniques are being explored in preparation for the fast prototyping of future flight control applications, ref 5, which are likely to involve highly cross-coupled dynamics with many control variables.

The technique described in this paper is an extension of an idea detailed in ref 6. The designer has the option of specifying the desired system dynamics or deriving these from a solution of the optimal regulator. The method is simple, applicable to multi-axis systems and easily adaptable to attitude control where measurements of rates and attitudes are readily available.
A comparison is made between the performance of the current autostabiliser and the modified version using simulation results obtained from a six degree of freedom non-linear model of the EH101 provided by Westland Helicopters Ltd. Whilst this model does not provide an exact representation of the dynamics of the EH101 helicopter which has been found to be significantly more stable from the results of flight testing, it allows an assessment of the controller design to be made.

Aircraft Dynamics and Controller Design

The controller design was based upon a model of the EH101 dynamics linearised at an airspeed of 146kt. The performance of the controller was simulated using the six degree of freedom non-linear model provided for the preliminary autostabiliser design work.
The TSIM computer package, ref 7, was used to generate the results included in the text.
The design procedure, a simple extension of the method proposed in ref 6, is included for completeness.

Describing the system in state variable form

$$dx/dt = Ax + Bu$$
$$y = Cx$$
$$\int y = C_i x \qquad \text{........(1)}$$

where the system dynamics are augmented with the integrals of the states used by the controller and the matrix C_i chosen accordingly.

A controller is chosen to be of the form

$$u = Py + D\,dy/dt + I \int y \qquad \text{........(2)}$$

Substitution of eqn.(2) into eqn.(1) yields,

$$dx/dt = (E-BDC)^{-1}(A + BPC + BIC_i)x \qquad \text{........(3)}$$

To compute P,I and D such that the system behaves as

$$dx/dt = Tx \qquad \text{........(4)}$$

implies

$$T = (E-BDC)^{-1}(A + BPC + BIC_i) \qquad \text{........(5)}$$

where the dynamics of T may be chosen arbitrarily. Thus:

$$T-A = BPC + BDCT + BIC_i \qquad \text{........(6)}$$

which can be rewritten

$$Z = BMF \qquad \text{........(7)}$$

where

$Z=T-A$

M is the partitioned matrix,

$M=[P|D|I]$

and F is the partitioned matrix,

$F=[C|CT|C_i]^T$

In general B and F are non-square matrices thus,

$$M=(B^TB)^{-1}B^TZF^T(FF^T)^{-1} \quad \text{........(8)}$$

The matrix inverses exist if the columns of B and rows of C and C_i are linearly independent,otherwise the model is not of minimal order and is reducible.The rows of T must be linearly independent of the unit matrix E.

Use of optimal control gain matrix to choose T

T was chosen using the gain matrix G derived from a solution of the matrix Riccati equation,ref 8.
Thus T becomes

$$T=A-BG \quad \text{........(9)}$$

Equation (6) can be simplified to

$$-G=PC+DCT+IC_i \quad \text{........(10)}$$

Equation (8) then becomes

$$M=-GF^T(FF^T)^{-1} \quad \text{........(11)}$$

From which the P,I and D matrices can be found.

Selection of weighting matrices

The weighting matrices Q and R required to solve the Ricatti equation were selected to provide a damping factor of at least 50% on each of the control axes. This was ascertained by checking the closed loop system poles obtained using the computed P, I and D matrices. The weighting was applied with priority being given to the attitudes, rates and the integral terms in this order. The roll axis was weighted more than the pitch and yaw to provide the required response in this axis.

Simulation study

A simulation study was performed to investigate the following,

a) the effectiveness of the PID controller as a design starting point via comparison with the default autostabiliser.

b) the robustness of the method over the flight envelope when used with the non linear model.

c) the ability of the PID controller to reduce the inter-axis cross-coupling effects.

The following terminology has been used in labelling the results. The default autostabiliser is based on that under development on the EH101 helicopter and the modified autostabiliser is based on the method presented in this paper.

Figures 2A and 2B show the response of both autostabilisers to a pulse input in the pitch axis at an airspeed of 146 kts.
Figures 3A and 3B show the response of both autostabilisers to a similar input injected into the roll axis at the same airspeed.
In both cases the default autostabiliser is marginally better damped that the modified version. However, the cross coupling effects are noticeably reduced with the latter system.

Figures 4A, 4B and 5A, 5B show the results for the same pulse input conditions in the pitch and roll axes respectively for the hover condition.
The modified autostabiliser provides a marginal improvement in the pitch damping with considerably less cross coupling. In the Roll axis the modified autostabiliser exhibits a less oscillatory response, than the default version and demonstrates that the control law provides acceptable performance throughout the flight envelope.

Figures 6A and 6B present the response of both autostabilisers to a trim input of five degrees nose up in the pitch axis. The modified autostabiliser provides a marginally smoother response than the default version at this speed and shows that the design is suitable for both autostabilisation and aircraft retrimming.

Conclusions

The results of this study show that the algorithm presented is readily adaptable to the task of helicopter stabilisation. A reduction in the inter-axis cross coupling effects is achieved without excessive actuator demands. The design was rapidly and easily implemented on a digital computer and certainly could be used as a good starting point for simulator development including a test pilot.

