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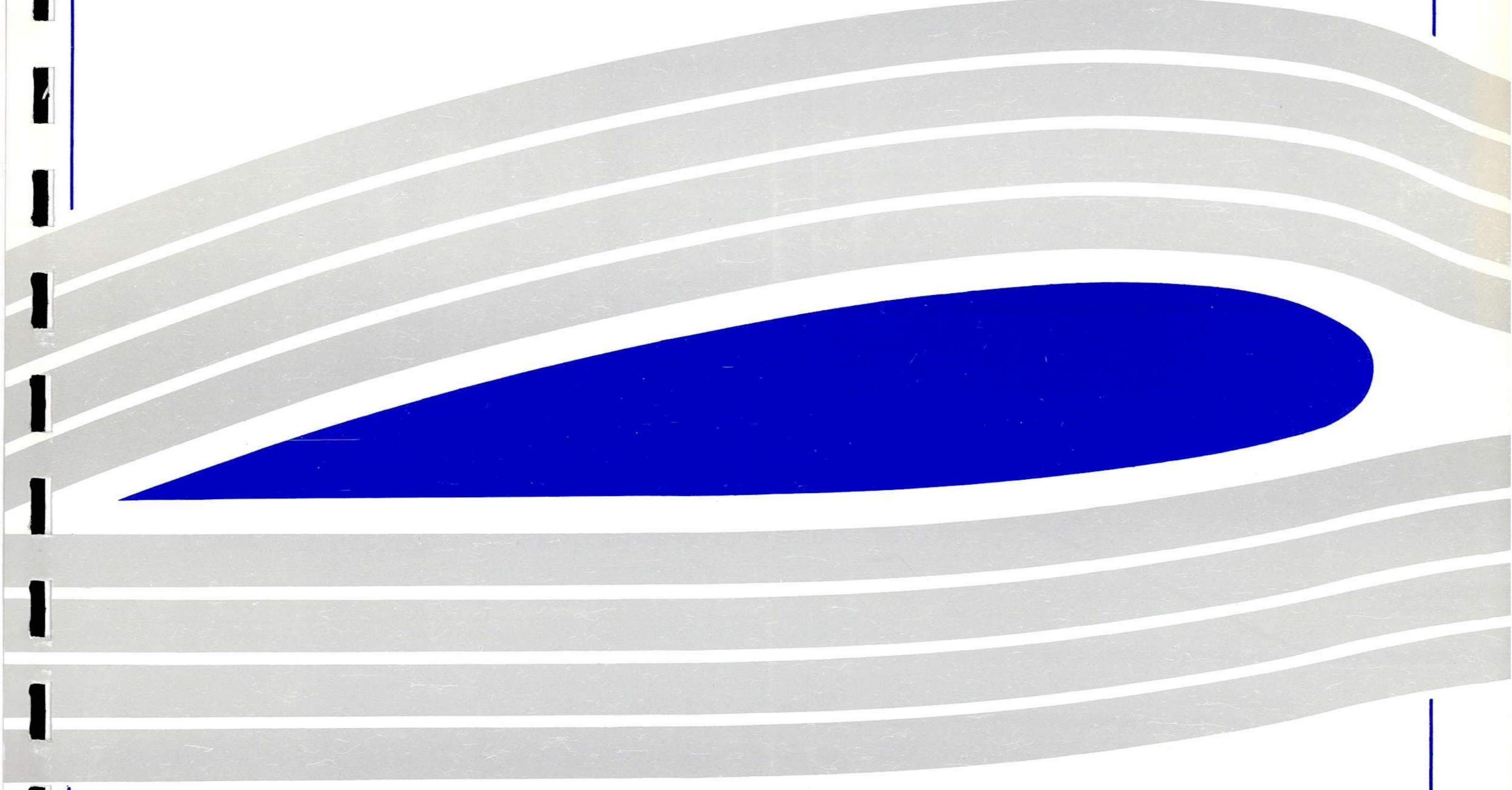
Internal Report No. 9802 February 1998



On The Development Of Multiple Manoeuvre Mission Sequences For Inverse Simulation

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Abstract

As part of the continuing programme of work and collaboration between the Defence Evaluation and Research Agency (DERA) and Glasgow University (GU), the author was invited to attend the final phase of flight simulation trials entitled 'TWIN3' at DERA, Bedford; using the Advanced Flight Simulator (AFS) large motion system. The precise nature and details of the five-day trial are given in [1] but the main thrust of the trial was essentially divided into two areas:

1. The simulation of American Design Standard (ADS) Mission Task Elements (MTEs) using a software image database of Coltishall airfield with the appropriate ADS-33 visual cues.

2. The simulation of a mission sequence based on the Haxton Down software image database which comprised fourteen individual tasks. The tasks were either based on ADS MTEs or Nap-of-the-earth (NOE) flight. A full description of the manoeuvre elements is given in Appendix A of [1].

The inverse simulation package HELINV at GU contains a library of manoeuvres based both on ADS MTEs and NOE flight. However, the manoeuvres are separate and individual and until recently it was not possible to run a simulation of combinations of two or more manoeuvres. A request was put forward to develop a method whereby it was possible to choose several elements (MTE or NOE) from the manoeuvre menu and piece them together to form what has been termed a 'mini-mission sequence' and then inverse simulate the mission as a whole. This report describes that development and presents the results from several simulated mission runs.

1. Introduction

Although the development of a method of simulating more than one manoeuvre at a time has been addressed before at GU, a comprehensive treatment of the subject of conjoining several different manoeuvres to create a mission that may last several minutes remains a largely uncharted field of enquiry. Previously, it was thought that combining the results from inverse simulation runs of several individual manoeuvres would be exactly the same a those results obtained from one inverse run of a number of manoeuvres combined in a mission sequence. The first point to be considered in this report which will further demonstrate the results found by Thomson and Bradley, [2], [3], and illustrate the fact that one manoeuvre may have some influencing effect on another which follows on from it. This, as will be shown, is particularly noticeable when, for example, a constant velocity longitudinal manoeuvre is preceded by what is commonly known as the 'Pop-up' manoeuvre, Figure 1.

Currently HELINV, [4] has two manoeuvre menu options, one pertaining to NOE flight and the other being biased towards those manoeuvres described in the ADS-33C, [5] and ADS-33D, [6], i.e. the MTE manoeuvres. It was decided to select those manoeuvres from both flight regimes that were thought to be most appropriate and useful to the construction of a mission sequence, indeed this decision was part influenced by the information already obtained from DERA. A stand-alone software program was developed which permitted linking to the manoeuvre library within HELINV. A user has the simple task of entering the required number of elements (manoeuvres) that comprise the mission sequence and the corresponding data for each element, which may include flight speed, acceleration times and values and any other data relevant to that particular element. It should be noted that no special precautions were taken to ensure that the user conformed to the obvious criterion of manoeuvre continuity, by which it is meant that if one manoeuvre is carried out at a constant velocity, it follows that the initial point of the subsequent manoeuvre must have the same velocity.

The 'Mission-Builder', (MIBIL) program operates by generating large files of data, which, to all intents and purposes, describe the flight path that the user has generated for inverse simulation. A further menu option within HELINV has been created to allow this data to be read in before setting the inverse simulation algorithm in motion. The output results can then be put into graphical form for interpretation and analysis.

This report consists of four main sections of research, the common theme being the development of multiple manoeuvre missions using MIBIL and the inverse simulation of the resulting flight path. The first section, as stated will investigate the effects of piecing together manoeuvres and the possible effects that one manoeuvre may have on another that follows it. Part two of the report will deal with recreating a small section of the Haxton Down mission sequence to illustrate that it is possible to at least divide a large mission into several smaller components each of which represent approximately thirty percent of the entire sequence. Unfortunately, however, due to time limitations and the need to further research in other areas it was not possible to simulate all of the Haxton mission sequence as HELINV requires the development of several new manoeuvres. The research time was utilised implementing the changes within the HELINV algorithm and development of MIBIL; this has lead to the creation of a useful tool for analysing multiple manoeuvre sequences.

The subsequent two sections have been devoted to creating two simple mission profiles for performing different tasks, for example the tracking and destroying of a target in a military environment. The decision was taken, for the purpose of improved illustration of results, to create two mini-mission sequences, the first being carried out at a constant heading and the second having all manoeuvres performed at constant side-slip. It was found that when certain manoeuvres were combined, which involved specifying either heading or side-slip, the graphical results were uncertain and it was unclear where one manoeuvre ended and another began.

Since the work at DERA is moving into a culminating phase, it is likely that this section of research will also be the final phase of flight path and manoeuvre development within HELINV. It is hoped that a successful conclusion has been met with reference to the collaborative work between Glasgow University, Glasgow Caledonian University and DERA, regarding the deliverables produced, and the possibility of enabling further research to be undertaken.

2. Dynamic Characteristics Of Multiple Manoeuvres

The purpose of this study was to further investigate the effects of piecing together two manoeuvres which happen to also occur in the 'constrained' flight regime. Constrained flight path manoeuvres are commonplace in helicopter flight and may range from a military pilot following a particular section of terrain in NOE fashion, or in the case of a civil pilot the approach and landing to a helipad which may be located on an oil-rig or some other area of limited space. The possibility that constrained flight may have some sort of effect on helicopter flight was first appreciated during the development of HELINV and subsequent work has investigated the effects of so-called constraint oscillations.

