University of Glasgow

DEPARTMENT OF

AEROSPACE ENGINEERING

Mathematical Models Of Three Slalom Types For Inverse Simulation

Garry R. Leacock*

Dr. Douglas G. Thomson**

Internal Report No. 9716 August 1997

Mathematical Models Of Three Slalom Types For Inverse Simulation

Garry R. Leacock*
Dr. Douglas G. Thomson**

Internal Report No. 9716 August 1997

*Postgraduate Research Assistant
**Lecturer in Flight Dynamics

UNIVERSITY
of
GLASGOW

Department of Aerospace Engineering
University of Glasgow
Glasgow
G12 8QQ
U.K.

Abstract

In the absence of adequate data from flight trials, a request was put forward for the development of mathematical models of various configurations of slalom manoeuvres. The models were to be based on the existing manoeuvres as flown by United States Army, specified in ADS-33D, the Defence Evaluation and Research Agency (DERA), Bedford and the German Aerospace Research Establishment (DLR), the definitions of which have been stated previously by the DERA. This report describes the development of the manoeuvres and their utilisation within the inverse simulation package HELINV, at Glasgow University. It will be shown that data acquired from the inverse simulations of these manoeuvres can be used in workload calculations using software developed by Glasgow Caledonian University, and this process in itself will verify or disprove the validity of the manoeuvres that have been developed. Although there is potentially no real substitute for genuine data obtained from actual flight trials, it is hoped that these slalom simulations will prove to be a useful tool when used in conjunction with the inverse simulation, workload estimation metrics and handling qualities software.

1. Introduction

Throughout the evolution of helicopter inverse simulation within the Aerospace Department at Glasgow University there has been a continuing commitment to develop additional mathematical models of manoeuvres commonly found in helicopter flight. This work has been aided somewhat with the introduction of the Aeronautical Design Standard (ADS) documents to the department as there are numerous so-called Mission Task Elements (MTEs) described in some detail within. The manoeuvres are generally divided into two main categories, Precision Tasks and Aggressive Tasks and can be performed either in a good or degraded visual environment although this is of little consequence to inverse simulation.

The main emphasis of the report is placed upon one particular manoeuvre and its inherent variations that have cropped up within the Aerospace industry. It is performed as an aggressive task, and is generally known as the Rapid-slalom Mission Task Element. There are several objectives that are taken into account when performing such a manoeuvre, and include the assessment of the handling qualities while manoeuvring aggressively in forward flight as well as with reference to objects on the ground. The turn co-ordination and inter-axis coupling are also appraised under these extreme conditions in order to aid with the categorisation of the level of handling qualities that the aircraft can attain, and to ascertain if there are any objectionable or undesirable flying characteristics while in this regime of the flight envelope.

The report comprises four main sections, each of which consider the individual variations on the slalom manoeuvre that are available within HELINV, [1]. Initially, the first slalom as defined by ADS-33C, [2] is considered as it is more basic in form and serves well to introduce the manner in which some of the other slalom MTE profiles were established. This is followed by the ADS-33D, [3] definition of the manoeuvre, which is essentially the same but twice as long. Thirdly a version of the slalom as specified by the Defence Evaluation and Research Agency (DERA), at Bedford, [4] is described and the differences highlighted. One final slalom MTE is that of the German Aerospace Research Establishment (DLR), [4] and is considered lastly as it is the most difficult of the four to model and presents a ground track that is comparatively different from the previous manoeuvres. However it will be seen how this problem was surmounted by making various assumptions that were considered valid within the scope of the work, and in conclusion is was decided to keep two working variations of the manoeuvre to present the user with an additional choice of slalom MTE.

Part of the reason for the development of several variations on the same manoeuvre was to support research work currently being carried out at Glasgow Caledonian University. Presently, research is focusing on the determination of a method to estimate the pilot workload rating in aggressive manoeuvres, [5]. As an adequate amount of flight trials data is not available, it was decided to use the data obtained from inverse simulation runs 'flying' the same manoeuvre, hence the need for DERA and DLR variations. One main advantage of this, is of course that the work presented in this report can be validated against the existing flight data which to a certain extent will show if the correct assumptions have been made while developing the aforementioned manoeuvres.

Concluding the report are simple simulation runs using two of the developed manoeuvres with typical parameters for the slalom, for example, longitudinal distance of 1500m, lateral distance of 15m and speed of 60 kts. It was thought that this would be an appropriate culmination to this section of research work and serves to help co-ordinate work between The University of Glasgow and Glasgow Caledonian University.