Acknowledgements

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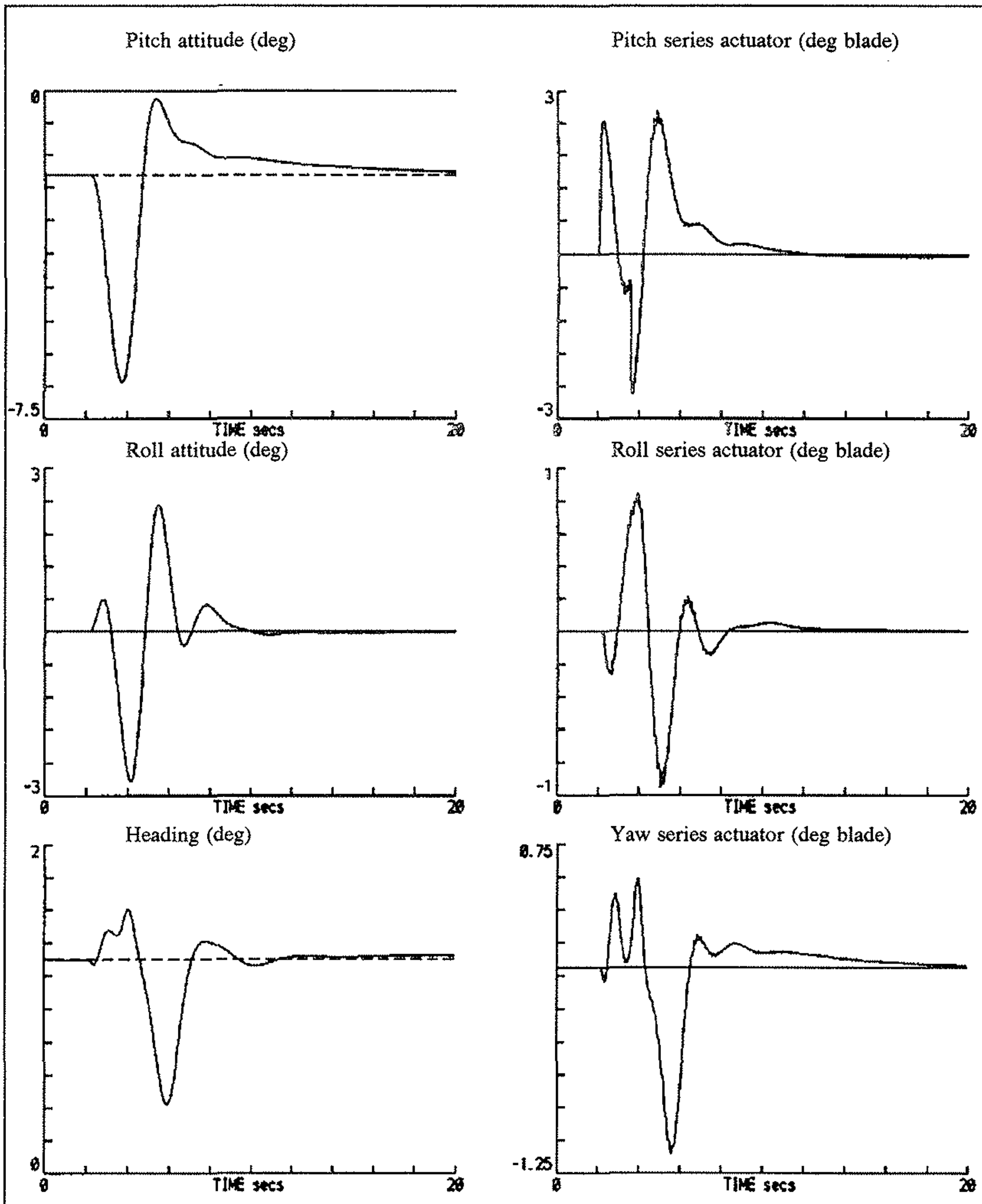


Figure 2A
Speed 146Kts. Pitch pulse input. Default autostabiliser.