It was decided to firstly look at longitudinal flight as in previous work, and in particular at the pop-up manoeuvre with a constant velocity linear section attached at the exit of the pop-up, Figure 1. The flight parameters were fixed at the following values:

Pop-up
Flight velocity - 65 kts
Distance and height at exit of pop-up - 200 m and 25 m respectively

Constant Velocity Section
Constant velocity section - 65 kts
Distance covered in constant velocity section - 500 m

One aspect of constraint oscillation investigation that has not been carried out before is the effect of varying the order of the polynomial on which the manoeuvre is based, and it is this point that will be mainly addressed. The flight path polynomial order for the pop-up can be fifth, seventh or ninth order. A full description of the manoeuvre and how the various polynomials were derived is given in [7], but the basis of the mathematics lies in examining the boundary conditions appropriate to such a flight path. For example if we specify the conditions,

$$\left.\begin{array}{llll} \text{i)}\ t = 0, & z = 0, & \dot{z} = 0, & \ddot{z} = 0 \\ \text{ii)}\ t = t_m, & z = -h, & \dot{z} = 0, & \ddot{z} = 0 \end{array}\right\} \qquad (1)$$

where,

t_m is the time taken to complete the entire pop-up manoeuvre
h is the height at the exit of the manoeuvre (see Fig. 1);

it can be seen that there are six conditions pertaining to the flight path and consequently the simplest possible function for z is fifth order in nature, Equation 2.

$$z = at^5 + bt^4 + ct^3 + dt^2 + et + f \tag{2}$$

Figure 2 illustrates the longitudinal stick displacement time-history for the pop-up / linear sequence for all three polynomial orders. The pop-up actually ends at about the six second mark (this can be seen in the fifth order diagram), and the linear section continues for another fifteen seconds approximately. The oscillations in all three diagrams are clearly noticeable and it is very apparent that the amplitude of the oscillations increases with the polynomial order, with the absolute value of the largest oscillation in the 5th order diagram being several orders of magnitude less than that of it's 9th order counterpart. This is due to the fact that the 9th order polynomial representation of the flight path presents curves of a higher gradient, which effectively means that transition from steady level flight to climb in the pop-up occurs in a more severe manner, hence the pilot must exercise more stick movement to complete the manoeuvre. It is for reasons such as this, that it is necessary manoeuvres to define manoeuvres as realistically as possible, and the ADS documents have aided this process. Figure 2 also allows an initial guess at the period of the oscillations, which is approximately 1.5 seconds. Upon further investigation, and using a software package, to enable more accurate results, the period was found to be 1.2432 seconds, again agreeing with previous results obtained at GU, where the period was found to vary between 1.1939 and 1.2007 seconds. It is difficult to say in which diagram the oscillations subside back to a steady state value first, but in each manoeuvre the time taken for this is something of the order of ten seconds. A time-step of 0.02 seconds was used as an input to the numerical differentiation scheme, the justification being that this was necessary to curb the truncation error which itself would act like a numerical damper, [8]. As the helicopter model used in the inverse simulation is representative of an semi-rigid rotor configuration, a high degree of coupling longitudinal-lateral coupling is present and the effect is noticed on corresponding plots of lateral cyclic or indeed roll angle, as will be seen later in the report. Figure 3 presents the pitch angle and pitch-rate for the seventh order version of this manoeuvre, again the oscillations are clearly seen on both plots.

Figure 4 illustrates the point that it is difficult to inverse simulate combinations of elements that contain the level-turn manoeuvre. Here a level-turn is joined, like the pop-up, with a section of constant velocity. The turn is performed at 35 knots and the constant velocity section traverses a distance of 300 m. Due to the fact that the level-turn involves a heading change of 180 degrees, it is not possible to specify a constant heading for the manoeuvre and this determines that the simulation must be carried out at constant side-slip. At the exit of the level-turn (after 48 seconds approx.) large oscillations, at reduced magnitude are again visible on the pitch angle plot. The roll attitude plot illustrates the coupling factor mentioned earlier, although it is evident that this is a manoeuvre which necessarily contains elements of lateral cyclic behaviour. Difficulty would arise if, for example, a side-step MTE had to be performed after the turn (providing of course that an element had been included to bring the vehicle to a trimmed hover, such as the speed-vary element). At this stage the helicopter would have a heading of 180 degrees and this may induce problems in the side-step where a fixed heading has to be specified. If this were to be set at 180 degrees, this in turn would cause problems for other subsequent elements, for example the slalom which must be performed at constant side-slip.

3. Inverse Simulation Of Haxton Down Course

The full mission sequence of the Haxton Down course is shown in Figures 5 and 6. It is clear that there are fourteen distinct elements to perform in the sortie ranging from simple MTEs like the side-step or bob-up / bob-down to more complicated manoeuvres such as the rapid-egress. It was originally hoped that it would be possible to define the whole of the Haxton mission sequence within MIBIL and then run this data through HELINV to obtain the inverse simulation results, unfortunately, time limitations have prevailed, and as yet the rapid-egress and curved-approach have not been mathematically defined and converted to actual manoeuvres within HELINV and subsequently MIBIL. It is possible that the climbing-turn manoeuvre within HELINV could be modified to represent the curved-approach and thus providing a solution to that particular problem.

Nevertheless the exercise here is to demonstrate that it is possible to re-create at least some portion of an actual flight sortie. There are of course a number of other problems that potentially need to be addressed. For example the length of the course is such that the total flight time is approximately 20 minutes. Even using a time-step of 0.1 seconds in HELINV will lead to the generation of data files that contain twelve-thousand data points. This would increase the inverse simulation time by several orders of magnitude and may prove to be a difficult obstacle when using plotting routines to view the data.

To illustrate the ability of MIBIL and HELINV to inverse simulate a section of the Haxton Down course it was decided to have two MTEs and two sections of NOE flight. This requirement was met within the last four elements of the Haxton sequence. There are two elements that essentially relocate the helicopter, NOE, to two different hover points and then at the two hover points the MTEs, acceleration / deceleration and bob-up / bob-down are executed, respectively. Due to problems associated with combining manoeuvres that require constant side-slip, such as the level-turn manoeuvre, and MTEs that are defined as having constant heading, it was decided to perform these four elements in a longitudinal manner so that the results would show more clearly the individual manoeuvres performed and the controls required to execute that task.

Although the manner in which the four elements of the Haxton sequence is different to that given in Figure 6, the main point is that four manoeuvre elements from the Haxton Down sequence were inverse simulated and the results can be seen in the form of firstly the pilot stick controls, Figure 8 and secondly in the longitudinal and lateral states given in Figure 9. Figure 9a of pitch angle is particularly good as it distinctly shows the four elements of the sequence. The first is a deceleration (speed-vary) element from 35 kts to 0 kts. This takes approximately 58 seconds, whereupon the helicopter is in a trimmed hover condition and ready to execute the next section. It can be seen that by comparison element 2 is more aggressive and this is characteristic of the ADS MTEs. This quick-hop could be used for example in a battlefield situation to move across open ground from one place of cover to another. Element 3 is similar to the quick-hop but is not as aggressive and is more likely to be realistic in that there is a more smooth transition into the acceleration phase and perhaps more time is spent at some constant velocity, say 80 kts, before entering the deceleration phase and eventually reaching a trimmed hover condition again. When the aircraft is finally in the hover at the required position, a target heading is given and the helicopter performs a bob-up / bob-down MTE to acquire the target and launch weapons if that is the requirement.

Note that small constraint oscillations in both cyclic channels are observable in the transition between the quick-hop MTE and the dash-stop NOE section of flight. The final target acquisition task also produces small opposing variations in roll, but very little can be seen in the illustration of pitch angle.

4. Inverse Simulation Of A Constant Heading Mission

Figure 10 illustrates a simple mission containing seven elements, three side-steps, two speed-vary manoeuvres, an acceleration / deceleration and a bob-up / bob-down MTE combined in such a manner as to simulate a helicopter acquiring a target from a distance and following the target to a point where engagement can take place. The mission is performed at constant heading and all of the elements contained therein, with the exception of the speed-vary tasks are defined in the American Design Standard documents, such as ADS-33D.

The mission starts at point 1 where a ground target is initially sighted moving from the east, a side-step is used to move behind cover and also to follow the target to point 2. It is realised that to get closer to the target open ground must be covered and the helicopter is repositioned via another side-step to point 3. At point 3 a gap in the cover promotes the possibility of being spotted, and therefore it may be necessary to investigate this before dashing out. Between points 3 and 4 two speed-vary manoeuvres are executed. The first accelerates the helicopter from the hover to a speed of 5 knots over a small distance and the second repeats this manoeuvre in a decelerating manner, bringing the helicopter back to the hover just before the edge of the cover at point 4. At this stage an acceleration / deceleration MTE is carried out to traverse the distance past the gap to another point, 5, in which the vehicle is again in the hover state. A bob-up / bob-down MTE at this point enables the pilot to once again track the movement of the target on the ground. When the target continues to move in a westward direction, a third side-step is executed to bring the helicopter into a position where the pilot is able to engage the target, and the mission sequence ends at point 6.