2. The Aeronautical Design Standard ADS-33C Slalom Manoeuvre

The first slalom manoeuvre to be developed at Glasgow was based on the 'Rapid-slalom MTE' definition described in Section 4.2.5 of ADS-33C, a schematic of which is shown in Figure 1. Section 4.2.5 states,

"The manoeuvre is initiated in level unaccelerated flight, and in the direction of a line or series of objects on the ground. Manoeuvre rapidly to displace the aircraft 15.2 m (50 ft) laterally from the centreline and immediately reverse direction to displace the aircraft 15.2 m (50 ft) on the opposite side of the centreline as quickly as possible. Maintain a reference altitude below 15.2 m (50 ft). Accomplish the manoeuvre so that the initial turn is both to the right and to the left.

- *Desired performance*
  - *Maintain altitude within ±3 m (10 ft)*
  - *Maintain airspeed at or above 60 knots*
  - *Maximum bank angles should be at least 50 degrees"*

The manoeuvre ground track was developed using a continuous polynomial to describe the desired shape in terms of time, and was generated by specifying particular boundary conditions at the beginning and termination of the manoeuvre and at the time points into which the manoeuvre is divided. For example in the above case the conditions cited at the relative time points were as follows:

1. At time : $t = 0$ $\quad y = 0 \quad \dot{y} = 0 \quad \ddot{y} = 0$
2. At time : $t = t_1$ $\quad y = h \quad \dot{y} = 0$
3. At time : $t = 2t_1$ $\quad y = -h \quad \dot{y} = 0$
4. At time : $t = 3t_1$ $\quad y = 0 \quad \dot{y} = 0 \quad \ddot{y} = 0$

Using the ten boundary conditions a ninth order polynomial was calculated by solution of simultaneous algebraic equations and the unknown coefficients determined. The assumption made to develop the MTE was to divide the track into three time sections, each of length 't_1', or one third of the total time taken to complete the manoeuvre. The final equation describing the ground track in terms of t_1, is of the form shown by equation (1) below.

$$y(t) = \left[-\frac{1}{8}\left(\frac{t}{t_1}\right)^9 + \frac{27}{16}\left(\frac{t}{t_1}\right)^8 - 9\left(\frac{t}{t_1}\right)^7 + \frac{189}{8}\left(\frac{t}{t_1}\right)^6 - \frac{243}{8}\left(\frac{t}{t_1}\right)^5 + \frac{243}{16}\left(\frac{t}{t_1}\right)^4 \right] h \qquad (1)$$

and can be readily differentiated to yield velocity and acceleration profiles.

A plot of the resulting polynomial using typical values for the MTE confirmed the required ground track. It should be noted that Figure 1 is not drawn exactly as it would be flown in real life, but is drawn in schematic format to illustrate the assumptions made about the time divisions in the manoeuvre, the actual polynomial describing the MTE is shown in Figure 2.

3. The Aeronautical Design Standard ADS-33D Slalom Manoeuvre

Superseding ADS-33C is ADS-33D, which is illustrated schematically in Figure 3, and is a manoeuvre profile which is essentially double that of ADS-33C. Section 4.2.6 of ADS-33D gives the following description of the manoeuvre,

"Initiate the manoeuvre in level unaccelerated flight and lined up with the centreline of the test course. Perform a series of smooth turns at 152m (500 ft) intervals. The turns shall be at least 15.2m (50 ft) from the centreline, with a maximum lateral error of 15.2m (50 ft). The manoeuvre is to be accomplished at a reference altitude below 30.5m (100 ft). Complete the manoeuvre on the centreline.

- *Desired performance*
    - *Maintain airspeed of at least 60 knots throughout the course*

- *Adequate performance*
    - *Maintain airspeed of at least 40 knots throughout the course"*

A suggested test course to perform this manoeuvre is using an airport runway, most of which have touch-down stripes at 500m intervals and can be conveniently used instead of placing pylons or other such markers on the ground. The width of the runway must also be taken into consideration however, as it may be necessary to define the outer limits of the manoeuvre with reference markers. Notice that within the desired performance, no specific reference is given to the maintenance of altitude to within ±3m and it is no longer necessary to achieve a roll angles of at least 50 degrees.

