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VALIDATION OF HELICOPTER MATHEMATICAL MODELS BY COMPARISON OF DATA
FROM NAP-OF-THE-EARTH FLIGHT TESTS AND INVERSE SIMULATIONS

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Summary

In this paper it is shown that conventional validation techniques, based on comparison of responses after the application of standard control inputs to real and simulated vehicles, are not appropriate for models used in NOE studies. It is further shown that when control inputs measured during NOE flight tests are used to drive simulations, the simulated data quickly diverges from the measured data, even for minor modelling errors, giving little information on the validity of the model. The development of a new, more appropriate technique employing inverse simulations is described and its ability to identify inadequacies in mathematical models is demonstrated.

Nomenclature

C_T	main rotor thrust coefficient
C_{Ttr}	tail rotor thrust coefficient
p, q, r	body axes rotational velocities
s	length of linear translation
t	time
t_m	manoeuvre time
u, v, w	body axes translational velocities
V	helicopter velocity
\dot{V}	helicopter acceleration
x, y, z	helicopter position
$\dot{x}, \dot{y}, \dot{z}$	earth axes velocities
β_{1s}, β_{1c}	lateral and longitudinal flapping angles
θ, ϕ, ψ	pitch, roll and yaw attitude angles

1. Introduction

In helicopter nap-of-the-earth (NOE) manoeuvres the pilot's task is particularly demanding because of the constrained nature of the flight path. The pilot is often required to adhere to both a particular track (the projection of the flight path on the ground) and altitude. Limits on the allowable flight path may be imposed by the need for concealment or to follow closely features of the terrain. If flight mechanics studies of the helicopter's behaviour under these conditions are to be successful then the mathematical models used must provide reliable predictions. Flight dynamicists are continually improving and updating their models in

order to meet these needs. As the models become more complex there is always the danger that large scale modification to existing, proven codes may yield only small improvements in model validity, but at the same time incur significant increases in computation time. It is therefore of great importance that validation techniques are adopted which are appropriate to the situation so that effective use can be made of established models.

Conventional validation techniques (as used by the authors of References 1 - 3, for example) have depended on comparison of responses of simulated and real aircraft to a simple control input (typically a step input to one or more controls). This gives an indication of the model's effectiveness in predicting the helicopter's behaviour in unconstrained flight, but does not give any idea of how well it will predict the behaviour in the tightly constrained realm of NOE flight. This paper describes a new approach to model validation intended to overcome this problem by using an inverse simulation method. An inverse simulation uses a given model to determine the control displacements necessary to fly a specific manoeuvre. Comprehensive details of an inverse simulation package for helicopters, HELINV, are given in References 4 and 5. It has been developed specifically to study constrained manoeuvring flight such as that encountered during NOE operations (Refs. 6 and 7). The modification of this package for model validation purposes is detailed in this paper, but to begin with, a discussion of the simulation tools used in the development of the new model validation methodology is presented.

2. Description of Conventional and Inverse Simulation Techniques

The mathematical model from the Royal Aerospace Establishment's HELISTAB helicopter simulation package will be used to demonstrate the new validation technique. This model is widely used and has been extensively validated for the Aerospatiale Puma, while its validation for the Westland Lynx is a continuing exercise. It is, therefore, an appropriate choice for this demonstration, and its incorporation into the HELINV package is the basis for the approach to validation discussed in this paper. A comprehensive description of the HELISTAB model is given by Padfield (Ref. 1) but it is appropriate at this stage to list the main features of the model, together with a brief description of HELINV in this context.

2.1 The HELISTAB Mathematical Model

HELISTAB can be used to simulate single main and tail rotor helicopters. Several versions of HELISTAB have been developed as various refinements have been incorporated into the basic model. In this paper "HELISTAB" refers to an early version, "HELISTAB2". It is a six degrees of freedom model where the rotor blades are assumed to be rigid and have constant chord. Blade aerodynamic loads are calculated by assuming a constant lift curve slope with steady incompressible flow (stall and reversed flow effects are ignored). The flapping behaviour of hingeless and small offset articulated rotors is simulated by the use of a centre spring representation. The coupling between blade pitch and lag motions is ignored and the rotor forces and moments are calculated by assuming quasi-steady flapping and coning. The fuselage, tailplane and fin aerodynamic loads are found from empirical expressions which were developed using data from wind tunnel tests of fuselage models. On the

basis of these assumptions a series of expressions relating the rotor and fuselage loads to the helicopter's states have been developed. The external forces and moments are calculated directly from these expressions allowing solution of the equations of motion by standard means.

2.2 Inverse Simulation Package : HELINV

The main inverse algorithm within HELINV is a modification of the HELISTAB trim routine. In its original form this routine solved the equations of motion for the helicopter states and controls in a predefined steady flight condition (i.e. all of the acceleration terms were neglected). By introducing the acceleration terms into the equations it is possible to find solutions for unsteady manoeuvring flight. The preliminary stage when performing inverse simulations is to define the manoeuvre of interest.

2.2.1 Analytical Definition of Helicopter Manoeuvres

Conventional helicopters have four controls : main rotor collective, lateral and longitudinal cyclic and tail rotor collective. If a unique inverse solution of the equations of motion is to be found then four constraints must be applied on the motion of the vehicle. The most obvious method of constraint is to force the helicopter to fly a particular flight path. In effect this imposes three constraints on the vehicle

$$\left. \begin{aligned} x &= f_1(t) \\ y &= f_2(t) \\ z &= f_3(t) \end{aligned} \right\} \quad (1)$$

The form taken by the above functions is dependent on the shape of the flight path. Various flight path generating algorithms have been developed for use in HELINV and are documented in Ref. 8. In purely simplistic terms the three flight path constraints correspond to the three controls : longitudinal cyclic controls displacements in the x-direction, lateral cyclic the y-direction and collective the z-direction. As the pedals (tail rotor collective) are used chiefly to control the heading of the helicopter, it would seem logical to make this the fourth constraint, i.e.

$$\psi = f_4(t) \quad (2)$$

Choice of this set of constraints is consistent with the work of Charlton et al (Ref. 9) who use these four parameters for task definition in NOE flight trials.

2.2.2 Inverse Algorithm

The displacements (x, y, z) are differentiated to give earth axes velocities and accelerations which are transformed through the fuselage angles (θ , ϕ , ψ) to give the corresponding body axes quantities. Numerical differentiation is used to determine the attitude rates (hence body axes rotational velocities). Adopting this approach, the equations of motion become algebraic and can be solved for the attitude angles θ , ϕ and the rotor parameters C_T , $C_{T_{tr}}$, β_{1s} , β_{1c} by a Newton-Raphson iterative

process. Finally, the control angles are calculated.