Figure 11 illustrates the pilot stick time-histories in both the longitudinal and lateral cyclic channels and is immediately apparent that here is a task that is quite aggressive and may prove to be quite demanding on the pilot. The main reason for this is that all of the manoeuvres with the exception of one have been defined mathematically to be correlative with the definitions given in ADS-33. As with the Haxton mission sequence it is perhaps more useful to analyse the roll and pitch attitudes of the aircraft to enable a clear distinction to be made as to where one manoeuvre begins and another terminates. With reference to the difference in manoeuvre aggression between NOE and MTE flight this is demonstrated if a comparison is drawn from the two speed-vary manoeuvres, which are executed between the side-steps at the initiation of the sequence, and the quick-hop. The traces of longitudinal cyclic stick of the speed-vary elements are hardly visible on the time-history and are essentially non-existent on the lateral stick. The bob-up / bob-down MTE is not really apparent on either of time time-histories and can be seen only as small variations in the linear nature of the trace in the time succeeding the quick-hop, and before the final side-step.

It is particularly useful to have time-histories of these attitudes as in pitch the quick-hop is clearly visible and reaches a maximum nose down attitude in the region of 25 degrees and an absolute increase of 5 degrees when flaring in preparation for the return to the hover. In full complement to this, the roll attitude provides and excellent illustration of the three side-steps performed during the sequence, each of which attains attitude changes of the same magnitude as in the quick-hop, suggesting that these were also performed in a relatively aggressive manner.

Attention is drawn to the fact that each element is performed instantaneously after the previous one and there is no time allowed for pilot preparation for following manoeuvre or perhaps for more realistically, easing the vehicle into a more favourable position in order that the subsequent element may be accomplished with less workload. This is perhaps better demonstrated in Section 5, where particular elements have been deliberately inserted into the manoeuvre sequence to investigate the effect of introducing a settling time for the aircraft dynamics.

5. Inverse Simulation Of Constant Side-slip Manoeuvres

The purpose of introducing a mission sequence with constant side-slip was largely to illustrate the mission building capability of other manoeuvres within the MIBIL program. Here, illustrated in Figure 13 is a simple mission sequence which theoretically involves flying round in a large oval shaped circuit. The circuit actually consists of seven elements although as before they are not all different and there is some repetition, particularly with the speed-vary NOE task. This however permitted the vehicle to settle into a trim state before the execution of a more aggressive task such as the level-turn or the large slalom MTE as defined in ADS-33D.

Since the mission sequence is largely influential on the roll attitude of the aircraft, it is the lateral pilot stick and the roll angle time-histories that are most useful in analysing the elements. During the slalom, which incidentally, is that MTE described in ADS-33D, it is clear that the aircraft reaches maximum bank angles of just over 30 degrees to port and just under 30 degrees to starboard. Similarly, during the dash-stop element, the pitch attitude varies from minus twelve degrees to plus seventeen degrees approximately. As with the constant heading mission sequence, where MTEs were mixed with NOE flight, the large variation in what could be termed 'manoeuvre aggression' is noticeable. In this constant side-slip sequence, all the elements, with the exception of the ADS slalom, are selected from the NOE manoeuvre menu in HELINV. Event though there is a speed increase during the slalom which would effectively increase the severity, the level-turn elements are seen not to be as aggressive and only achieve relatively small angles of bank, when compared to the slalom.

The plots of longitudinal and lateral pilot stick time-histories, Figure 14a and b respectively, show large movements in the stick immediately after each level-turn, (at 110 and 310 seconds respectively). This is accounted for simply by the fact that the aircraft is changing it's heading angle by 180 degrees and it was not always possible to fix the heading of the subsequent manoeuvre at 180 degrees so that the output results fit together exactly, the resulting plots highlight this particular disagreement. This problem was not considered to be paramount in the analysis, as the effective pilot movements can still be easily determined from the plots. However, one difficulty that was identified early on in the inverse simulation runs was the fact that the control limits were more likely to be exceeded whenever level-turn elements were included, hence the reason that this NOE constant side-slip sequence was executed with relative low aggression in all elements except the slalom. Figure 15 presents the corresponding pitch and roll attitude angles, the pitch attitude illustrating very well, the seven different elements, where the level-turn elements appear as straight lines and are more readily identifiable on the roll attitude diagram.

6. Conclusions

The request to develop a method whereby several manoeuvres can be combined into one large fight path before being inverse simulated has been fulfilled, with the results of several mission runs presented. The potential for utilising the scheme as a mission analysis tool has been highlighted and methods whereby further improvement may be implemented have been stated. It was decided at the outset when potential problems were realised, to divide the report into several sections. The resulting flight paths consisted of,

i) a section from the Haxton Down mission sequence
ii) a constant heading sequence,
iii) and a constant side-slip sequence.

It was felt that given the allotted time, this would encompass most of the possibilities that are now available within HELINV and MIBIL. It has been shown that several manoeuvres can be pieced together and the resulting flight path information used to obtain the inverse solution data.

Prior to simulating several manoeuvres together, the first experiment was to further investigate the work carried out by Thomson and Bradley regarding constraint oscillations. The concluding results highlighted the influence of flight path polynomial order on the constraint oscillations and it was illustrated that the higher order polynomials tended to produce larger oscillations in the constant velocity section of the flight path.

It was stated that, at present it was not possible to simulate the whole of the Haxton Down sequence and there are several reasons for this. The first is that the Haxton sequence would produce an extremely large amount of data to be fed into HELINV and would certainly take a lot longer to obtain the inverse results. Secondly, there are two manoeuvres that are in the Haxton Down sequence that are not available within the HELINV library of manoeuvres, although the possibility does exist in terms of modifying some manoeuvres to perhaps encompass the idea of the Haxton elements. Thirdly, and perhaps most importantly, the Haxton sequence contains a large number of elements that involve a change of heading for the vehicle. The problems created here have been clearly illustrated in the constant side-slip sequence and are based on the fact that the aircraft undergoes some heading change, away from the predetermined zero heading that is a prerequisite for many MTEs. This initially does not seem to be a problem, but difficulties are encountered in the output results, depending on the manoeuvre subsequent to the level-turn. Certainly it is not possible to have certain combinations of MTEs and NOE flight that involve constant angles of side-slip or heading that eventually become conflicting to the algorithm.

The research that has been carried out has been successful in that software has been developed, and to all intents and purposes fulfils the demands of building a mission sequence. As with most research problems, the final solution is at a stage where some refinements are required to produce a program that will output the required results recursively without failure. It is felt however that the large amount of time and resource allocation that would be necessary to fulfil this qualification and produce inverse simulation results for any number and combination of manoeuvres, is unlikely to yield more useful or detailed information, as the essentials of the exercise remain the same.

Figures

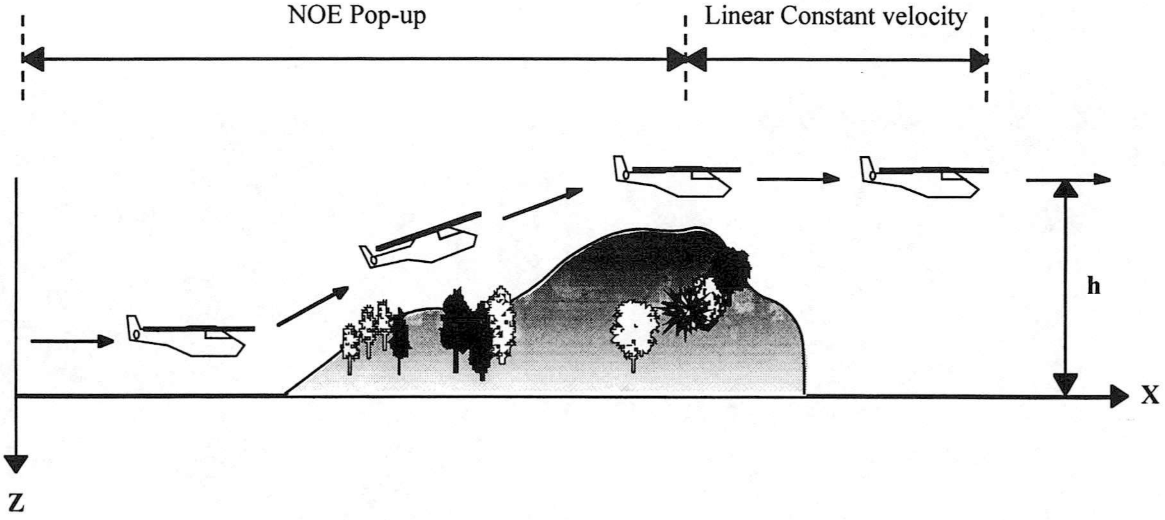
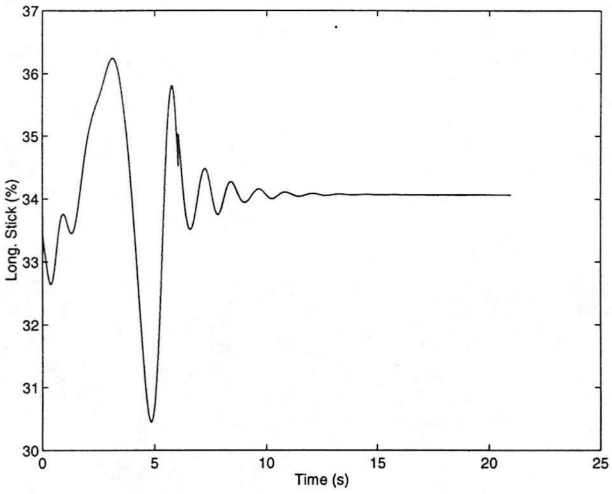
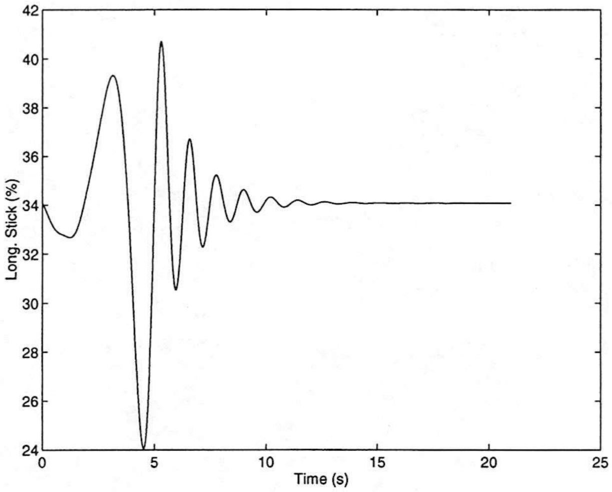