Like its predecessor this manoeuvre is designed to test the ability of the helicopter to manoeuvre aggressively in the forward flight regime while additionally checking for characteristics that would be detrimental to the handling qualities of the aircraft and thus placing a higher degree of workload upon the pilot.

Development of the slalom profile took place in much the same manner as the ADS-33C version in that certain boundary conditions were specified at the initiation and termination of the manoeuvre and at the remaining four time points into which the manoeuvre was split. Similarly, the assumption was made that the manoeuvre would be split into sections each of length t_1 permitting the ground track to be developed as one continuous polynomial. Presumably this assumption is more realistic from a piloting point of view, and would hopefully lead to generation of workload values that were consistent in nature with those calculated using data from simulation trials.

It was necessary to stipulate the following 14 boundary conditions in order to obtain the required flight path of this particular slalom,

1. At time : $t = 0$ $y = 0$ $\dot{y} = 0$ $\ddot{y} = 0$
2. At time : $t = t_1$ $y = h$ $\dot{y} = 0$
3. At time : $t = 2t_1$ $y = -h$ $\dot{y} = 0$
4. At time : $t = 3t_1$ $y = h$ $\dot{y} = 0$
5. At time : $t = 4t_1$ $y = -h$ $\dot{y} = 0$
6. At time : $t = 5t_1$ $y = 0$ $\dot{y} = 0$ $\ddot{y} = 0$

The resulting 11 unknown coefficients were obtained algebraically and substituted into the 13^{th} order polynomial equation, which was plotted to ensure that the correct ground track profile had been calculated correctly. The final equation was of the form,

$$y(t) = \left[-\frac{1}{13824}\left(\frac{t}{t_1}\right)^{13} + \frac{65}{27648}\left(\frac{t}{t_1}\right)^{12} - \frac{247}{6912}\left(\frac{t}{t_1}\right)^{11} + \frac{9295}{27648}\left(\frac{t}{t_1}\right)^{10} - \frac{29603}{13824}\left(\frac{t}{t_1}\right)^{9} + \frac{86545}{9216}\left(\frac{t}{t_1}\right)^{8} - \frac{95807}{3456}\left(\frac{t}{t_1}\right)^{7} + \frac{1444105}{27648}\left(\frac{t}{t_1}\right)^{6} - \frac{392825}{6912}\left(\frac{t}{t_1}\right)^{5} + \frac{198125}{6912}\left(\frac{t}{t_1}\right)^{4} - \frac{625}{216}\left(\frac{t}{t_1}\right)^{3} \right] h \tag{2}$$

Although this equation yields a profile as shown in Figure 4, this may not be strictly correct if the text in ADS-33D is to be taken literally. The italicised paragraph given previously states that a series of turns are to be performed to one side and then the other to a distance of 15.2m. This does not necessarily mean that the manoeuvre is double that of ADS-33C, however, Figure 4(4.2) page 70 of ADS-33D illustrates a profile very similar to that developed above and this was assumed to be an adequate enough specification of the manoeuvre.

4. The Defence Research Agency (DRA) Slalom Manoeuvre

The third slalom to be considered is defined by DERA Bedford and is similar in many ways to the previously described ADS-33 manoeuvres. It consists of two smaller slaloms separated by a gap where the aircraft is assumed to be again in trimmed flight. The first section of the manoeuvre is in essence the opposite from the third, (the second being the linear section). If the first 'mini-slalom' is initiated to the left then the third will be initiated to the right and vice-versa. Although it was immediately obvious that this manoeuvre could be constructed from two ADS-33C MTEs the approach taken to develop the ground track in terms of 'y(t)' was somewhat different from that already described. It was evident that a single continuous polynomial would not be sufficient in describing the exact track that was required for this manoeuvre.