2.2.3 Examples of Inverse Simulation

It is possible to simulate many types of manoeuvre using HELINV (wing-over, hurdle-hop etc), however those of most interest in this study are simple translations along a constant height, linear flight path from one hover condition to another. This class of manoeuvre has been chosen mainly because of the large amount and availability of flight data recorded during helicopter agility trials at RAE Bedford (Ref. 9, 10). There are two types of manoeuvre : side-step (translation in lateral direction) and quick-hop (translation in the longitudinal direction). Manoeuvres of this sort are typically used to move swiftly between areas of cover as indicated in Figure 1. As the flight path is a straight line, manoeuvre definition is achieved by specifying the velocity profile of the helicopter. If it is assumed that the helicopter reaches its maximum velocity, V_{max} , midway through the manoeuvre, Figure 2, then the following conditions must be satisfied

$$\left. \begin{aligned} t = 0, \quad V = 0, \quad \dot{V} = 0 \\ t = t_m/2, \quad V = V_{max}, \quad \dot{V} = 0 \\ t = t_m, \quad V = 0, \quad \dot{V} = 0 \end{aligned} \right\} \quad (3)$$

where t_m is the manoeuvre time. The simplest appropriate function which will satisfy the above conditions is a fifth order polynomial

$$V = at^5 + bt^4 + ct^3 + dt^2 + et + f \quad (4)$$

If the length of the flight path is s , then

$$s = \int_0^{t_m} V(t) dt \quad (5)$$

An algorithm has been written to calculate the manoeuvre time which satisfies equation (5) as well as conditions (3) for a user defined maximum velocity and distance. For convenience the helicopter is assumed to start the manoeuvre pointing along the earth x-axis, hence the earth fixed axes velocities are given by

$$\left. \begin{aligned} \dot{x} = V \\ \dot{y} = \dot{z} = 0 \end{aligned} \right\} \text{Quick-Hop} \quad \left. \begin{aligned} \dot{y} = V \\ \dot{x} = \dot{z} = 0 \end{aligned} \right\} \text{Side-Step}$$

The time histories shown in Figure 3 were generated by inverse simulation of a Westland Lynx helicopter flying both side-step (to the right) and quick-hop manoeuvres. In each case the length of the flight path is 100m and the maximum velocity reached was 30 knots. In the quick-hop a nose down attitude is adopted to produce the required acceleration, and the nose is brought back up to decelerate the helicopter. In the side-step manoeuvre the helicopter is rolled in the required direction to produce accelerations, only very small excursions in pitch are noted. The time histories of collective indicate a similar thrust requirement.

3. Conventional Model Validation

Traditionally, validation of aircraft mathematical models has been achieved by comparing the responses to given control inputs of a real vehicle with its corresponding simulation. The size of the inputs is often kept small in order to prevent displacements from trim which would take the helicopter beyond the region of linear responses. The control sequences used usually consist of one or more step or ramp inputs. There are problems associated with faithfully reproducing step or ramp inputs in a real helicopter but they can be overcome, for example, by applying preprogrammed inputs via the autostabiliser equipment (Ref. 12). A more fundamental drawback is that simple step or ramp inputs are not representative of control inputs the pilot is likely to use in NOE flight. In this flight regime the pilot will be constantly updating his control inputs to meet the constraints of his desired flight path. It is possible that a model may not simulate the behaviour of the helicopter in constrained flight (due, for example, to poor prediction of coupling effects), and use of simple control inputs for validation may not show this problem.

A new methodology is required rather than a different approach to existing techniques if this problem is to be overcome. The most obvious solution is to fly the real aircraft through a series of NOE type manoeuvres, recording the control displacements throughout. The measured control inputs could then be applied to the simulated helicopter and the responses compared. Problems arise when this process is attempted, as shown by the following example.

3.1 Time Response Calculation Using Control Displacements Measured In Flight Trials

The flight data used in the preparation of this paper was supplied by the Royal Aerospace Establishment. The data was gathered during helicopter agility trials at RAE Bedford. During the trials specific tasks were defined by giving the pilot limiting values for certain parameters. In the side-step manoeuvre, for example, the pilot's task is to fly side-ways between two markers as aggressively as possible, maintaining a constant heading and altitude. Flight path co-ordinates are recorded by kinetheodolites, and aircraft parameters (states, controls and accelerations) by a digital data acquisition system. Complete details of the trials are given by Padfield and Charlton (Refs. 9 and 10).

The example used here is that of a 300ft (91.5m) quick-hop manoeuvre flown by a Lynx helicopter. The helicopter's control time histories are shown in Figure 4. The rapid control changes needed to fly this manoeuvre are apparent from these plots. In an attempt to validate the HELISTAB model using this data, a time response calculation (using a standard Runge-Kutta-Merson technique) was performed. Points on the control time histories were joined by ramps, and the helicopter's trim states and controls correspond to a hover condition. Figure 5 shows a comparison of the helicopter's body velocities and attitudes measured during the flight trials with those generated by applying the control inputs from the same trial to the HELISTAB model. Figure 6 shows the actual flight path flown by the pilot and that calculated by integrating the helicopter's velocities.

Over the first few seconds there is good agreement between the simulated and actual velocity and attitude responses, however after about 5 seconds the two sets of data begin to diverge. It is clear that some deficiency in the model eventually leads the time response solution into a flight regime outside the validity of the model, so that after the first few seconds there is no basis of comparison between the flight data and the time response. Some inadequacy of modelling responds to aggressive control inputs in such a way as to introduce a divergence away from the flight results from which the model never recovers. As might be expected in a time response solution, without corrective action the simulation and flight path data gradually diverge, Figure 6, as slightly dissimilar velocities and rates are integrated. It reflects the fact that there is no closing of the loop in time response simulation and flight path variations are not corrected as they normally would be by the pilot.

4. Model Validation by Inverse Simulation

In section 3.1 the method used by the Royal Aerospace Establishment to define tasks in agility trials was discussed : the desired flight path geometry is specified, and a constant heading is adopted. This is similar to the manner in which manoeuvres are defined in HELINV, the difference being that in HELINV the position of the helicopter is a prescribed function of time whereas in the agility trials, the pilot is told to perform the manoeuvre "as aggressively as possible". It can be argued that the pilot has a perceived trajectory and uses his skill to achieve it, while at the same time maintaining a constant heading. If this is done successfully the conditions of HELINV are met. This is an important point because it has been shown (Ref. 7) that the constraints of HELINV can considerably modify the dynamics of the helicopter, and may contribute to the demanding nature of NOE flight. The stance taken in this paper is that the pilot is sufficiently skilled as to justify the use of HELINV in this context. There is evidence for this view in the flight data (Ref. 13).