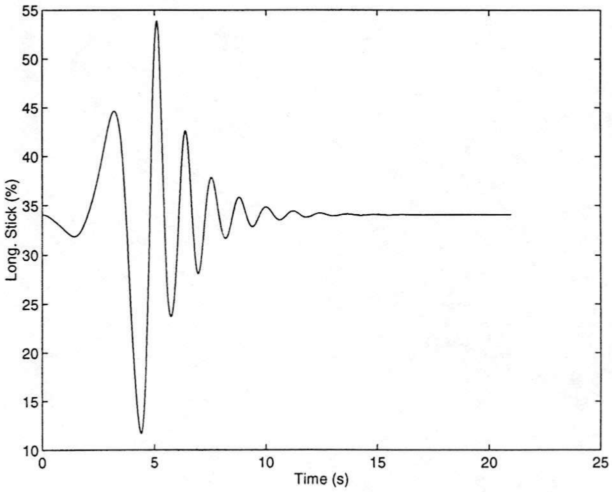
Figure 1: Nap-of-the-earth (NOE) Pop-up followed by linear section at exit



(a): 5th order

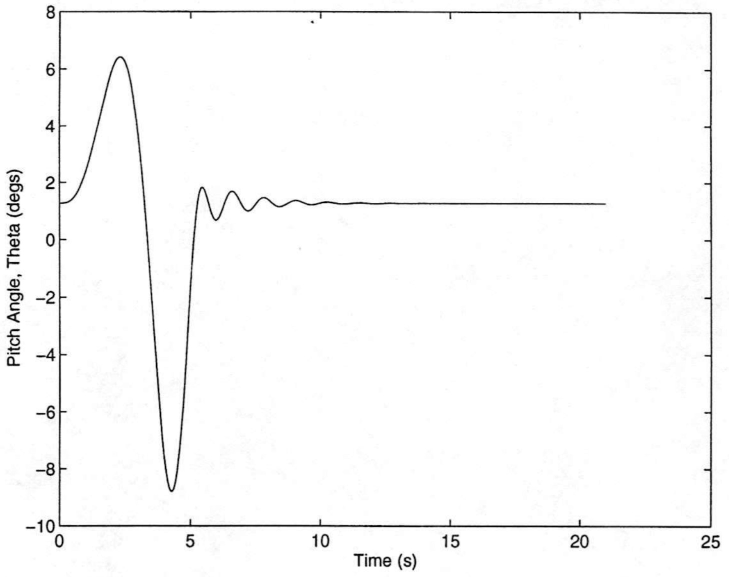


(b): 7th order

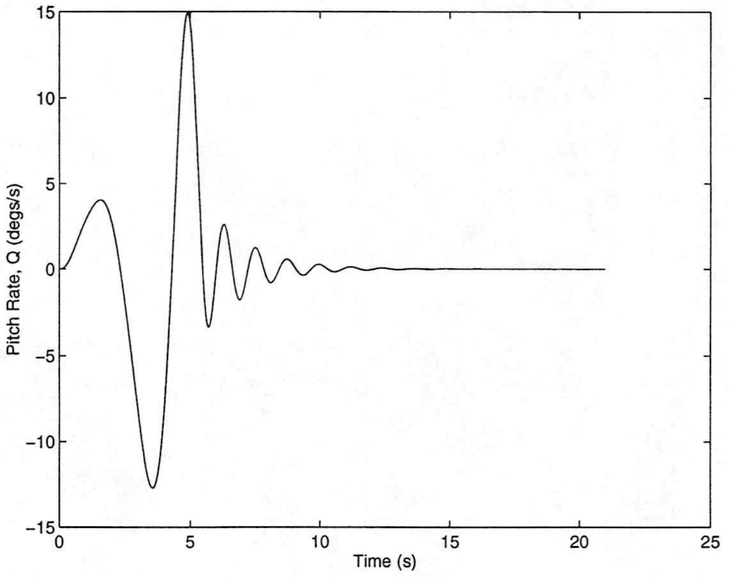


(c): 9th order

Figure 2: Longitudinal cyclic stick time-histories for 5th, 7th and 9th order polynomials

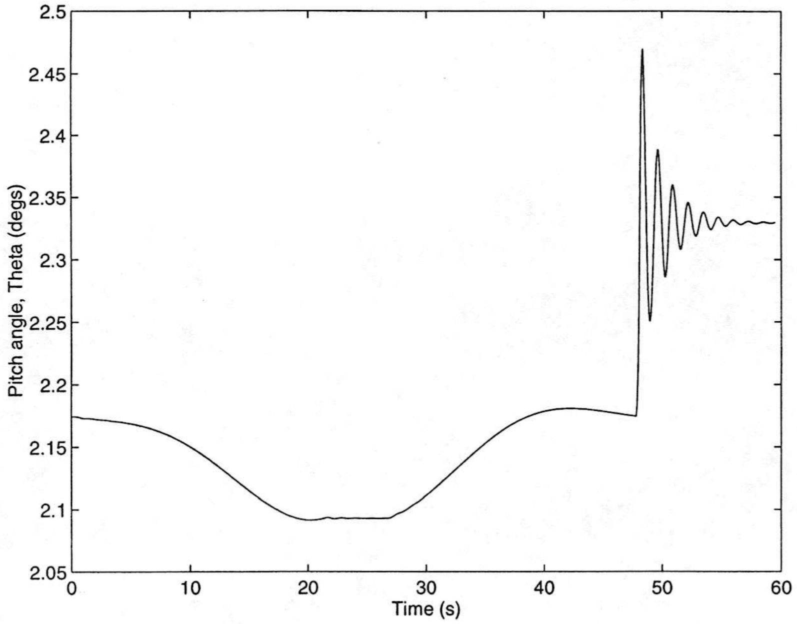


(a): Pitch angle, θ

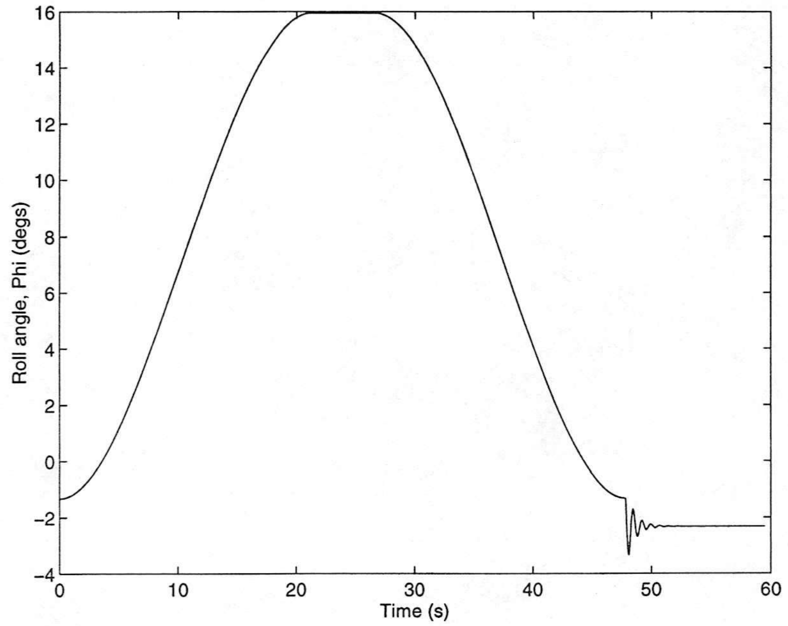


(b): Pitch-rate, Q

Figure 3: Pitch angle, θ and pitch-rate Q for 7th order poly. of pop-up with linear section