Alternatively, it was decided to tackle this problem in what has been termed a 'piecewise' method, that is, to divide the manoeuvre into several obvious sections and piece them together to obtain the whole manoeuvre. Figure 5 illustrates how this method was implemented, and the three individual sections are evident on the diagram. Unfortunately it was not a simple matter of using the same polynomial as for the ADS-33C slalom and then reversing the signs of the coefficients to obtain the opposite track, but a completely new polynomial had to be developed. The reason for this became apparent when analysis was carried out on the acceleration profile, which exhibited large spikes at the points corresponding exactly to the start and end of the linear section (Section 2) in Figure 5. Since the aircraft is assumed to be in a trim condition throughout this section, the lateral velocity and acceleration are zero, and of course the lateral distance during this section is also zero. Using these assumptions however was inadequate in producing a smooth lateral acceleration profile and it was required that the so-called 'jerk' term, that is, the rate-of-change of acceleration was also specified at the beginning and end of each mini-slalom section. When the polynomial was calculated using what now amounted to 12 boundary conditions, it was found that the 11^{th} and 10^{th} order coefficients were zero and this reduced the polynomial to it's original 9^{th} order form given by equation 1. The only method by which the polynomial could be calculated was to introduce rate-of-change of jerk, '$(\ddddot{y})$' terms so that there were 5 boundary conditions at the beginning and end of sections 1 and 3. This meant that each of these sections had the following 14 boundary conditions,

1. At time : $t = 0$ $\quad y = 0 \quad \dot{y} = 0 \quad \ddot{y} = 0 \quad \dddot{y} = 0 \quad \ddddot{y} = 0$
2. At time : $t = t_1$ $\quad y = h \quad \dot{y} = 0$
3. At time : $t = 2t_1$ $\quad y = -h \quad \dot{y} = 0$
4. At time : $t = 3t_1$ $\quad y = 0 \quad \dot{y} = 0 \quad \ddot{y} = 0 \quad \dddot{y} = 0 \quad \ddddot{y} = 0$

which lead to the development of the 13th order polynomial given in equation 3.

$$y(t) = \left[\frac{1}{32}\left(\frac{t}{t_1}\right)^{13} - \frac{39}{64}\left(\frac{t}{t_1}\right)^{12} + \frac{83}{16}\left(\frac{t}{t_1}\right)^{11} - \frac{1617}{64}\left(\frac{t}{t_1}\right)^{10} + \frac{2475}{32}\left(\frac{t}{t_1}\right)^{9} - \frac{9801}{64}\left(\frac{t}{t_1}\right)^{8} + \frac{1539}{8}\left(\frac{t}{t_1}\right)^{7} - \frac{8991}{64}\left(\frac{t}{t_1}\right)^{6} + \frac{729}{16}\left(\frac{t}{t_1}\right)^{5} \right] h \qquad (3)$$

It was found that when this equation was plotted the same track was obtained as for the ADS-33C manoeuvre, illustrated in Figure 2.

5. The German Aerospace Research Establishment (DLR) Slalom Manoeuvre

Unlike the previous MTEs where the aggression of the manoeuvre could be altered by changing either the length or lateral offset dimensions (i.e. aspect ratio), the DLR slalom is a fixed dimension task and the aggression is varied by increasing or decreasing the speed at which the manoeuvre is flown.

5.1 Piecewise Polynomial Method

After some consideration as to how the development of the manoeuvre would be approached it was decided to use the piecewise method and build the slalom from a number of smaller so-called transient components and linear sections. Figure 6 illustrates how the manoeuvre was dissected and it comprises five linear sections and six transient elements. The transient elements were calculated in the same manner as the continuous polynomials described previously, in that boundary conditions were specified at the beginning and end of each one, for example from time=zero to time=t_1 it was possible to specify six boundary conditions and derive a 5th order polynomial. The boundary conditions were as follows,

1. At time : $t = 0 \quad y = 0 \quad \dot{y} = 0 \quad \ddot{y} = 0$
2. At time : $t = t_1 \quad y = h \quad \dot{y} = 0 \quad \ddot{y} = 0$

and this yielded a transient track as shown in Figure 7, which essentially means that the helicopter does not have to instantaneously traverse from one position on the ground to another. It can easily be seen how several of these quintic polynomials coupled with linear sections of specific lengths could be used to construct the entire manoeuvre.

It was found however that the first version of the DLR piecewise slalom to be run within HELINV exhibited features in the lateral acceleration profile that caused the control limits to be exceed thus making the manoeuvre impossible to fly. This problem was somewhat alleviated by introducing jerk into the boundary conditions, as each transient section was immediately followed by a linear section, where a trimmed condition could be assumed; the presupposition that jerk would be zero during these sections was considered a valid assumption in the development of the manoeuvre. The number boundary of conditions for each transient section was increased to eight which correspondingly yielded a seventh order polynomial similar to that given by equation 4.