A measure of comparison can be obtained from the example of section 2.2.3 and flight data from a similar manoeuvre. Figure 3 shows control time histories from an inverse simulation of a Lynx flying a 100m quick-hop, whilst Figure 4 has the control time histories measured in a flight test where a Lynx was flown through a 300ft (91.5m) quick-hop manoeuvre. As the flight paths are geometrically similar and in both cases a constraint is applied to the helicopter's heading, the control time histories in Figures 3 and 4 are comparable. The main rotor collective plots are similar both in trend and magnitude, lateral cyclic and tail rotor collective both show the same trend but with small differences in magnitude. Only longitudinal cyclic shows poor correlation. In order to isolate modelling aspects from the discrepancies caused by variations in the flight path, the next section discusses the use of test data to define the trajectory for HELINV.

4.1 Processing Flight Data for Inverse Simulations

Because it is defined analytically, the quick-hop flight path used originally for inverse simulation consists of a perfectly straight line, and the heading is held exactly constant. This level of precision is

obviously not possible with a human pilot flying a real aircraft - the actual trajectory flown in the flight trial (shown by the broken line in Figure 6) is far from a straight line, and the heading varies slightly also. Comparisons of inverse simulations and flight trials data both should be made with identical simulated and actual manoeuvres. Since the flight path co-ordinates are recorded during flight trials, by means of kinetheodolite measurements, it is possible to do this.

4.1.1 Flight Path Data

The HELINV inverse algorithm is used to calculate helicopter states and controls purely on the basis of user supplied earth fixed axes system velocities and accelerations. Until now these have been in the form of analytical expressions (as demonstrated in section 2.2.3), but the aim now is to use flight path data measured in trials to produce the velocities and accelerations. Flight path co-ordinates are measured at a low frequency (usually 4/sec) in the earth axes frame because of wind conditions in particular. The flight path data can contain a degree of noise, and if used "raw" large and rapid fluctuations in velocity and acceleration will arise as a consequence of numerical differentiation. This can cause problems of a numerical nature within the inverse algorithm (often due to extremely high accelerations). To avoid this problem, cubic spline curves are fitted through each of the co-ordinate time histories. This has the effect of smoothing the data and eliminates large fluctuations in derivatives. Calculation of velocities and accelerations is then a simple matter of differentiating the spline.

4.1.2 Aircraft Heading

As discussed earlier, it is necessary to constrain heading if a unique inverse solution of the equations of motion is to be found. Rather than attempting to hold heading constant, and also to maintain consistency, the time history of heading measured in the flight trial is used. Heading is not directly measured during the flight trials and therefore has to be calculated from the attitude rates which are recorded. The heading angle is found by integrating

$$\dot{\psi} = (q \sin\phi + r \cos\phi) \sec\theta \quad (6)$$

where θ , ϕ , p , q , r are all measured as functions of time throughout the manoeuvre. Having calibrated the control displacements (from servo movements to degrees at the rotor) all of the flight data has been processed and it is possible to make direct comparisons between the control inputs and responses of the real aircraft and those of the simulated vehicle.

4.2 Comparisons of Flight Data and Inverse Simulation Results

Two examples of comparisons between data recorded during flight trials and inverse simulations using flight path data measured in the same tests are now presented. These examples will demonstrate the power of inverse simulations for model validation.

4.2.1 Quick-Hop Manoeuvre

The control time histories for the Lynx flying a simulated and real quick-hop manoeuvre (Figures 3 and 4) were compared at the start of this section. A more direct comparison is given in Figure 7 where both simulated and real helicopter have been "flown" through precisely the same manoeuvre. Correlation between the data sets is much better although there are still large differences in the plots of cyclic pitch angles and tail rotor collective angle. The discrepancies between the plots will be discussed in section 4.3.

4.2.2 Side-Step Manoeuvre

Figure 8 is a comparison of time histories (measured and simulated) for the Lynx flying a 200ft (61m) side-step manoeuvre (in the left hand direction). A trend similar to the quick-hop can be observed - good correlation in collective and attitude angles but relatively poor prediction of cyclic and tail rotor collective angles. Discussion of differences in the plots in Figures 7 and 8 follows in the next section.

4.3 Discrepancies Between Flight Data and Inverse Simulations

There are two main areas which cause the discrepancies between the flight path and inverse simulation data. The first concerns the nature of the flight test and the conditions under which it was flown - it is important that the inverse simulation is compatible with the flight test. The second cause of discrepancies arises from modelling faults. A minor problem is the numerically induced transient at the initial hover state of the inverse solution, where there is some difficulty in smoothing the data in a manner which is consistent across all the channels.

4.3.1 Comparison of Flight Test and Inverse Simulation

a) Pilot Control Strategy

The results in Figures 7 and 8 quickly reveal how the manoeuvres are flown by the pilot. Consider first the side-step of Figure 8. The collective shows the application of rotor thrust from the start of the manoeuvre at 3 seconds to its end at about 11 seconds. The application of thrust only drops for a short interval around 7.5 seconds, and inspection of the bank angle, ϕ , shows that during this interval the helicopter is rotating from large negative (port) bank to large positive (starboard) bank. The manoeuvre is thus flown by a rapid bank to port, then application of increased thrust to accelerate the helicopter until halfway through the manoeuvre where the thrust is dropped while the bank is changed rapidly from port to starboard, followed by an increase in rotor thrust, this time to decelerate to rest. The manoeuvre is completed with a rotation back to vertical. All of this is clear from the inverse solutions, and flight data. The control movements corresponding to this manoeuvre are expected to be a pulse of positive lateral cyclic at the beginning of the manoeuvre, a negative pulse about the mid point and another positive pulse at the end. These features are clear in the flight data but are not so well defined, although discernable, in the simulation results, and indicate a need for a close look at the modelling. The flight data for the tail rotor shows the pilot coping with the torque

variations introduced by sharp changes in the collective, but the inverse solution again omits these features.

The quick hop of Figure 7 has similar features to those discussed above, but in the longitudinal plane. There are, however, significant differences. Note that the changes in pitch are not so sharp as those in bank for the side step. The obvious explanation for this is that the moment of inertia about the pitch axis is larger than that about the roll axis, and so the manoeuvre takes a longer time and hence has a smoother look. The flight data shows the pilot sharply applying longitudinal cyclic in an attempt to overcome the pitching inertia, so much so that it has to be reduced and even changed in sign as the helicopter eventually responds. This behaviour is not present to the same degree in the inverse solution, and possibly indicates some transient degradation of control power not included in the model.

b) Wind Conditions and Ground Effect

No provision is made in the mathematical model for the prevailing wind conditions or the effect of ground on the helicopter which may have been present during the flight trials. The data used here was measured on days when the wind velocity was less than 5 knots hence any wind effects should be small. A helicopter's proximity to the ground can produce thrust augmentation due to an increase of induced velocity at the rotor. This effect becomes negligible at a height of about two rotor diameters, Reference 11, (approximately 25m for the Lynx). The sidestep manoeuvre was performed at a height of approximately 12m, and the quick hop at a height of 20m. The helicopter may, therefore, have experienced ground effect during the trials.