(a): Pitch angle, θ



(b): Roll angle, ϕ

Figure 4: Pitch angle, θ and roll angle, ϕ for level-turn with linear section

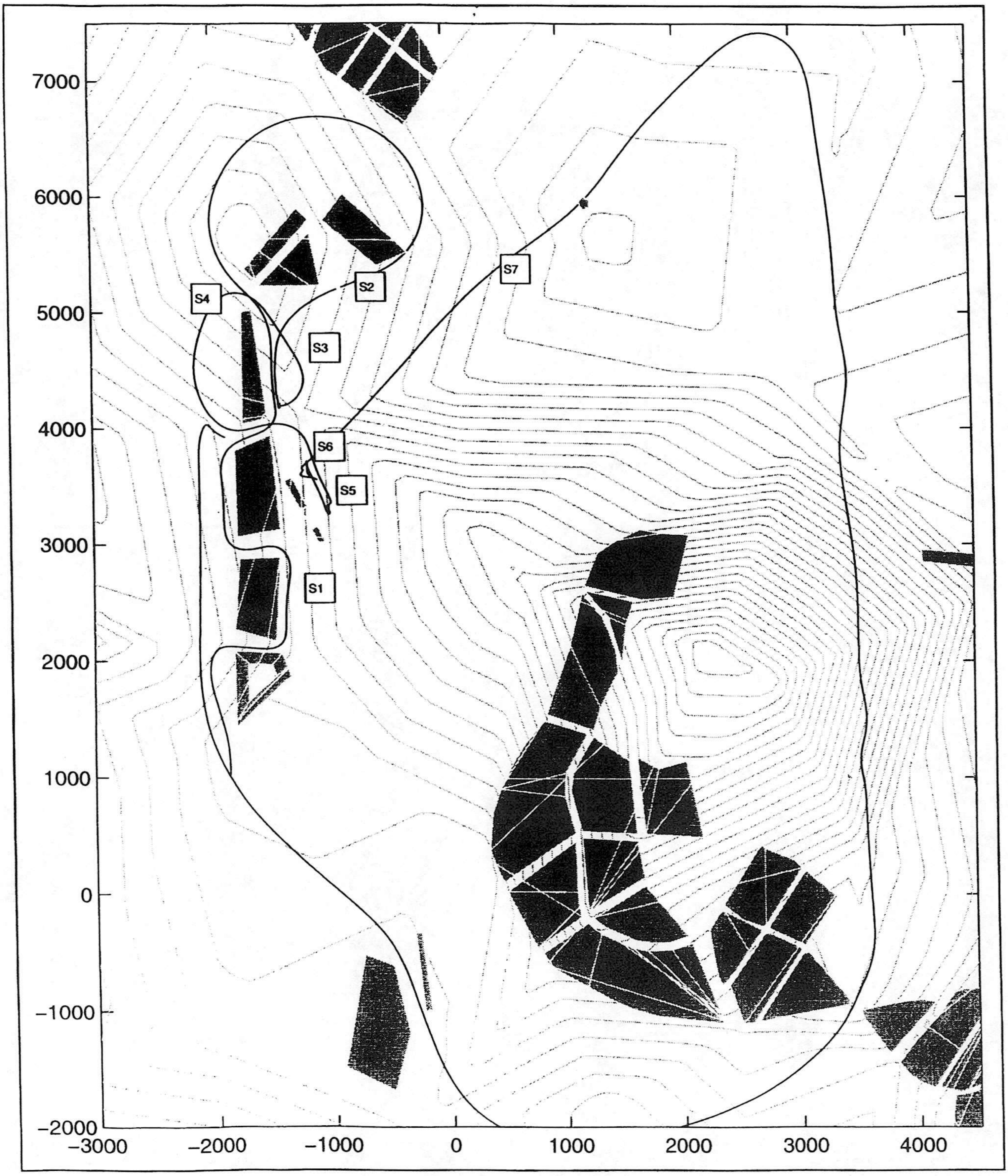


Figure 5: Haxton Down mission sequence - Section 1, [1]

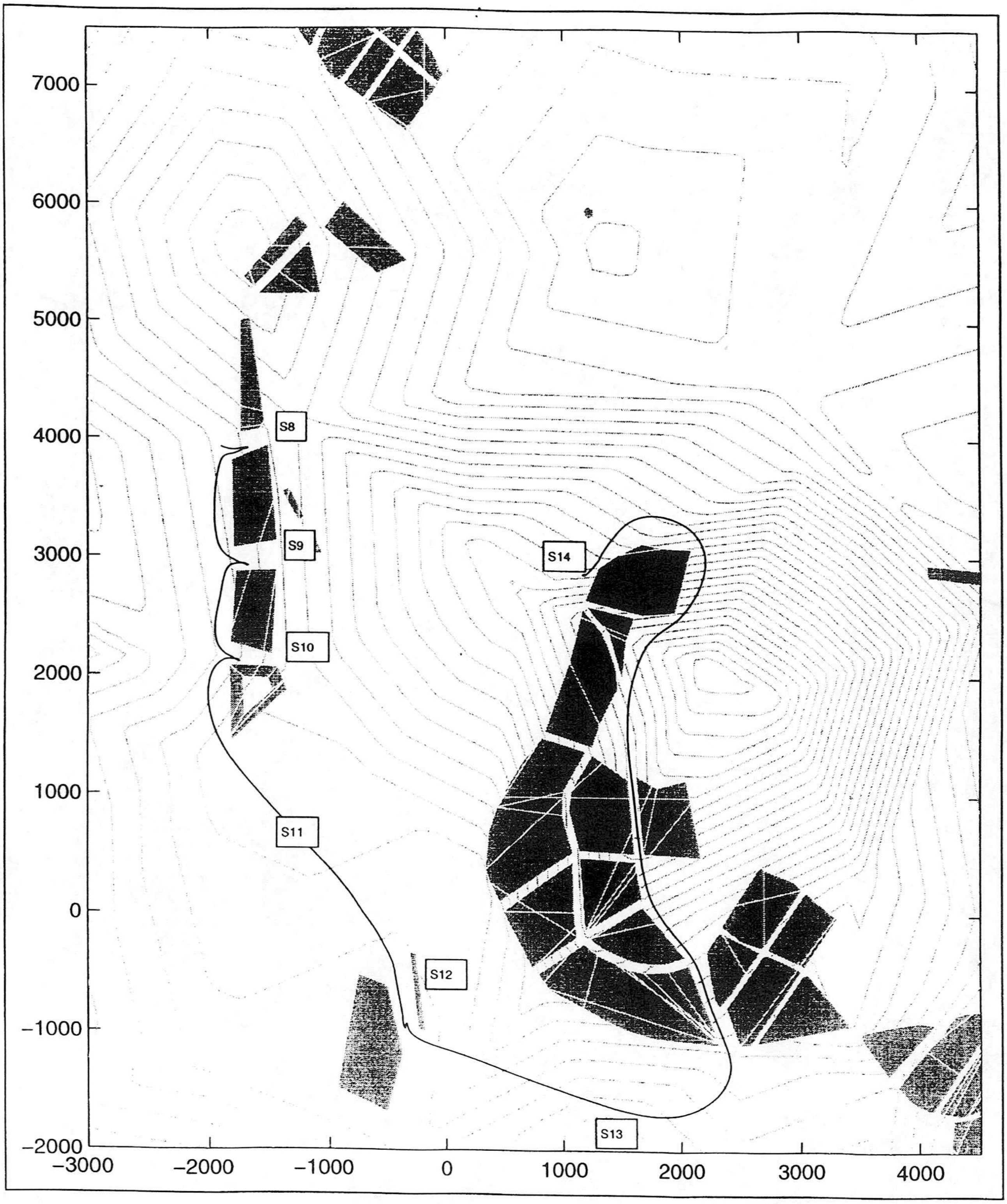
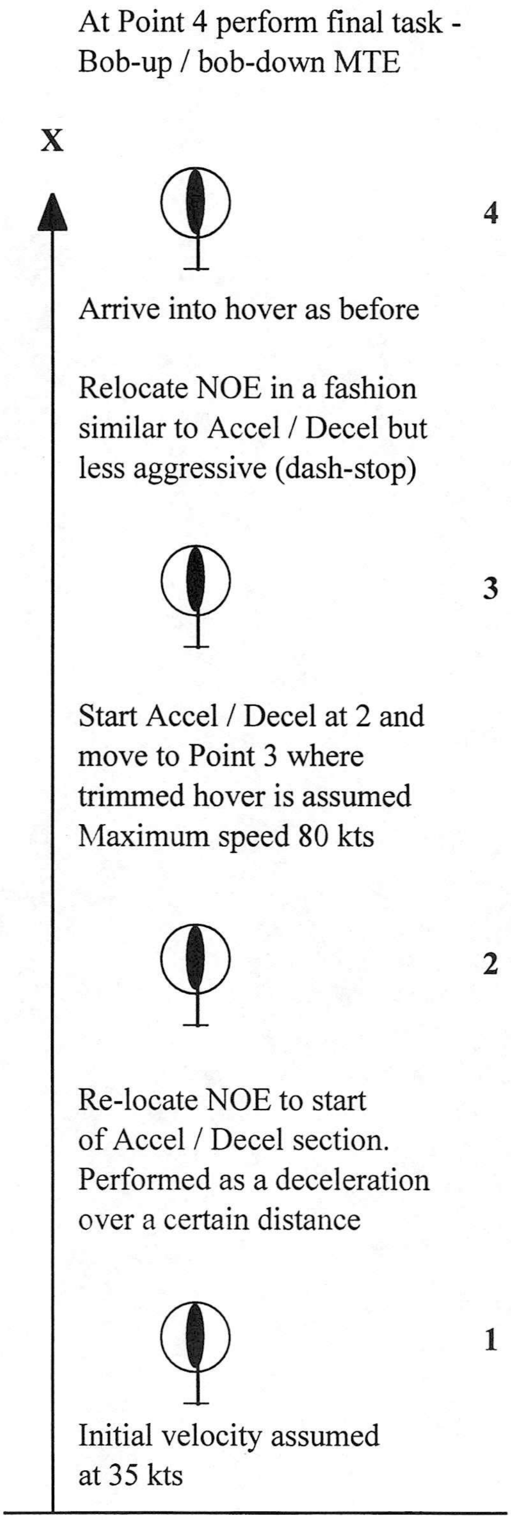