1. At time : $t = 0$ $y = 0$ $\dot{y} = 0$ $\ddot{y} = 0$ $\dddot{y} = 0$
2. At time : $t = t_1$ $y = h$ $\dot{y} = 0$ $\ddot{y} = 0$ $\dddot{y} = 0$

$$y(t) = \left[-20\left(\frac{t}{t_1}\right)^7 + 70\left(\frac{t}{t_1}\right)^6 - 84\left(\frac{t}{t_1}\right)^5 + 35\left(\frac{t}{t_1}\right)^4 \right] h \tag{4}$$

The unknown coefficients calculated in each case were slightly different depending upon the length of the transient section (t_1 or $0.5t_1$) and the gradient of the section which could be positive or negative depending on which component of the manoeuvre is being considered. A second method by which the problem of exceeding the control limits was attenuated was by altering the user input dictating the length of the manoeuvre. Although this does not fully comply with the specifications of the DLR slalom, it does provide the user with another variable to alter the manoeuvre severity, hence providing potentially more data from simulation runs.

5.2 Continuous Polynomial Method

Although described as a continuous polynomial the second method utilised to develop the DLR slalom profile is in fact piecewise but each half of the slalom was developed using a single polynomial, one having coefficients of opposite sign to the other, and being separated by a linear section in the middle. Figure 8 illustrates the ideal fight path that would be required to fly the manoeuvre. Obviously this is realistically impracticable and the proper approach is to fly the manoeuvre using transient elements as described in the previous section.

The polynomial developed for time=zero to time=t_1 was obtained by specifying the following boundary conditions,

1. At time : $t = 0$ $y = 0$ $\dot{y} = 0$ $\ddot{y} = 0$ $\dddot{y} = 0$
2. At time : $t = t_1$ $y = h$ $\dot{y} = 0$
3. At time : $t = 2t_1$ $y = (h/2)$ $\dot{y} = 0$
4. At time : $t = 3t_1$ $y = 0$ $\dot{y} = 0$ $\ddot{y} = 0$ $\dddot{y} = 0$

As in the description of the previous piecewise slalom, it was found that specifying the jerk term at the beginning and end of the slalom section disposed of the unwanted spikes in the lateral acceleration profile and prevented the control limits being exceeded. The specified boundary conditions produced an 11^{th} order polynomial with eight unknown coefficients and was determined as,

$$y(t)=\begin{bmatrix} 0\left(\frac{t}{t_1}\right)^{11}+\frac{3}{32}\left(\frac{t}{t_1}\right)^{10}-\frac{23}{16}\left(\frac{t}{t_1}\right)^{9}+\frac{291}{32}\left(\frac{t}{t_1}\right)^{8}- \\ \frac{243}{8}\left(\frac{t}{t_1}\right)^{7}+\frac{1809}{32}\left(\frac{t}{t_1}\right)^{6}-\frac{891}{16}\left(\frac{t}{t_1}\right)^{5}+\frac{729}{32}\left(\frac{t}{t_1}\right)^{4} \end{bmatrix}h \qquad (5)$$

with the lateral velocity and acceleration terms readily available from differentiation. This polynomial describes the flight path of the aircraft from time=zero to time=$3t_1$, see Figure 9. The signs of the coefficients are reversed to obtain the corresponding flight path profile from time=$4t_1$ to time=$7t_1$. As a level flight trimmed section is assumed between time=$3t_1$ and time=$4t_1$ the lateral position, velocity and acceleration during this segment of the flight path are zero.

6. Pilot Workload Rating From Inverse Simulation Of The Slalom MTEs

The approach taken to develop a system whereby the pilot workload can be obtained from a given manoeuvre, has firstly been to produce a so-called 'attack chart', [5]. The control movements made by a pilot during a manoeuvre can be divided into a series of discrete control demands known as 'worklets'. Each worklet is characterised by a specific maximum rate-of-change and an overall change in net displacement, which can be used to calculate an attack parameter which has been defined by the DERA, [4] as,

$$\textit{Pilot Attack} = Q = \frac{\dot{\eta}_{pk}}{\Delta\eta} \qquad (6)$$

where $\dot{\eta}_{pk}$ is the peak value in the derivative of pilot stick displacement and $\Delta\eta$ is the corresponding change in the net displacement of the stick. Equation 6 is generic in the sense that it can be applied to any of the four controls but will usually be the major control responsible for performing the manoeuvre, for example lateral cyclic in the slalom MTEs.