4.3.2 Model Deficiencies

The following are examples of where inverse simulation has highlighted specific deficiencies in the HELISTAB model, and in one case, led to an immediate enhancement of the model.

a) Incorrect Data in Model

Validation by inverse simulations have already led to improvements to the basic model. For example, the mass of the helicopter in the standard data file was corrected when main rotor collective angle was found to be consistently different to the flight data by an offset of a few degrees. The values of other parameters have still to be verified, for example the location of the helicopter's centre of gravity. This can influence the fuselage pitch attitude and longitudinal cyclic values.

b) Rotor Dynamics

Within the HELINV algorithm the six equations of motion are solved for the attitude angles (θ , ϕ), the main and tail rotor thrust coefficients (C_T , C_{TTR}) and the longitudinal and lateral flapping angles (β_{1C} , β_{1S}). Having solved for these parameters the control angles can be found by consideration of the rotor blade dynamics. As the principal fuselage attitude angle and collective angle are accurately predicted it can be assumed that the correct thrust, and rotor forces and moments, are

being calculated. However, as the cyclic pitch angles are being poorly predicted, it can be deduced that there are inadequacies in the rotor model.

c) Coupling Effects

The principal attitude angle in the side step manoeuvre is obviously the roll angle, and in the quick hop it is the pitch angle. Figure 7 (the quick hop) shows good prediction of pitch angle and reasonable prediction of roll angle. In Figure 8 (the side step) there is good prediction of roll angle but poor correlation between pitch angle traces. The ability of the model to predict coupling effects must therefore be in doubt. It appears as if HELINV is simulating the dominant motions of the helicopter without predicting its secondary motions quite so well.

5. Conclusion

The HELISTAB model when embedded in the inverse simulation, HELINV, gives realistic values for aggressive manoeuvres in NOE flight and may be used for validation when forward simulation is unsuitable. Some discrepancy between flight data and the inverse solutions must be expected to arise because the heading constraint which is applied exactly in the theoretical simulations is relaxed to some extent in the flight trials where a variation of ± 15 degrees is allowed. Despite this, the comparisons of flight and simulated data are encouraging, and while the interpretations of the data in terms of pilot strategy and model deficiency given in this paper may be open to discussion, the main point to make is that the inverse simulation, by obtaining realistic solutions through the whole manoeuvre has enabled analysis and interpretation to take place while the forward simulation gave little information towards model validation. The conclusion is that inverse simulation is an important contribution to model validation.

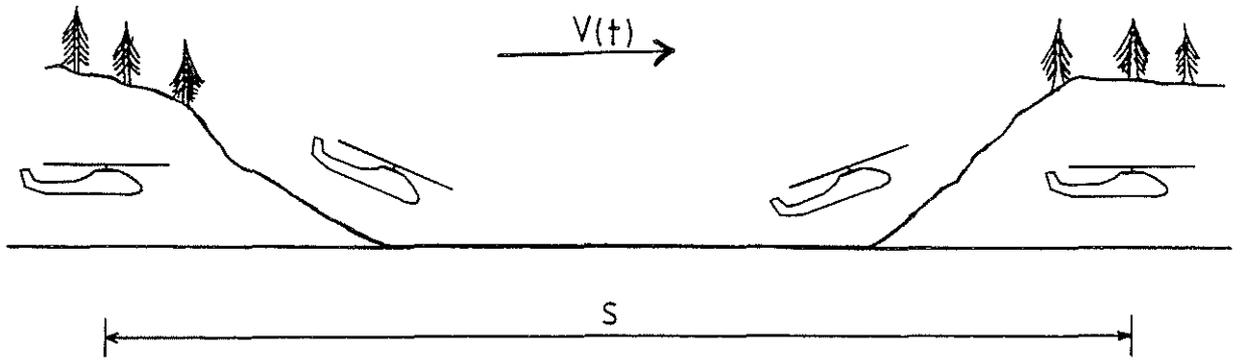
6. Acknowledgements

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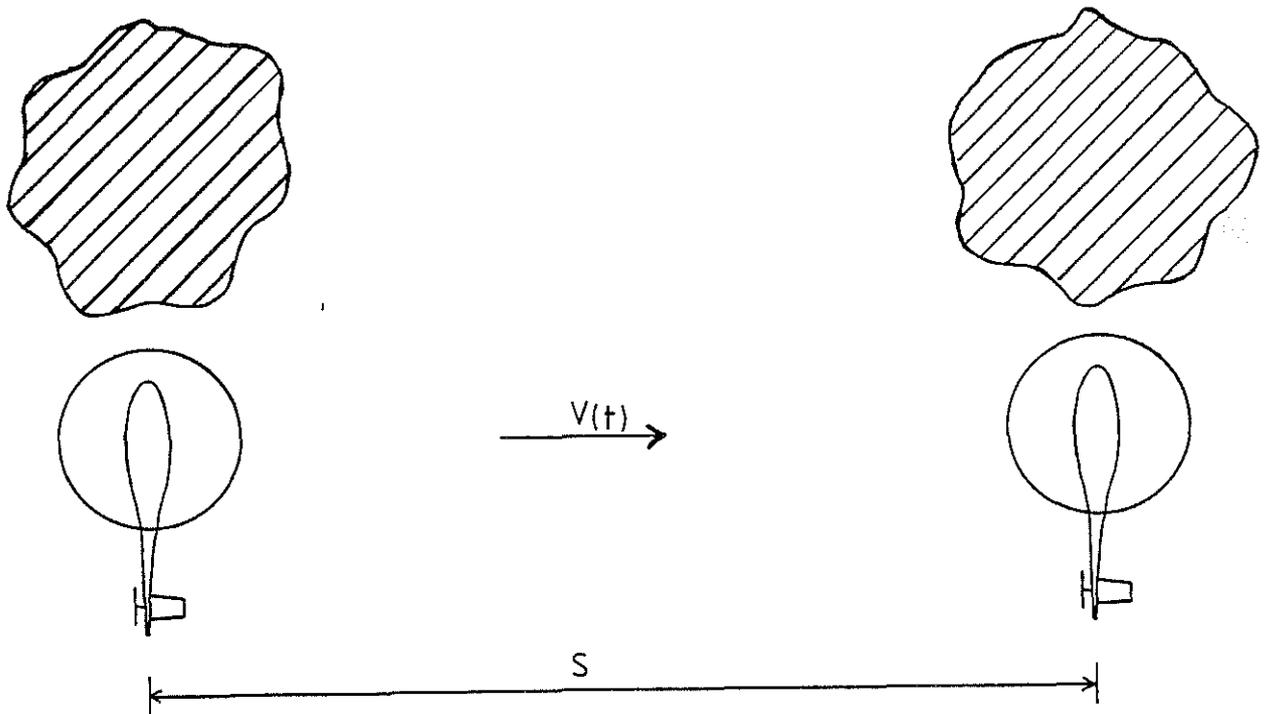
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a) The Quick Hop