Figure 6: Haxton Down mission sequence - Section 2, [1]



At Point 4 perform final task - Bob-up / bob-down MTE

Arrive into hover as before

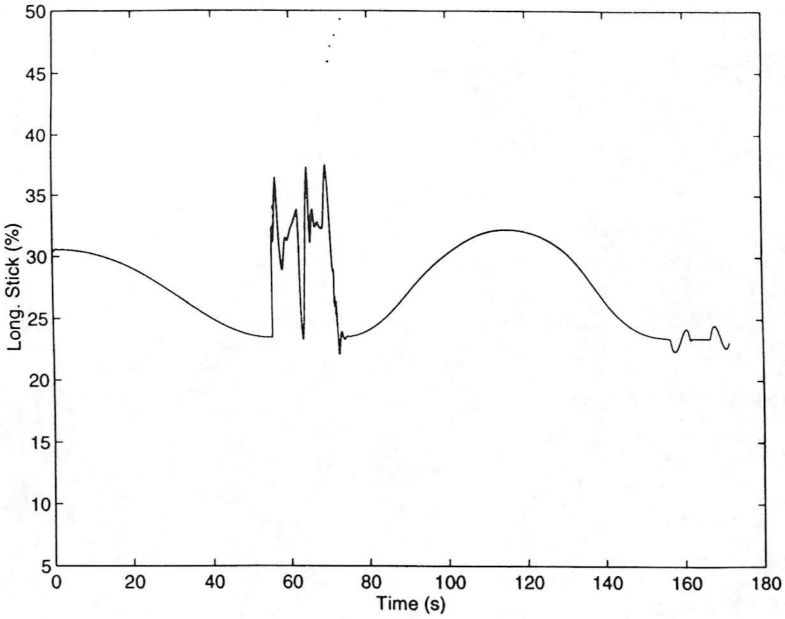
Relocate NOE in a fashion similar to Accel / Decel but less aggressive (dash-stop)

Start Accel / Decel at 2 and move to Point 3 where trimmed hover is assumed Maximum speed 80 kts

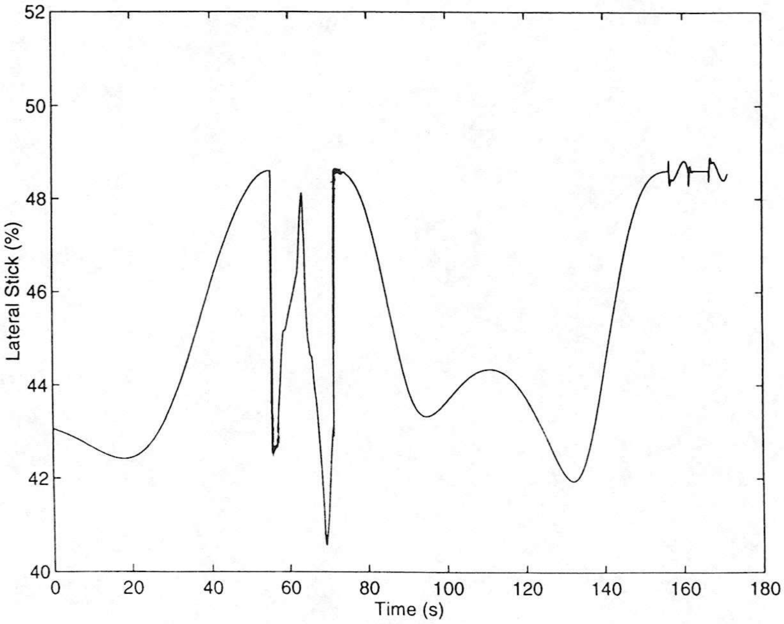
Re-locate NOE to start of Accel / Decel section. Performed as a deceleration over a certain distance

Initial velocity assumed at 35 kts

Figure 7: Possible representation of last four elements of Haxton Down mission sequence