Attack parameters from a stick-rate time history can be calculated and plotted on the attack chart as a function of stick displacement. It is accepted that points on the chart corresponding to higher displacement values are associated with the guidance of the aircraft, while those that have values of low net displacement are coupled with the stabilisation of the vehicle. On a time-history that contains a lot of noise it is commonplace to incorporate some threshold value in order to ensure that only relevant peaks are processed.

6.1 Example 1: Attack Chart For DERA Slalom MTE

A slalom inverse simulation run was conducted using HELINV with the following dimensional and flight parameters,

- Longitudinal or 'X' distance of slalom = 1500 m.
- Lateral or 'Y' distance of slalom = 15 m.
- Flight velocity 'V_F' = 60 knots
- Initial direction of roll was to the left

Figure 10 illustrates the lateral cyclic stick time history for this manoeuvre, with the derivative of lateral stick and the absolute value of the derivative being shown in Figures 11 and 12 respectively. Figure 13 shows the associated attack chart with each worklet being marked as a cross on the chart. It is using this in conjunction with a chart partitioning method and the application of rule induction techniques, that the pilot workload rating can be calculated, the method by which this process is carried out being described in [5].

6.2 Example 2: Attack Chart For ADS-33D Slalom MTE

An ADS-33D slalom MTE was simulated in HELINV using the same parameters as in the DERA one conducted previously, in order that a direct comparison could be drawn between the two. Figures 14, 15 and 16 respectively show the lateral cyclic time-history, the derivative of lateral cyclic and the absolute value of the derivative. Figure 17 illustrates the attack chart associated with the time-histories in Figures 14 and 15.

6.3 Workload Calculations

The pilot workload cannot be directly obtained from the attack charts illustrated in Figures 13 and 17. Instead a further partitioning of the attack chart must occur, and together with the application of Machine Learning (ML) techniques a workload value can be predicted. The machine learning technique essentially means that the pilot workload rating classifications obtained from real-life simulator trials are used to replicate a decision process, that led to the recording of the classifications in the first instance. The system, therefore learns the mechanism by which the rating is reached on the basis of the information obtained from the attack charts and is subsequently able to predict a pilot workload rating. Again the method used is described in greater detail in [5] and the reader is referred there for a more comprehensive analysis of the subject. However the general method is as follows; if the attack chart is partitioned into sections, the workload is assumed to be a function of the number of events (worklets) in each region. It can be seen therefore that the method of partitioning used is of some significance and various partitioning methods have been justified in the literature, [4], with variations including lines of constant attack, rectangles and several varieties of the hyperbolae family.

7. Conclusions

The requirement to mathematically model different slalom types for inverse simulation has been fulfilled. The method used has been tried and tested previously at Glasgow and is known to produce satisfactory results when compared to data obtained from flight trials. This of course was one of the main reasons for developing models of such manoeuvres, and it is hoped that data produced from inverse simulation runs will be adequate for the prediction of workload ratings.

Research within the Aerospace Department at Glasgow University has been carried out in conjunction with the development of workload prediction software at Glasgow Caledonian University, which in turn has been used to compare workload results with those obtained from the DERA and their flight simulator trials. At the moment it is unclear as to which method will be used for the partitioning of attack charts, although using horizontal lines of constant attack has to date, proved to be the most successful in yielding results that have compared favourably with DERA results.

Utilising polynomials to develop models of manoeuvres appears to be relatively successful, however care must be taken to ensure that continuity exists in higher order derivatives in cases where manoeuvres are constructed using two or more polynomials in a piecewise method. If the model fails to meet this requirement the resulting pilot stick time-history from inverse simulation will almost certainly contain 'spikes' at the points where polynomials have been joined together. To make certain this does not happen it may be necessary, as in the case of this report to specify additional boundary conditions in order to obtain the a smooth profile in lateral acceleration for example in the case of the DERA slalom MTE .

Finally the usefulness of the transient sections during the development of the piecewise DLR slalom was noted, Figure 7, as in effect they could be used to construct any desired manoeuvre by piecing together sections of various lengths and differing severity. The slalom manoeuvres consisted of sections derived in the lateral or 'y' direction, but of course this can equally be extended to the other axes of the aircraft and indeed the forward velocity as well as other parameters describing the attitude or rate of attitude change in the aircraft. This is a useful point to note for future development of new MTEs for application to inverse simulation.