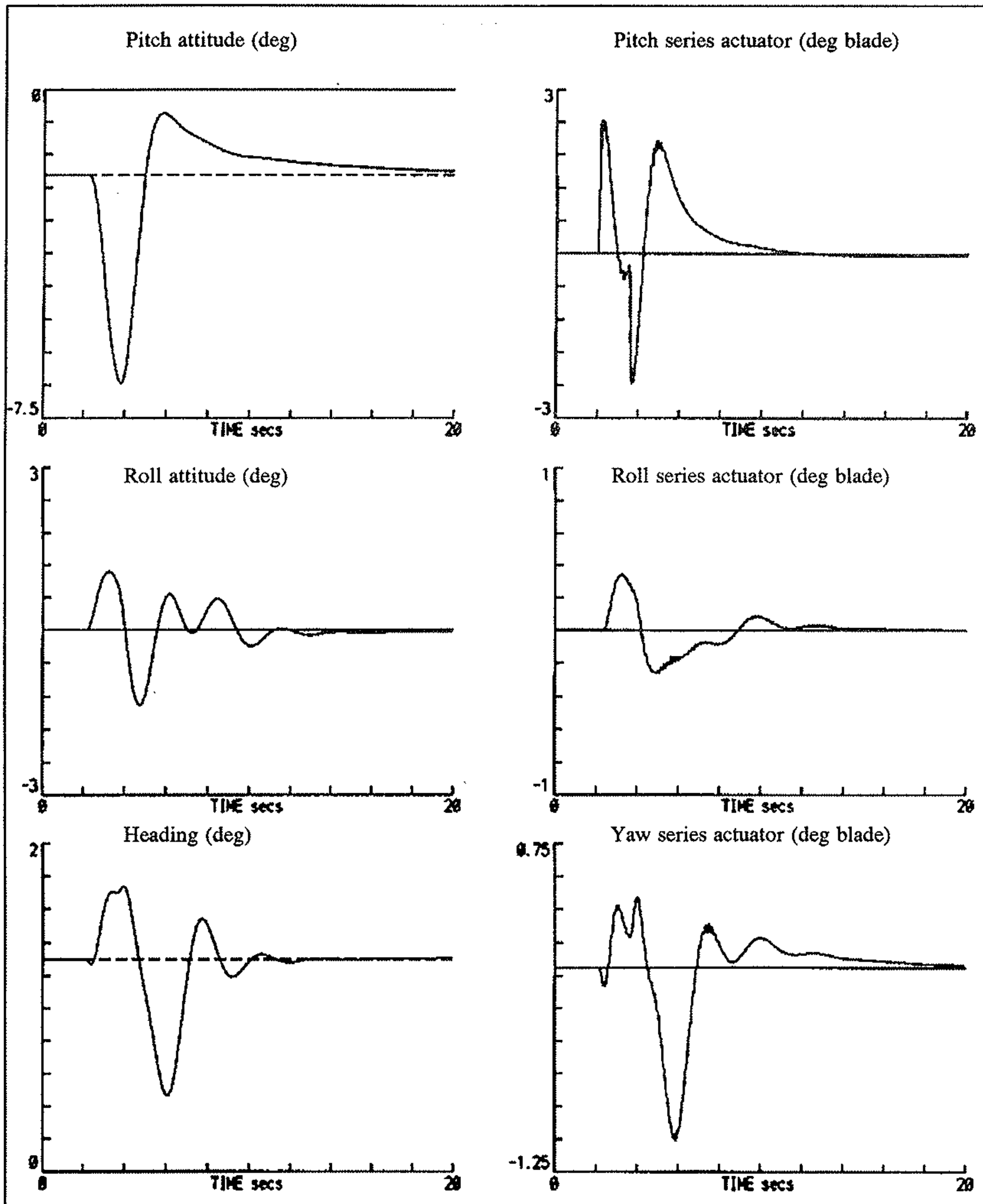
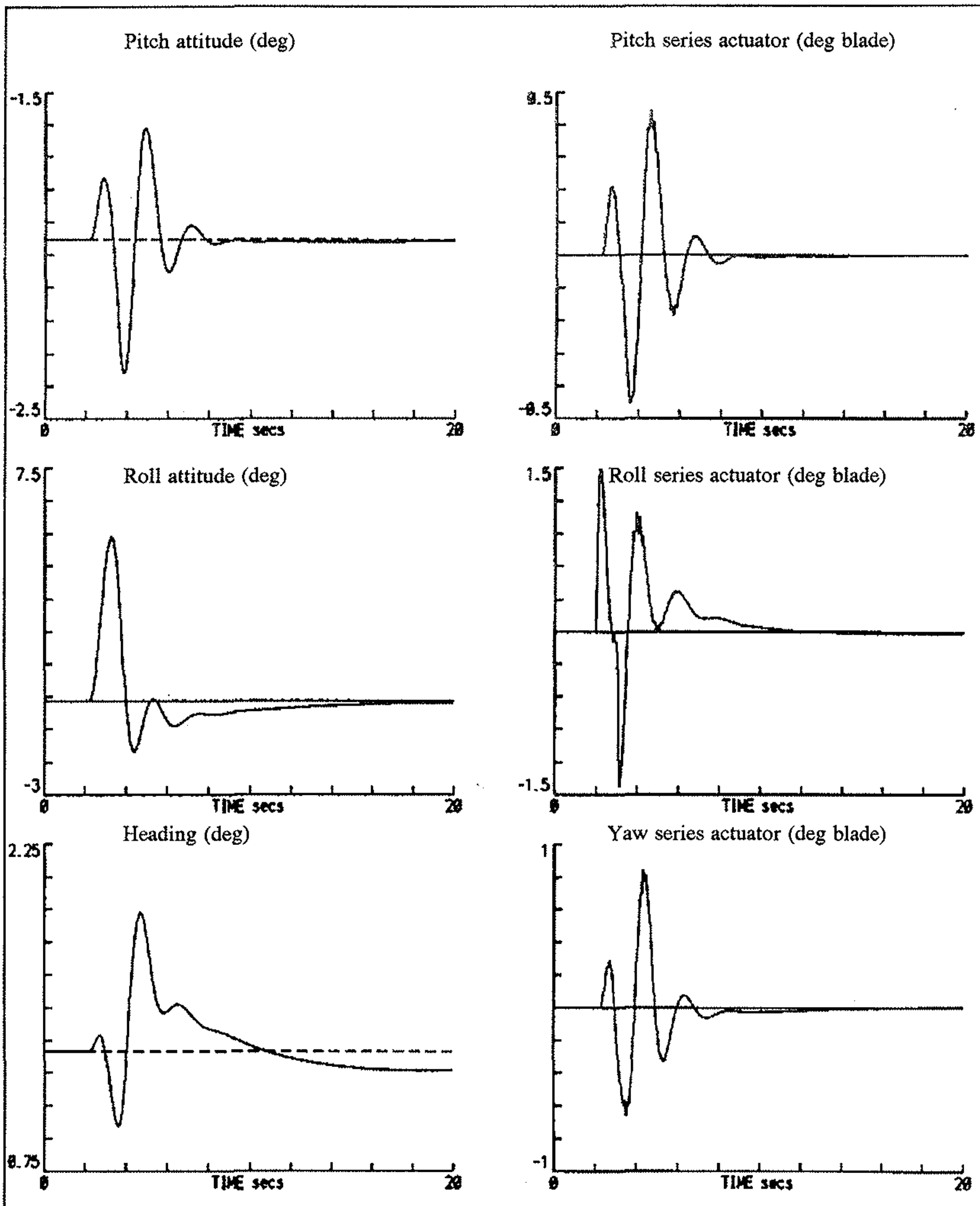


Figure 2B
Speed 146Kts. Pitch pulse input. Modified autostabiliser.