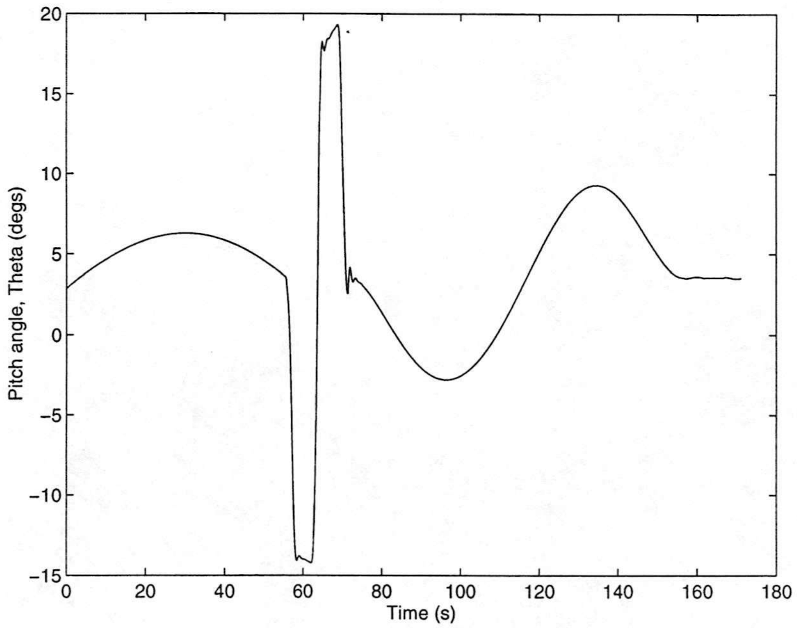


(a): Longitudinal stick, η_{1s} time-history for Haxton Down mission

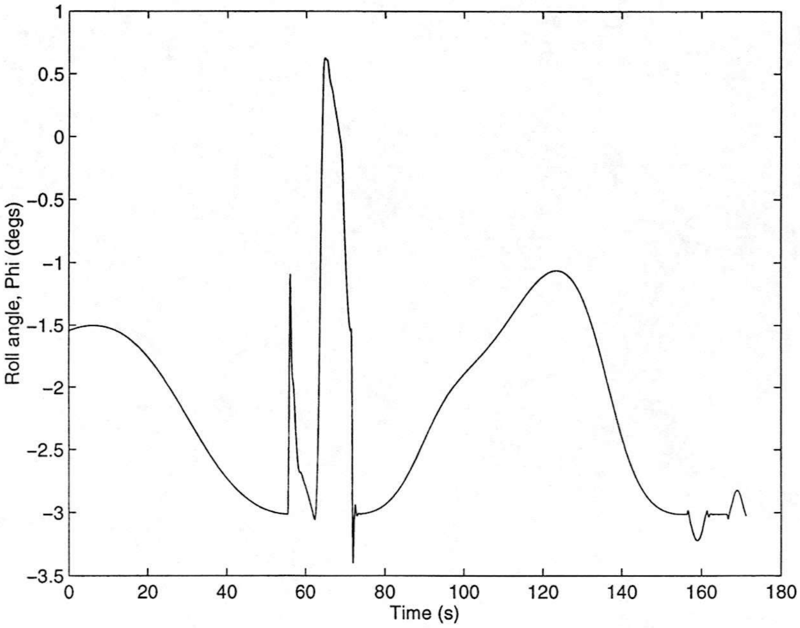


(b): Lateral stick, η_{1c} time-history for Haxton Down mission

Figure 8: Longitudinal and lateral stick time-histories for Haxton Down mission



a): Pitch angle, θ



(b): Roll angle, ϕ

Figure 9: Pitch angle, θ and roll angle, ϕ for MTE constant heading mission

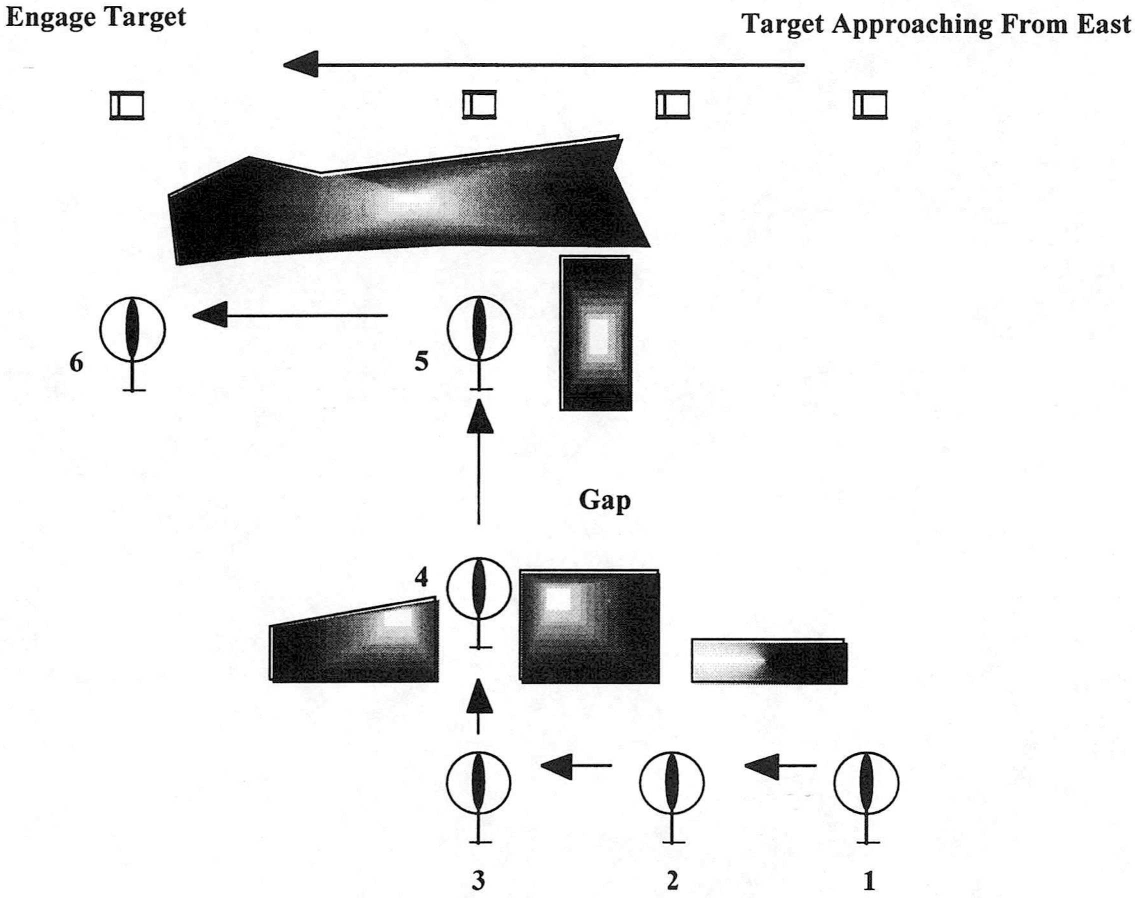
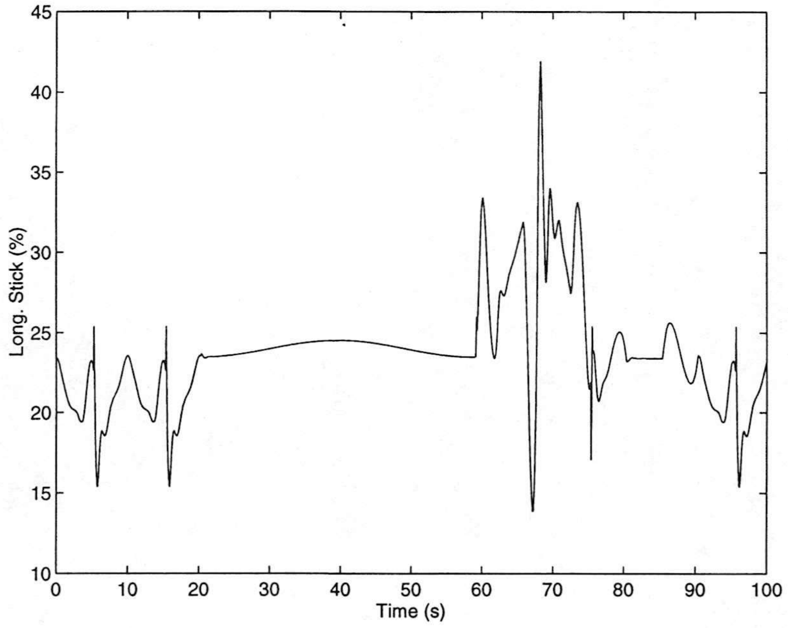
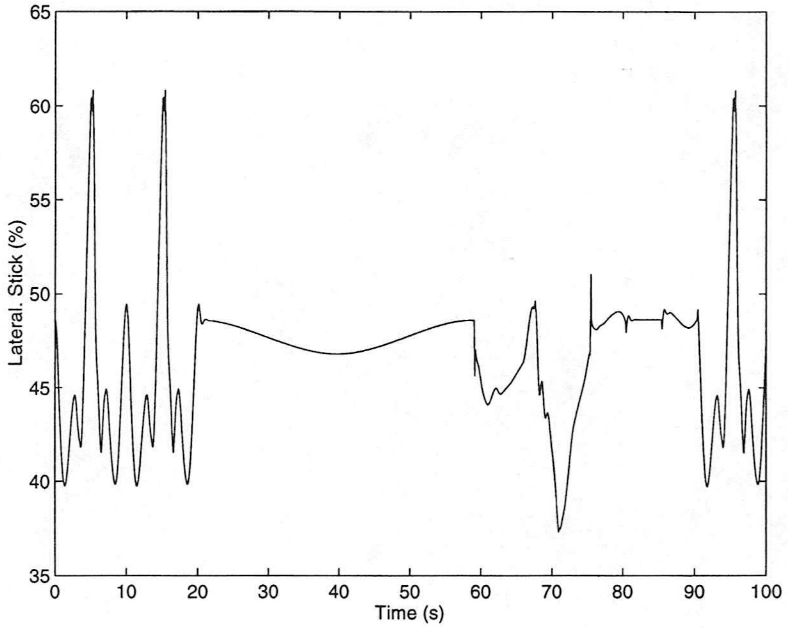


Figure 10: MTE mission sequence at constant heading

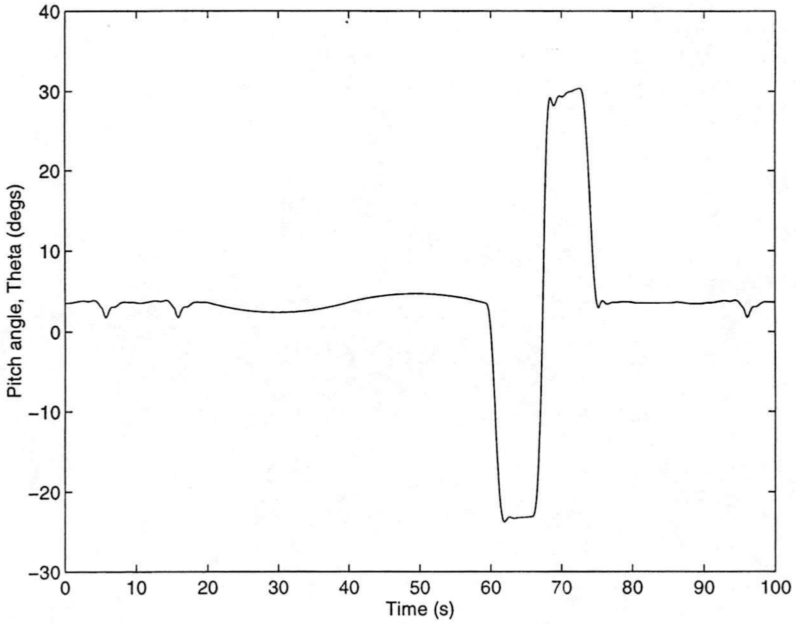


(a): Longitudinal stick, η_{1s} time-history for MTE mission

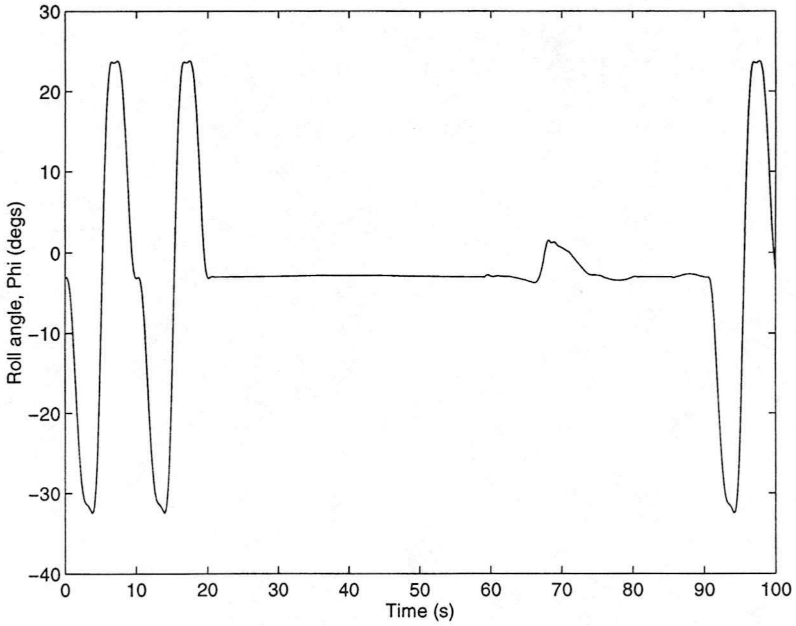


(b): Lateral stick, η_{1c} time-history for MTE mission

Figure 11: Longitudinal and lateral stick time-histories for MTE constant heading mission