b) The Side Step

Figure 1 : Linear Translation Manoeuvres

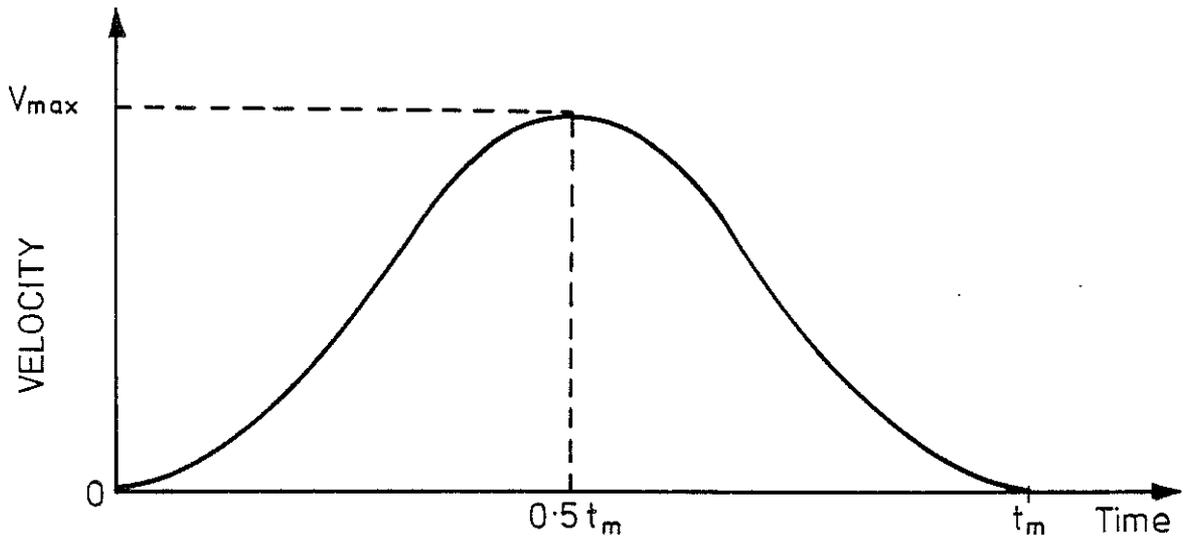


Figure 2 : Helicopter Velocity Profile for Linear Translation Manoeuvres

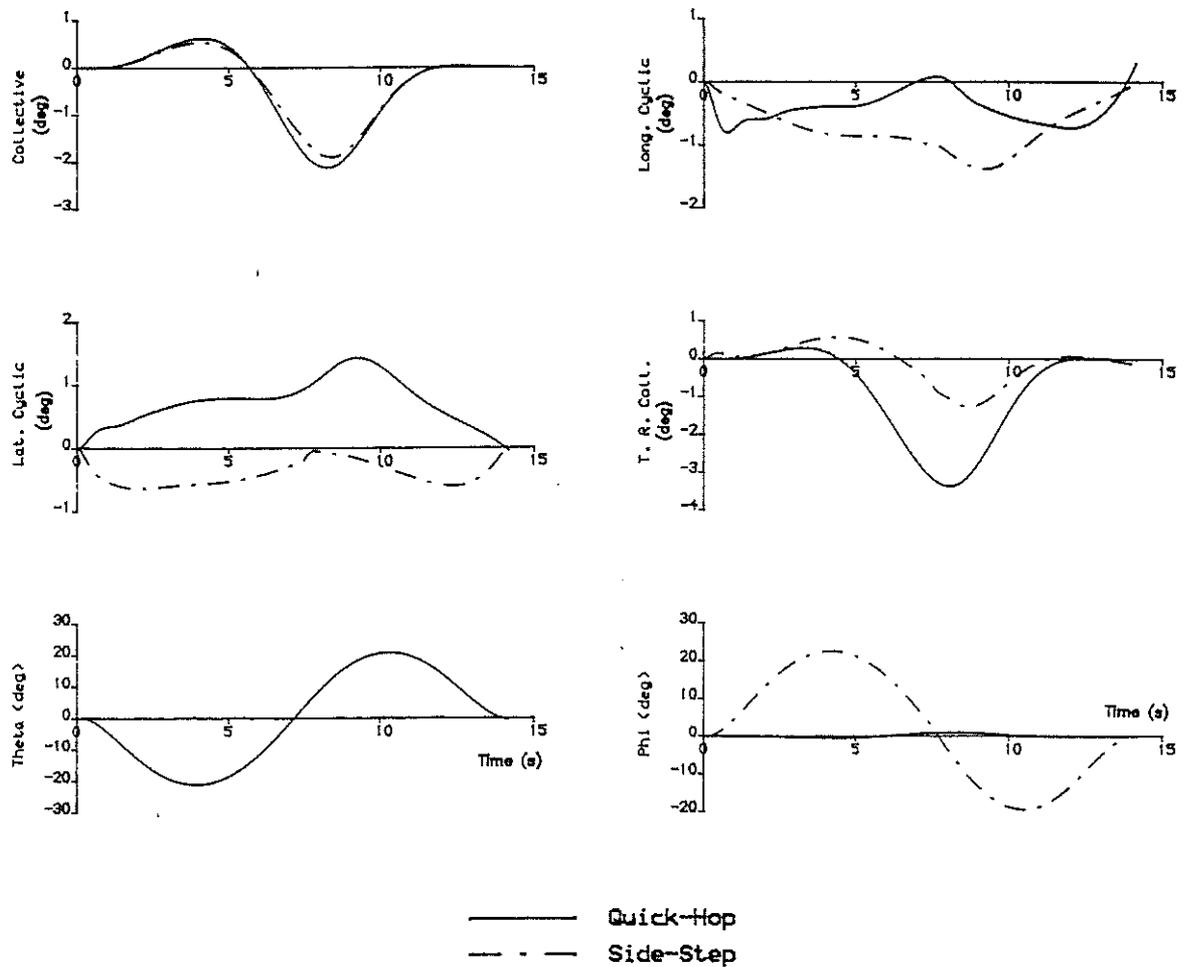


Figure 3 : Simulated Time Histories for LYNX Flying 100m
Linear Translation Manoeuvres with $V_{max}=30$ knots