Figures

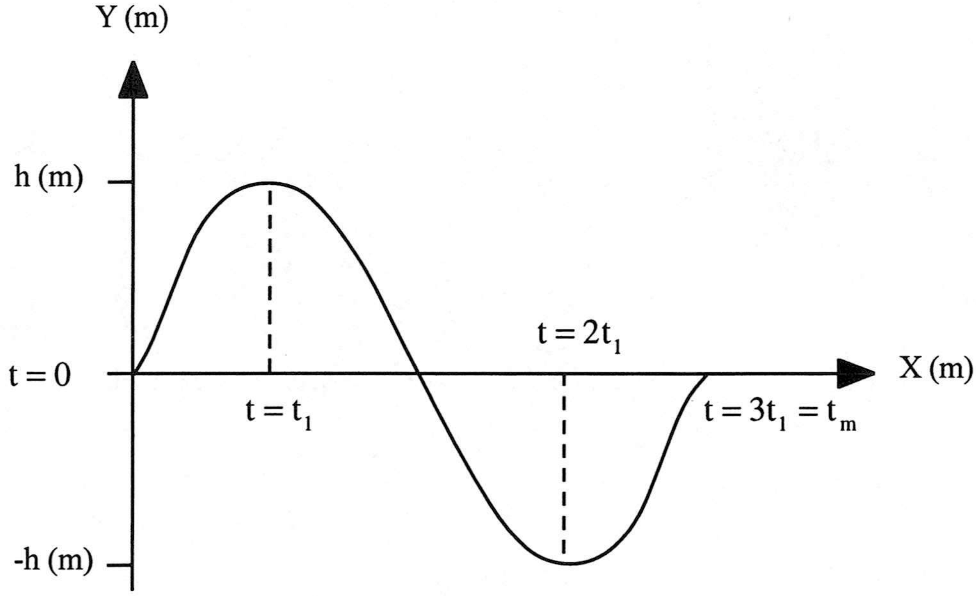

Figure 1: Schematic of ADS-33C Slalom MTE

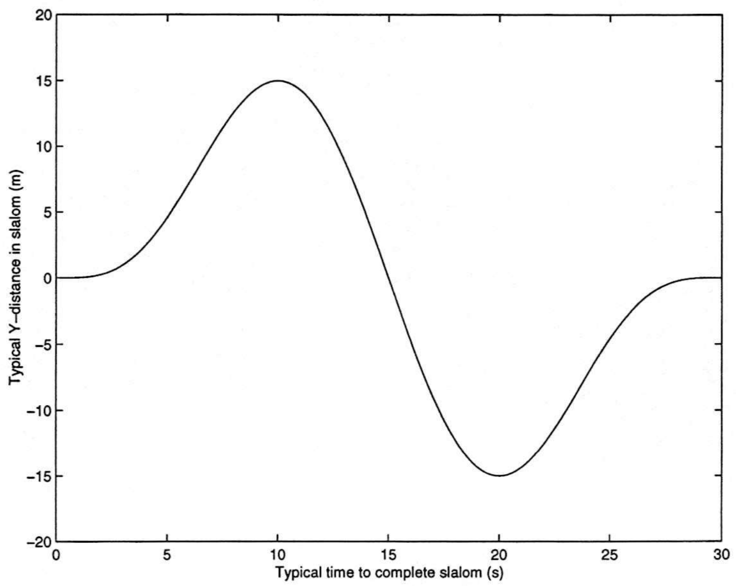

Figure 2: Plot of polynomial developed for ADS-33C MTE

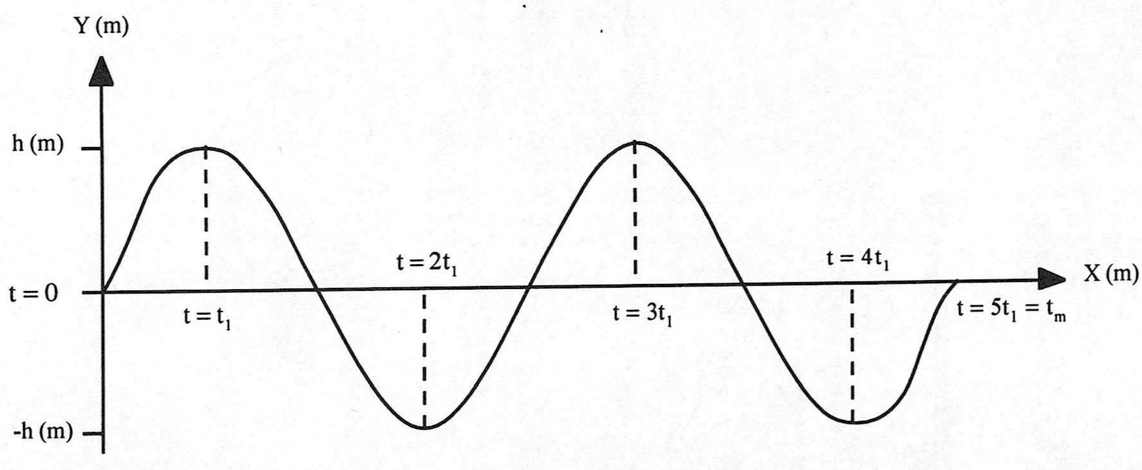