Pitch attitude (deg)

Pitch series actuator (deg blade)

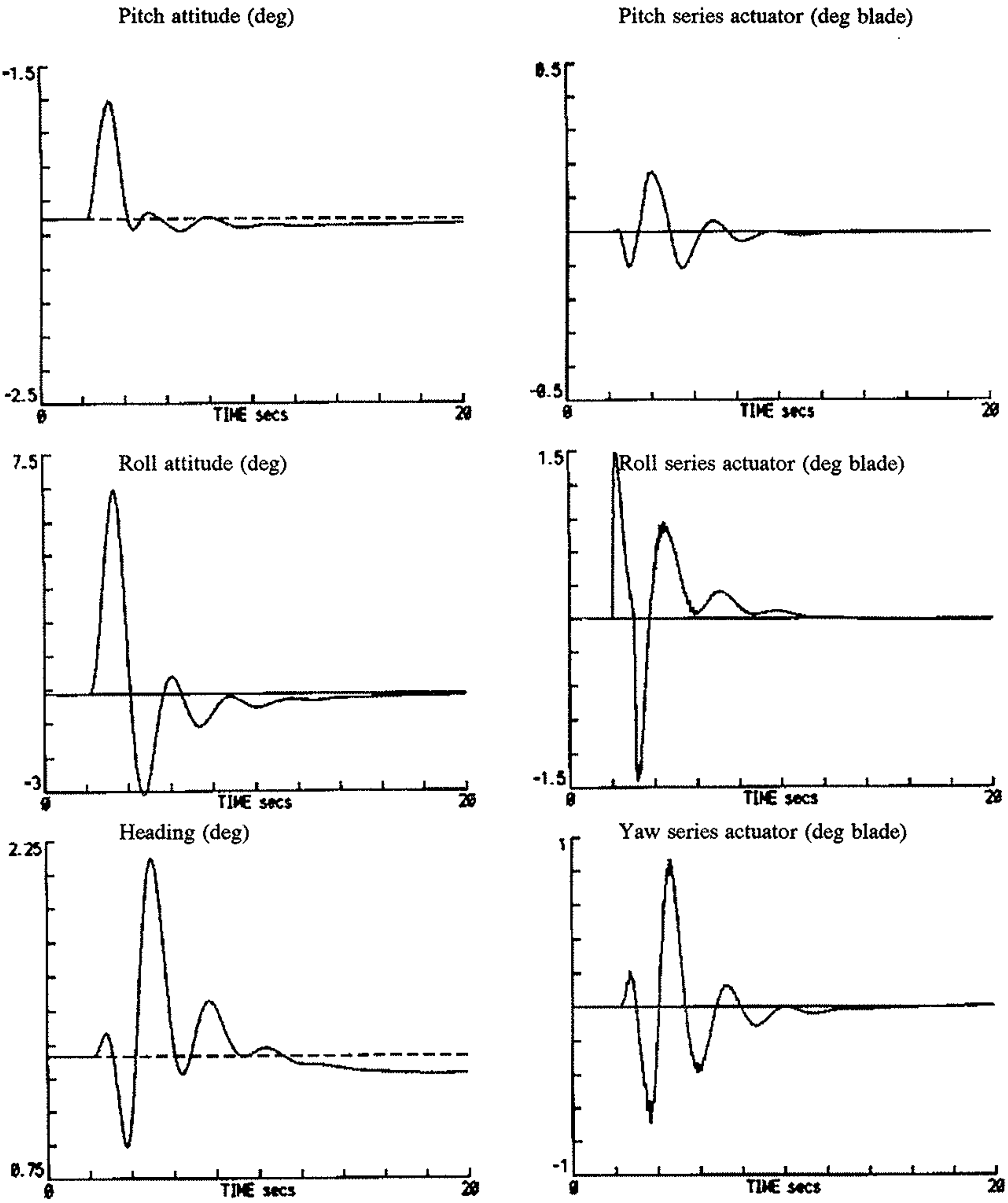
Roll attitude (deg)

Roll series actuator (deg blade)

Heading (deg)

Yaw series actuator (deg blade)

Figure 3A
Speed 146Kts. Roll pulse input. Default autostabiliser.


Pitch attitude (deg)

Pitch series actuator (deg blade)

Roll attitude (deg)

Roll series actuator (deg blade)

Heading (deg)

Yaw series actuator (deg blade)

Figure 3B
Speed 146Kts. Roll pulse input. Modified autostabiliser.