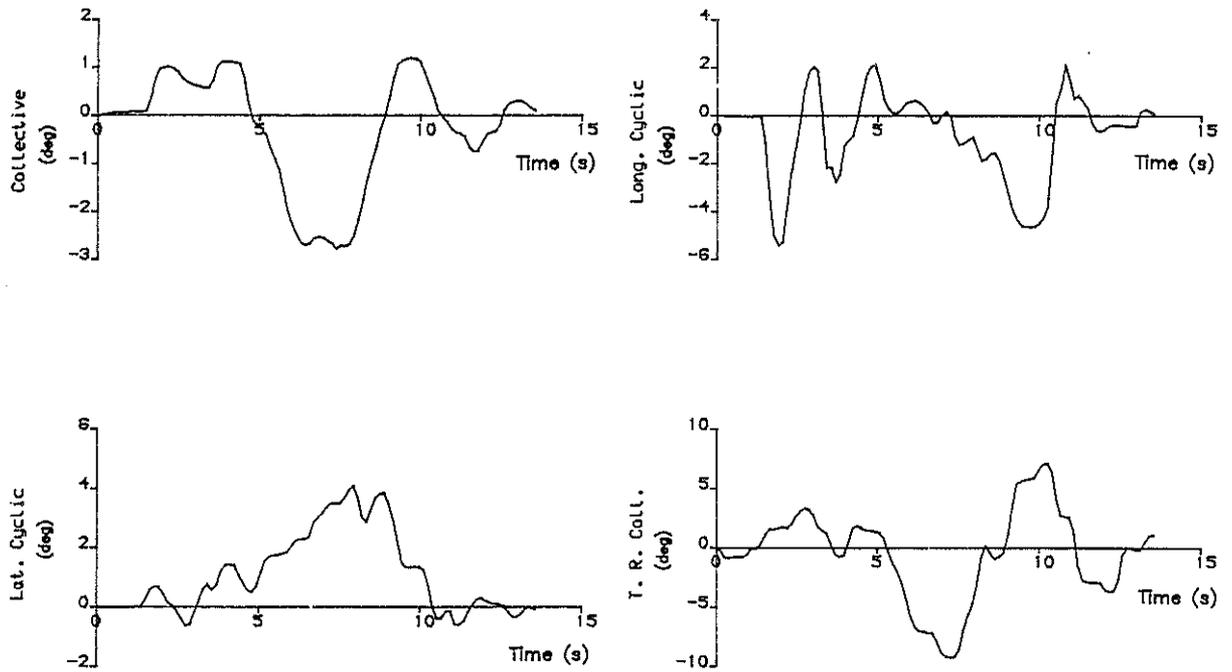


Figure 4 : Control Displacement Time Histories Measured During 300ft Quick Hop Flight Trial with LYNX Helicopter

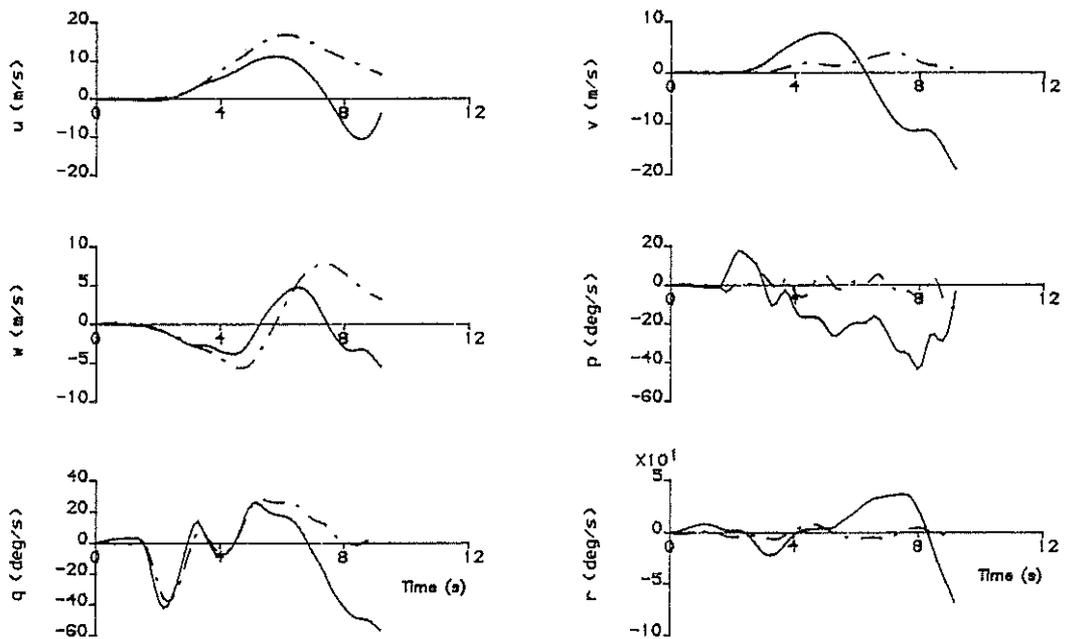


Figure 5 : Comparison of Measured States with Those Calculated Using a Time Response Solution Driven by Measured Controls (LYNX - 300ft Quick Hop)