a): Pitch angle, θ



(b): Roll angle, ϕ

Figure 12: Pitch angle, θ and roll angle, ϕ for MTE constant heading mission

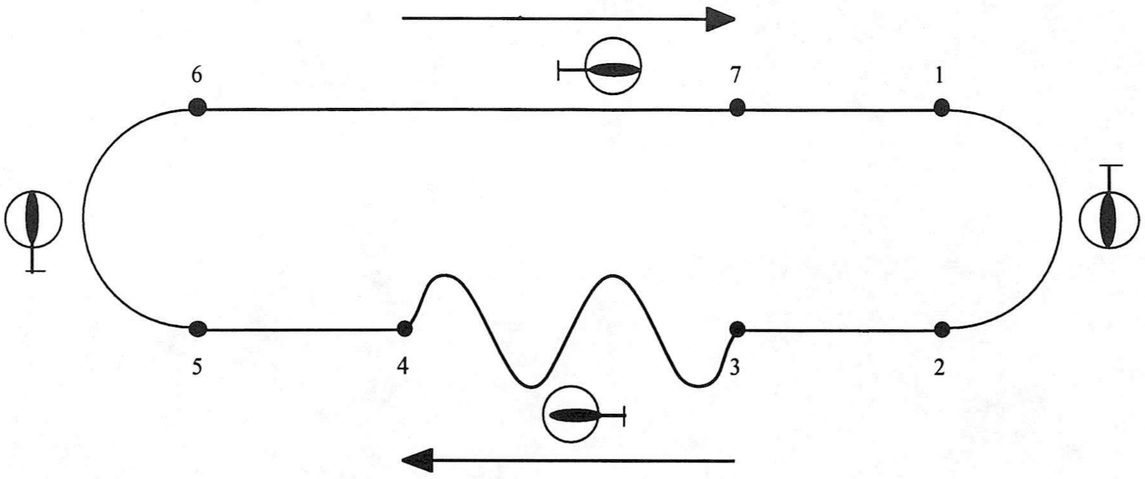
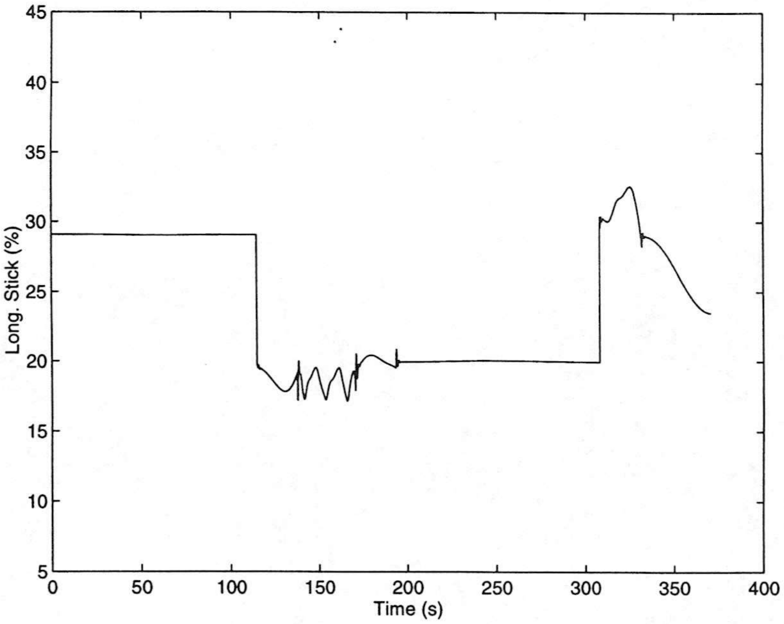
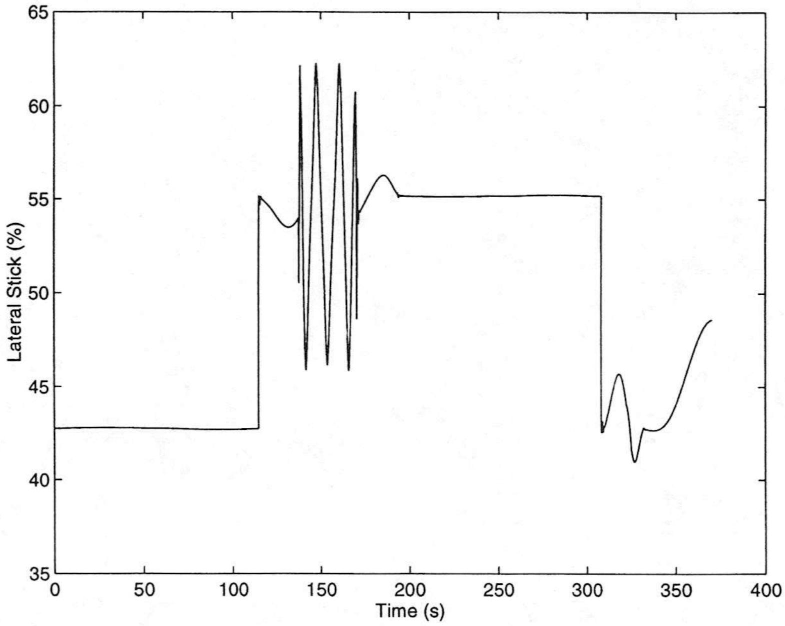


Figure 13: NOE mission sequence at constant side-slip

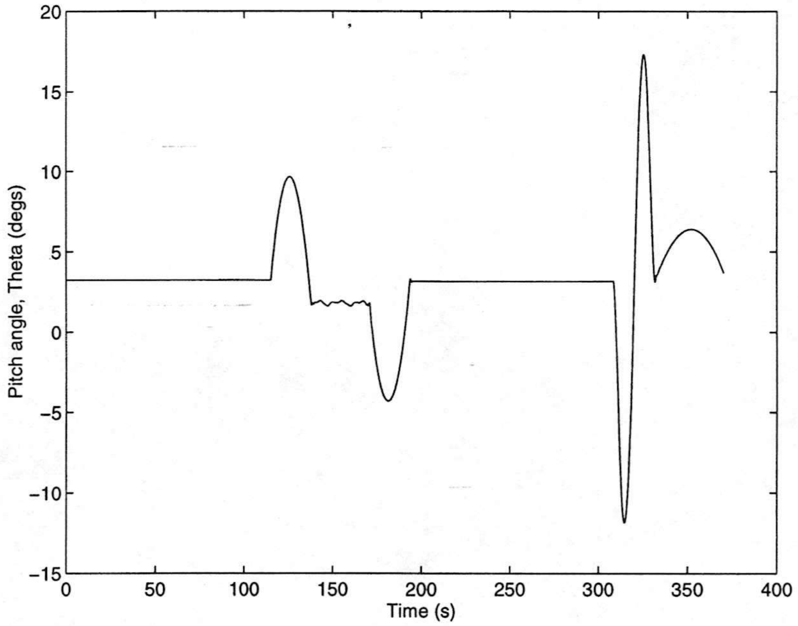


(a): Longitudinal stick, η_{1s} time-history for NOE mission

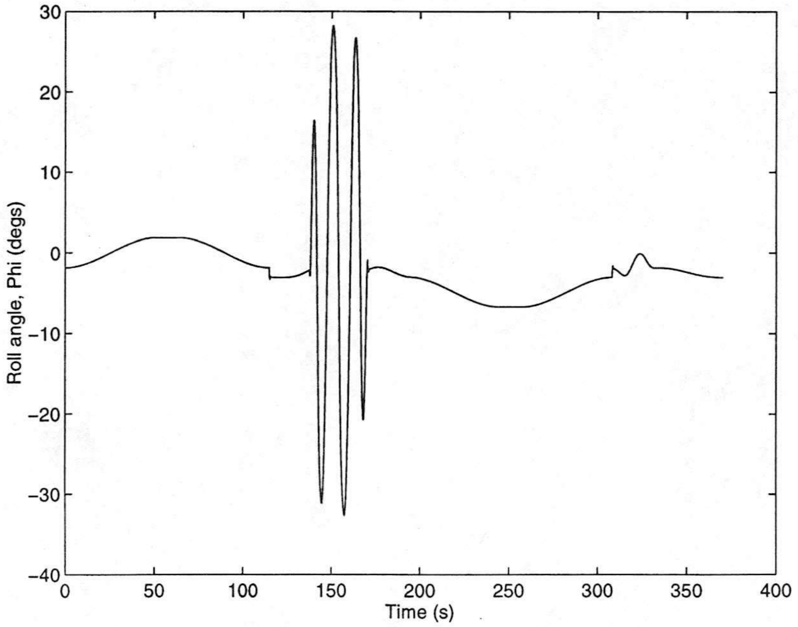


(b): Lateral stick, η_{1c} time-history for NOE mission

Figure 14: Longitudinal and lateral stick time-histories for NOE constant side-slip mission



a): Pitch angle, θ



(b): Roll angle, ϕ

Figure 15: Pitch angle, θ and roll angle, ϕ for NOE constant side-slip mission

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