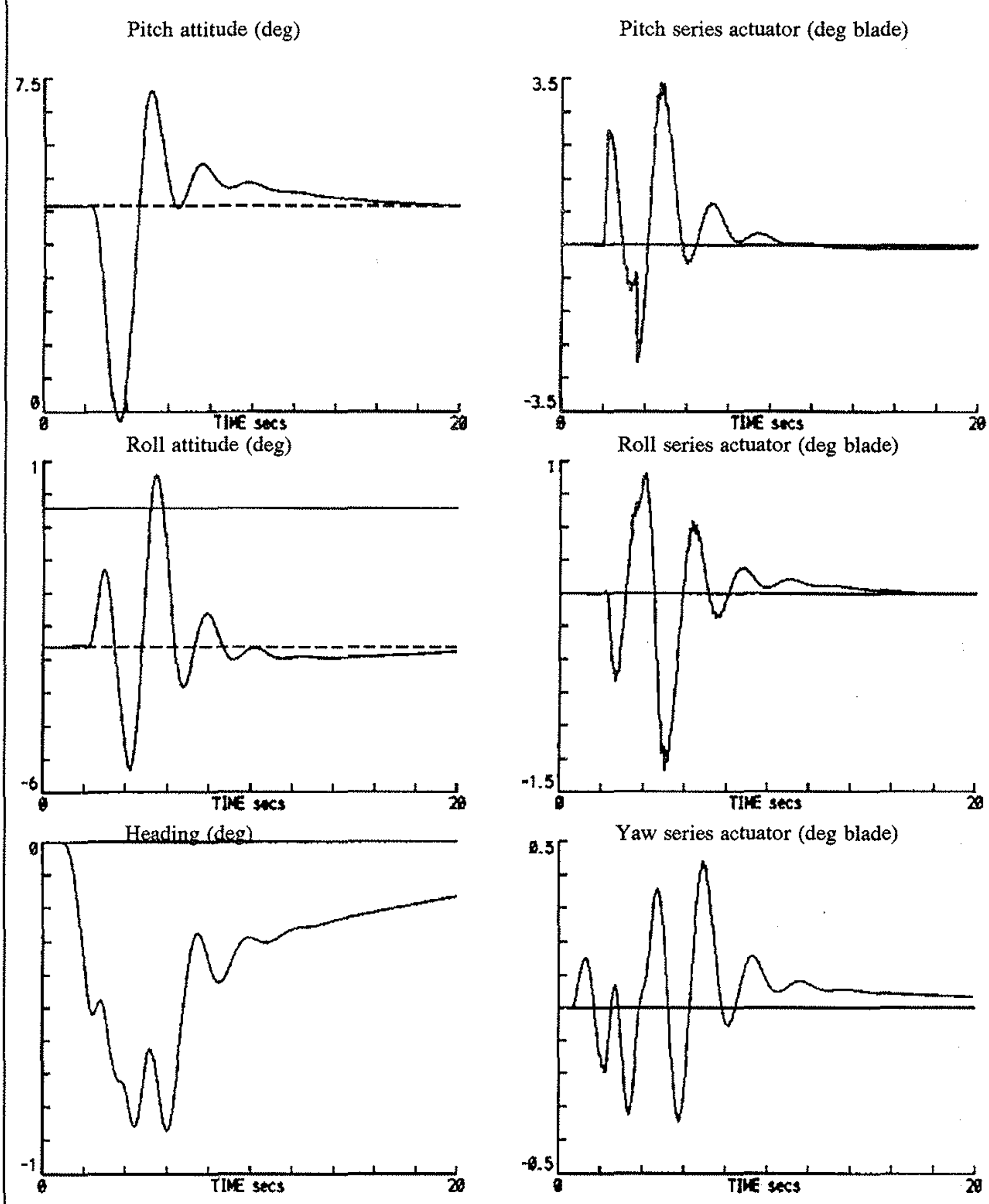


Figure 4A
Hover. Pitch Pulse Input. Default autostabiliser.