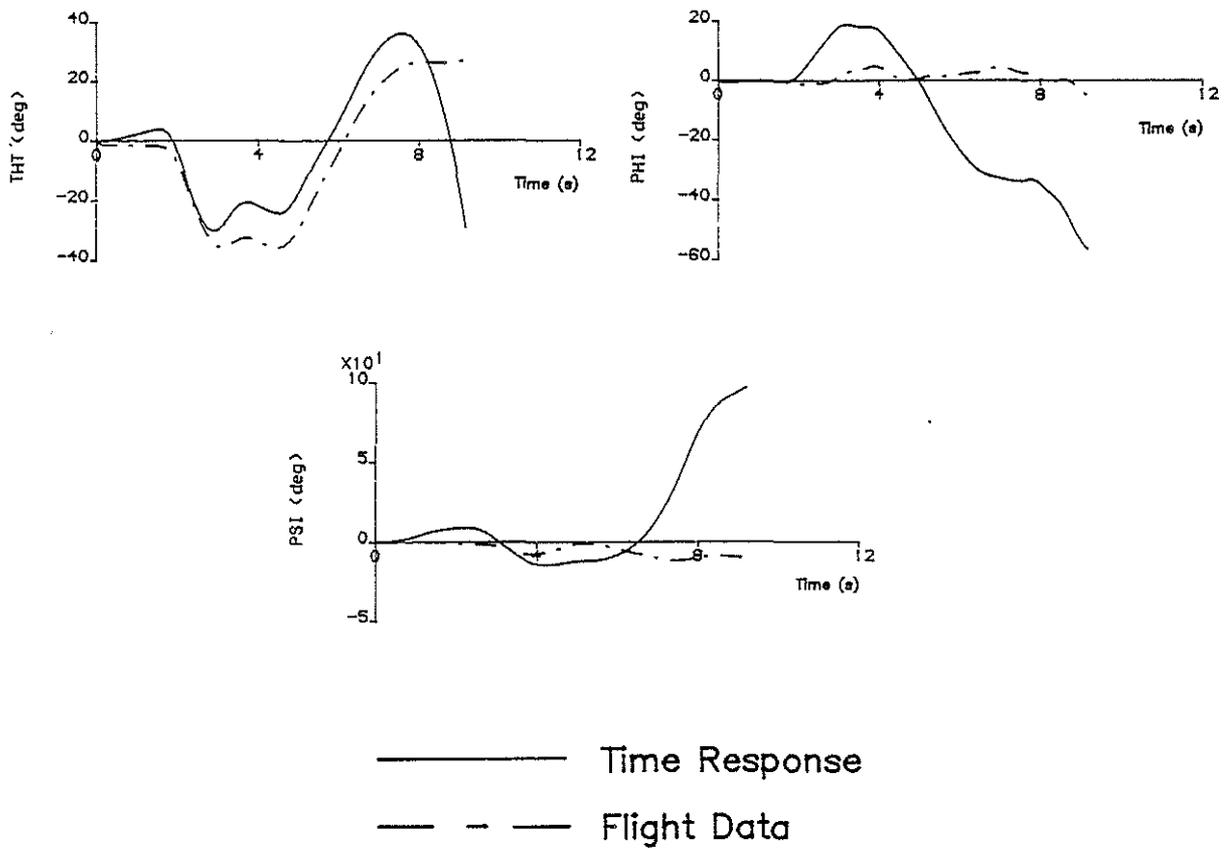


Figure 5 : Cont.

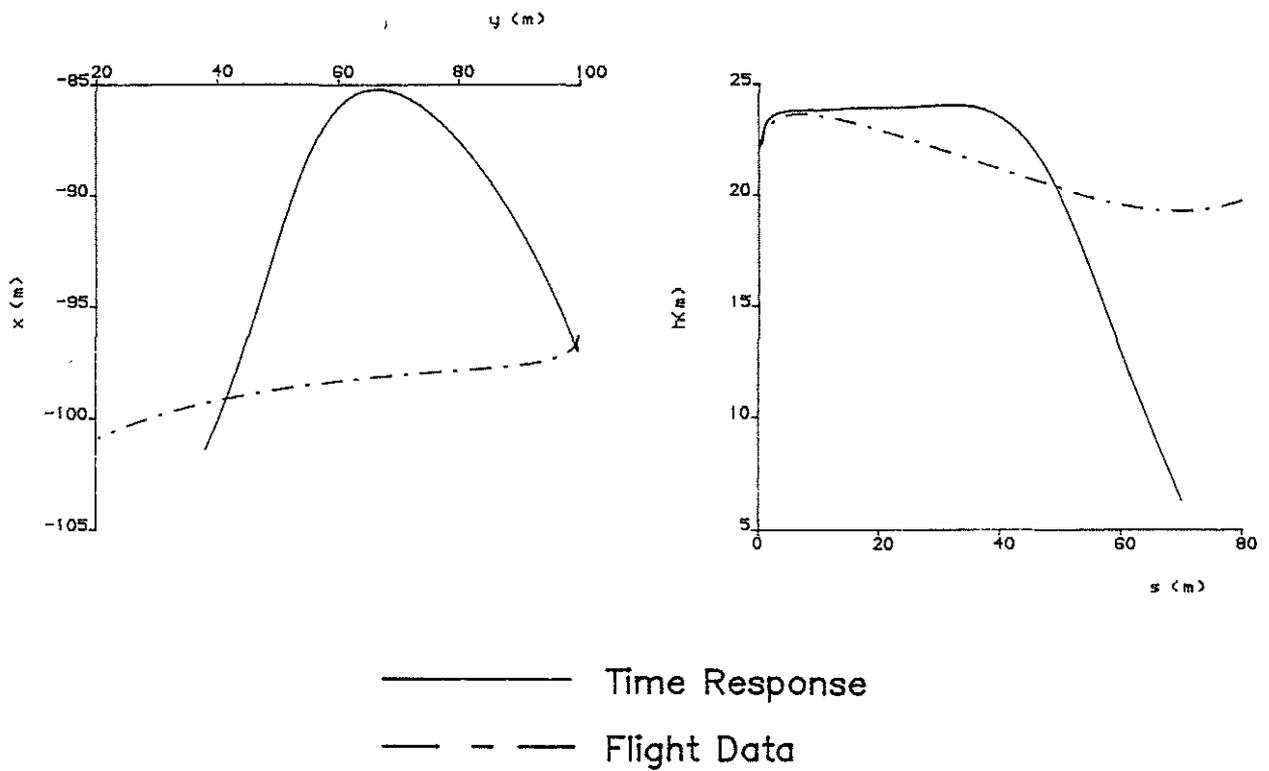


Figure 6 : Comparison of Actual Flight Path with That Resulting From Time Response (LYNX - 300ft Quick Hop)