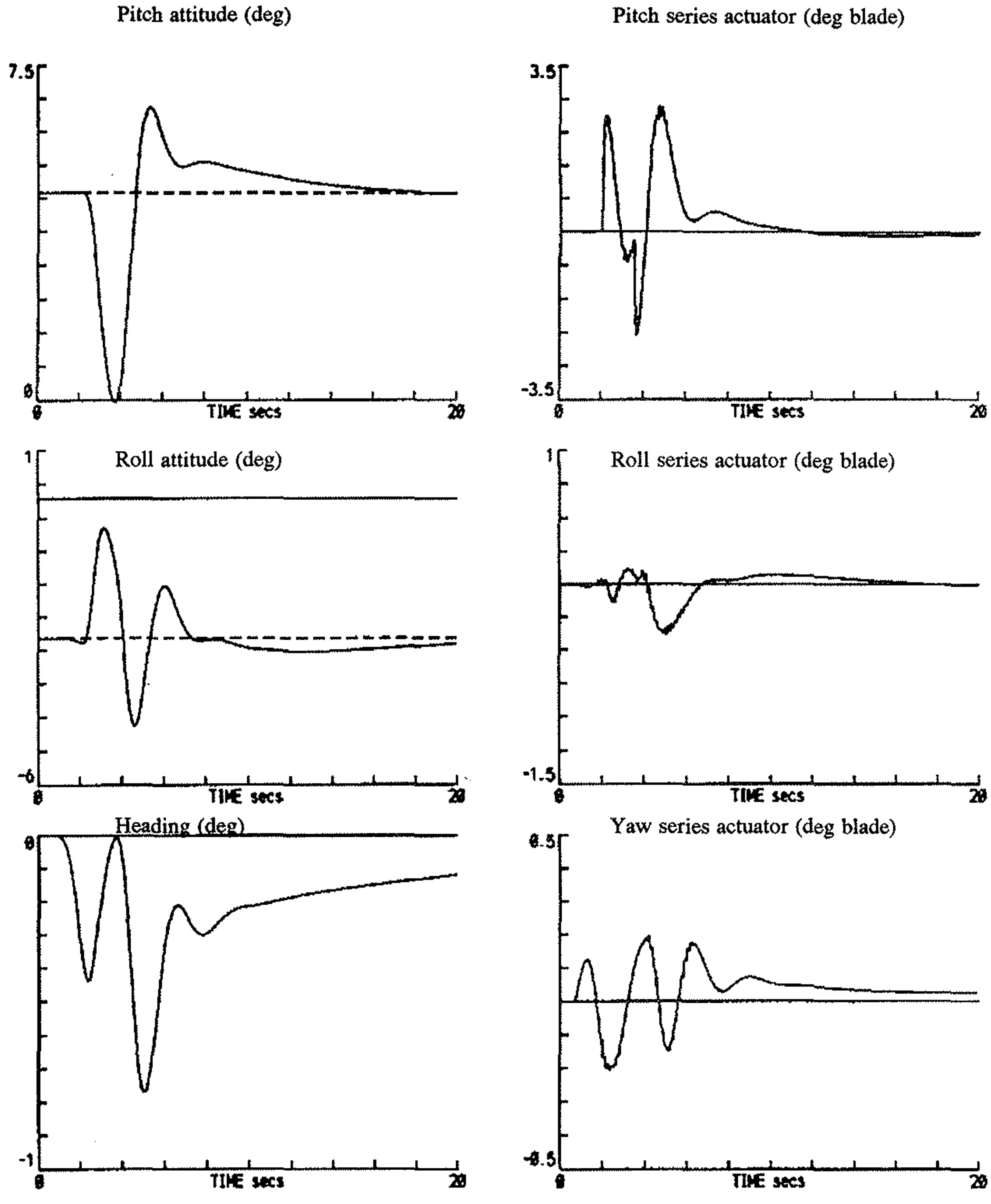
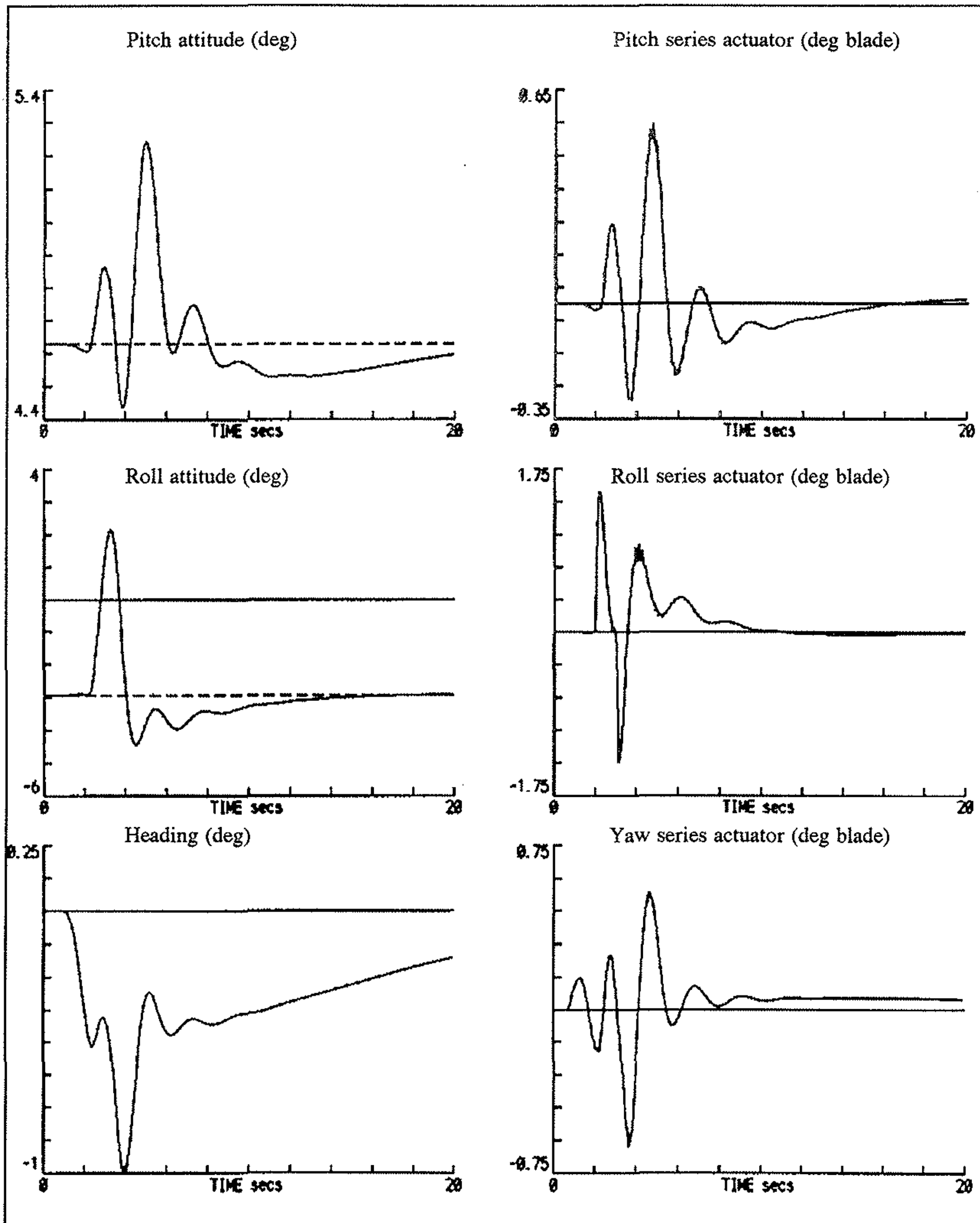


Figure 4B
Hover. Pitch Pulse Input. Modified autostabiliser.



Pitch attitude (deg)

Pitch series actuator (deg blade)

Roll attitude (deg)

Roll series actuator (deg blade)

Heading (deg)

Yaw series actuator (deg blade)

Figure 5A
Hover. Roll Pulse Input. Default autostabiliser.

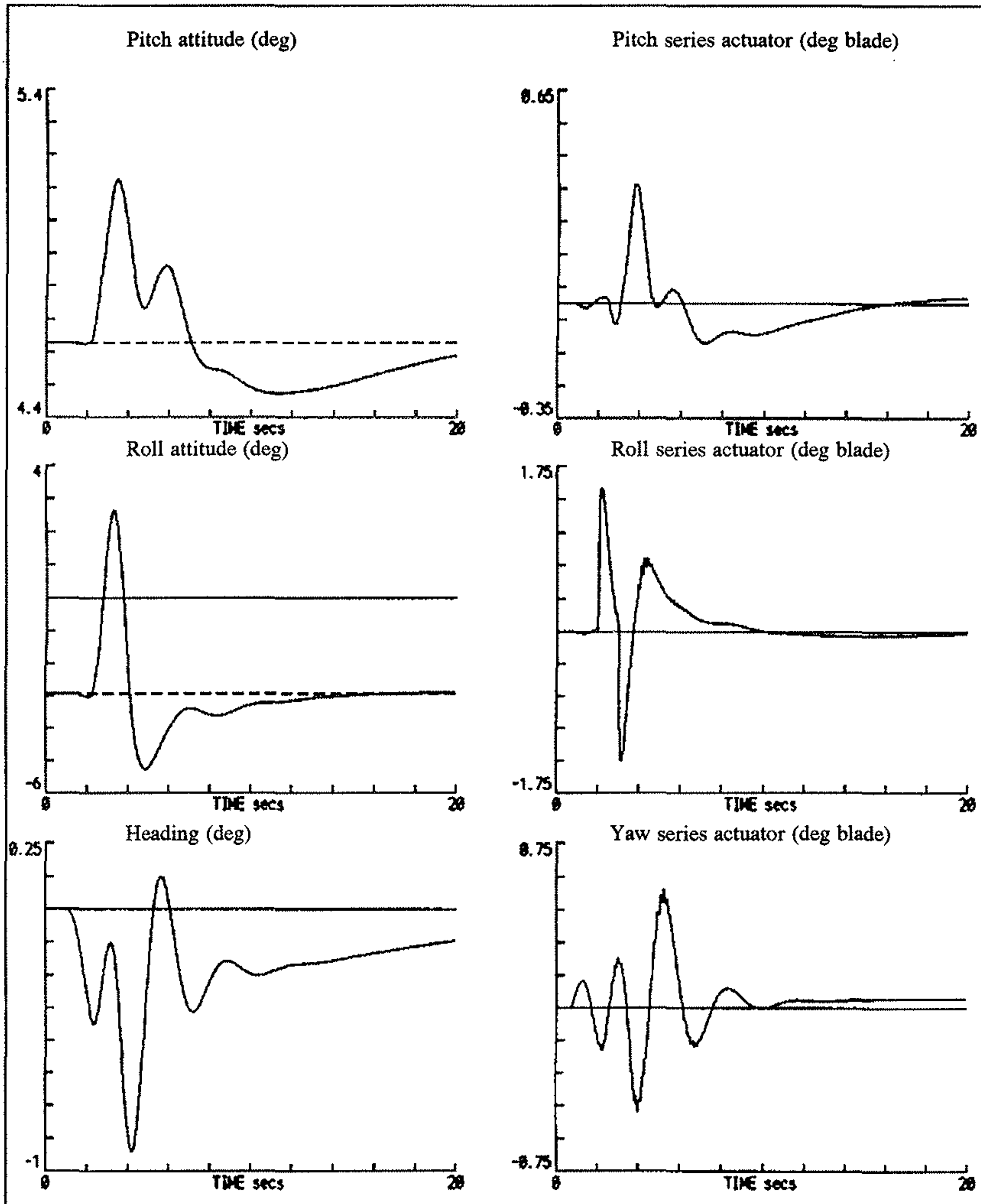
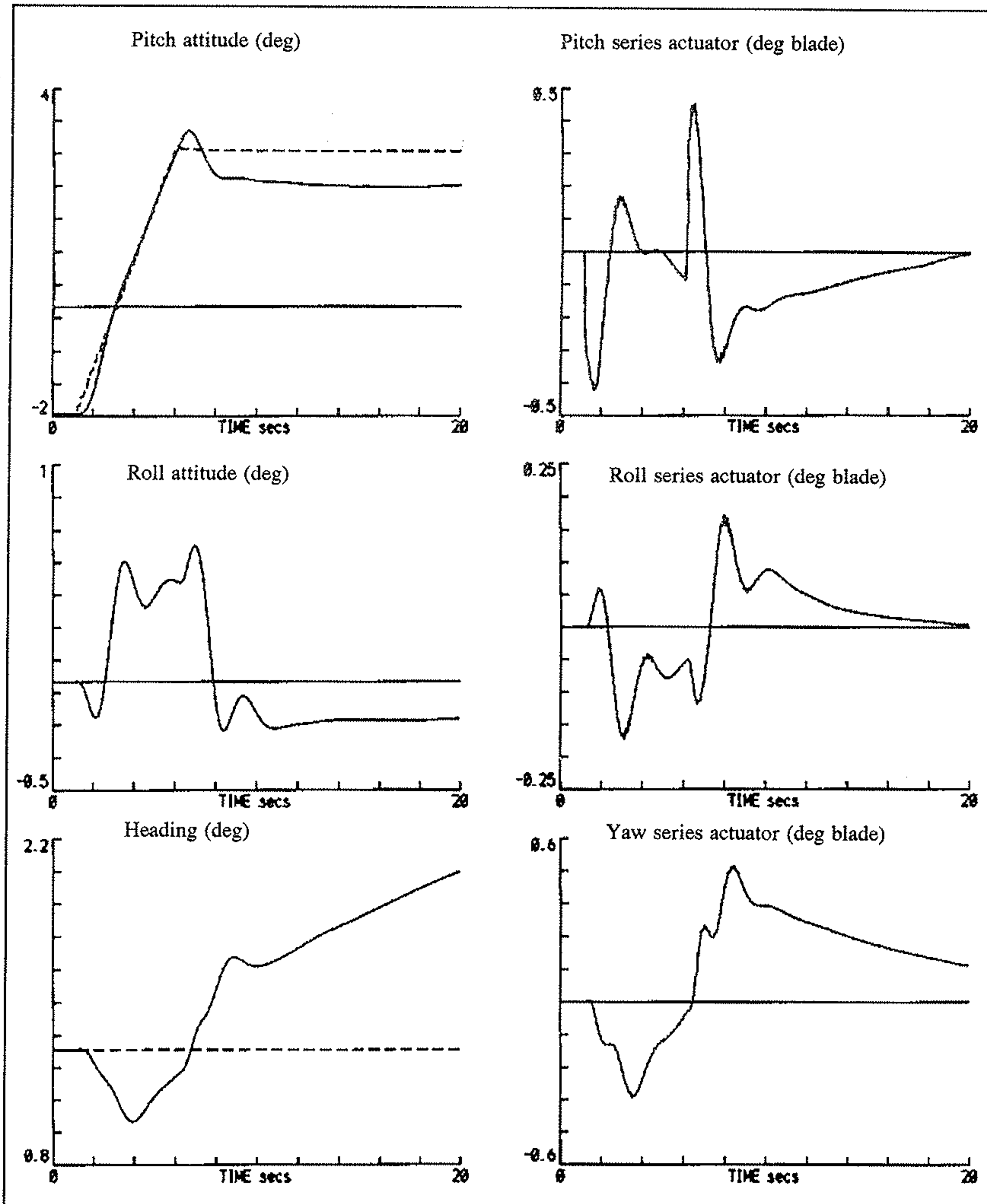