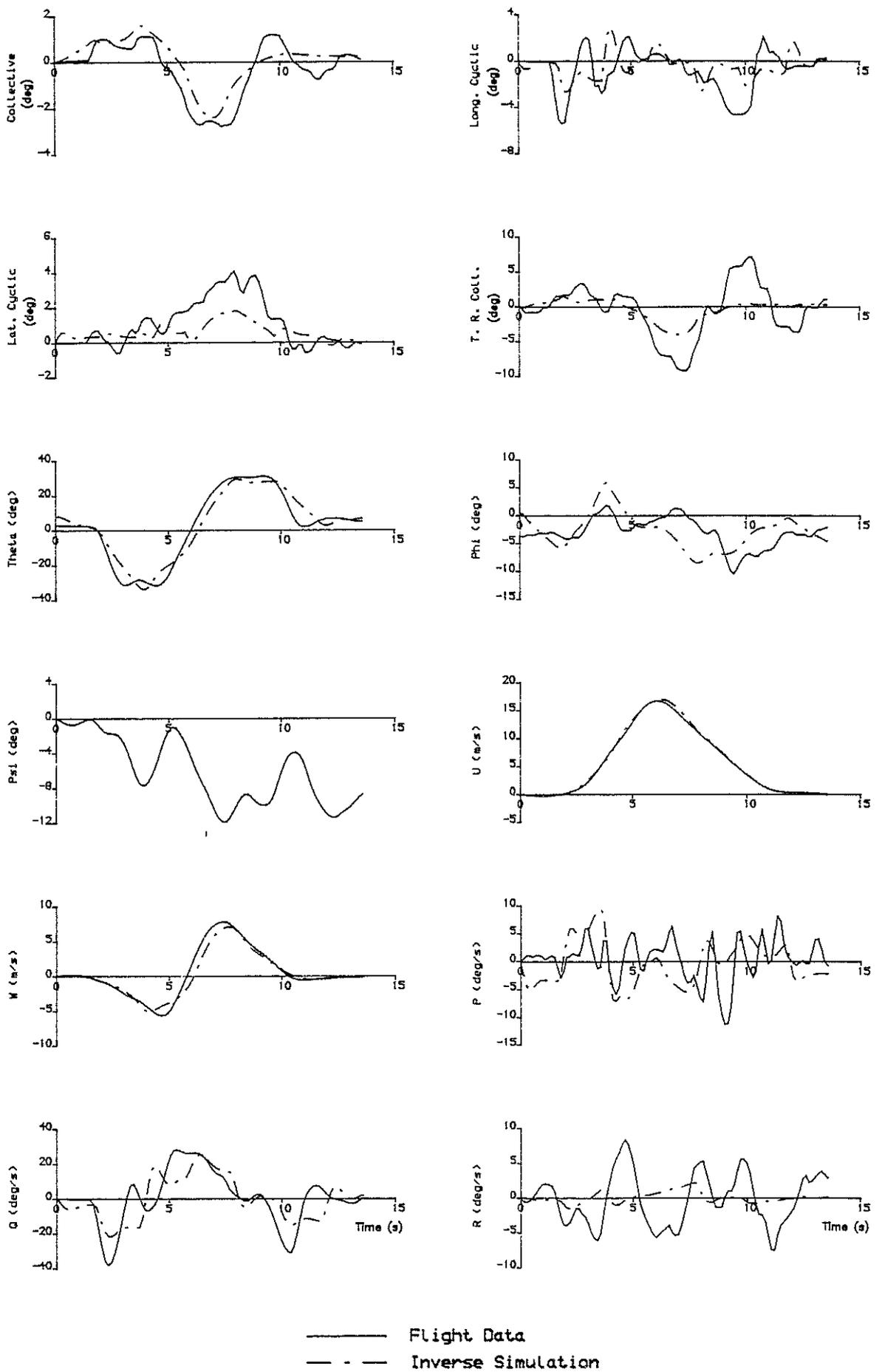


Figure 7 : Comparison of Flight Data and Inverse Simulation for LYNX Flying a 300ft Quick Hop Manoeuvre

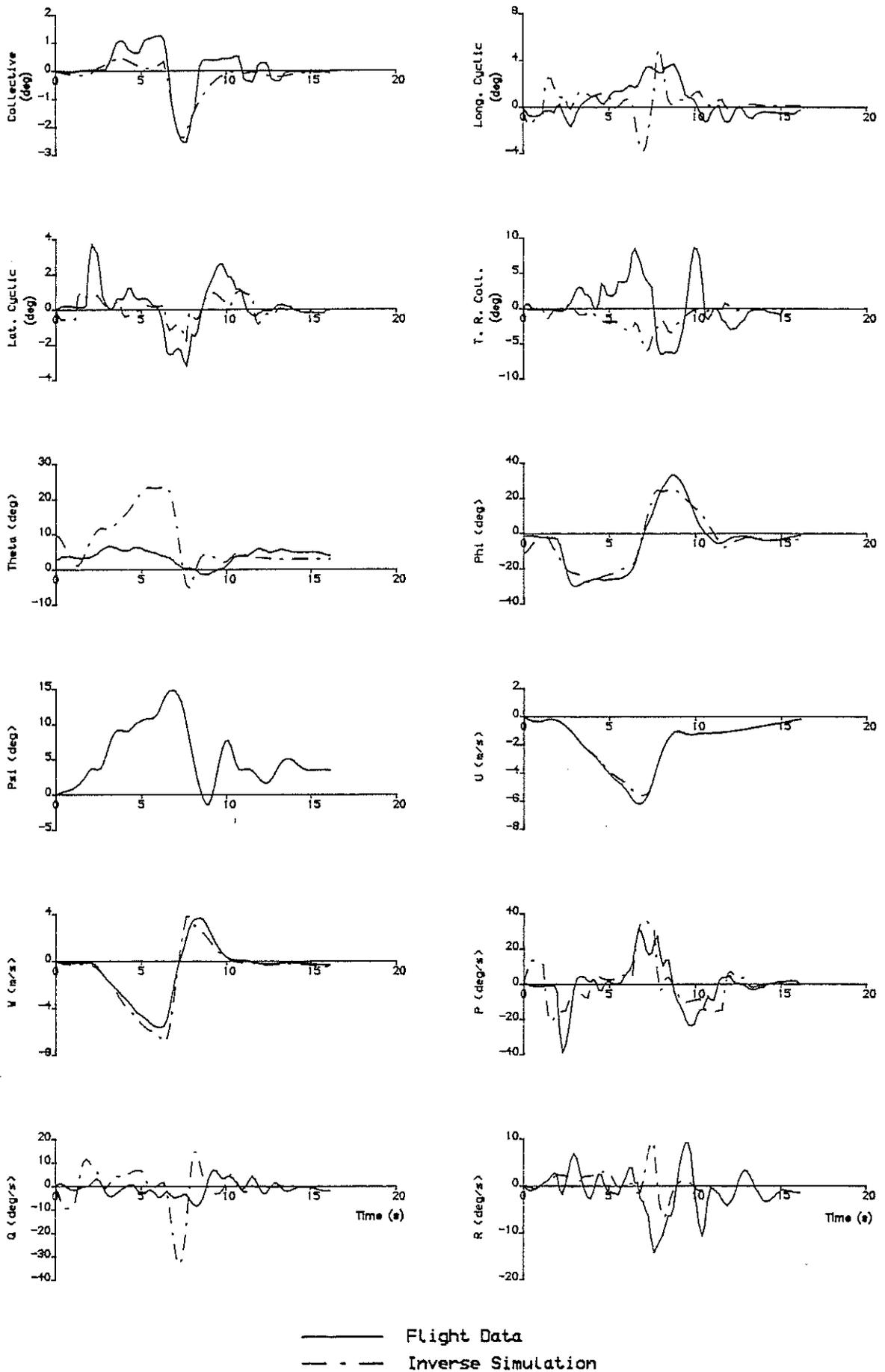


Figure 8 : Comparison of Flight Data and Inverse Simulation for LYNX Flying a 200ft Side Step to the Left