Figure 5B
Hover. Roll Pulse Input. Modified autostabiliser.



Pitch attitude (deg)

Pitch series actuator (deg blade)

Roll attitude (deg)

Roll series actuator (deg blade)

Heading (deg)

Yaw series actuator (deg blade)

Figure 6A
Speed 146 Kts. Pitch Trim Change. Default autostabiliser.

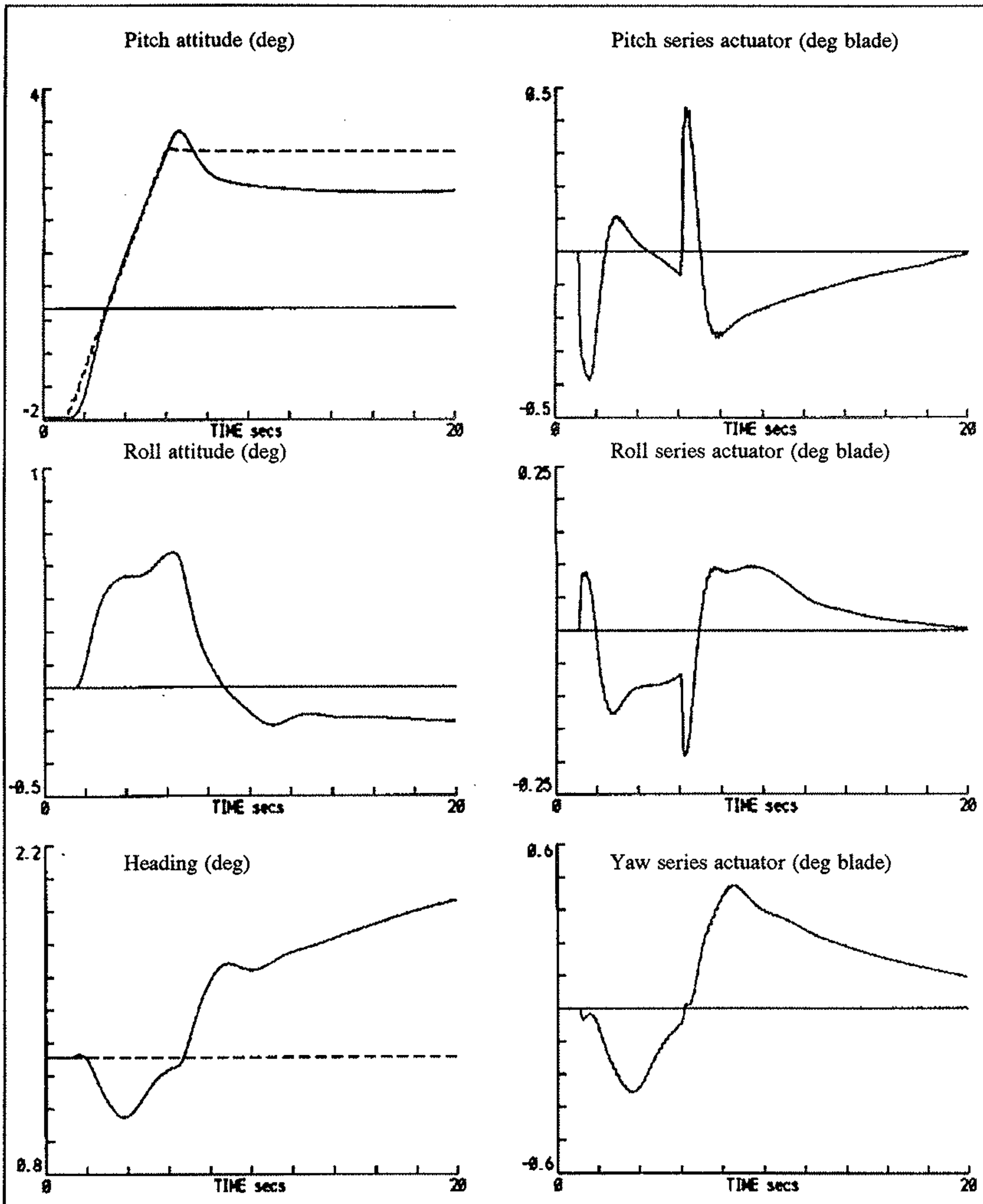


Figure 6B

Speed 146 Kts. Pitch Trim Change. Modified autostabiliser.