Figure 3: Schematic of ADS-33D Slalom Mission Task Element

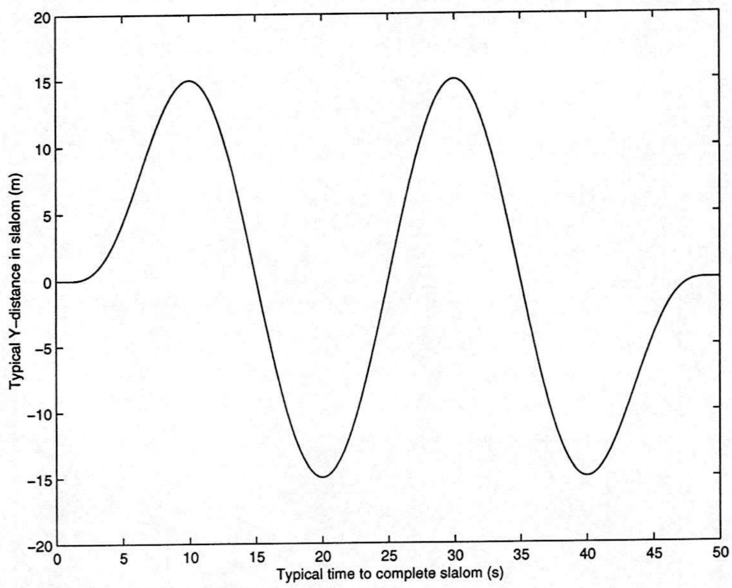

Figure 4: Plot of polynomial developed for ADS-33D MTE

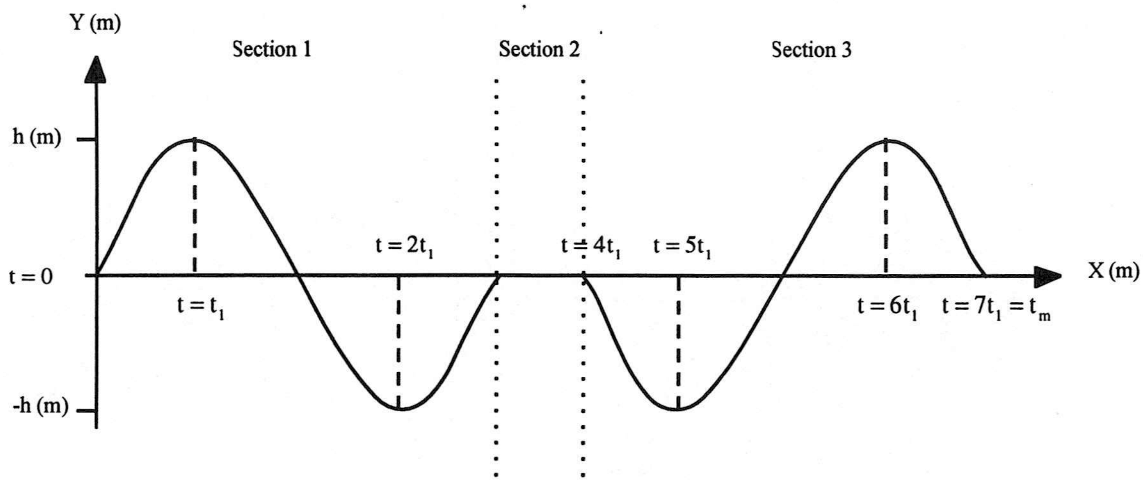

Figure 5: Schematic of DERA Slalom

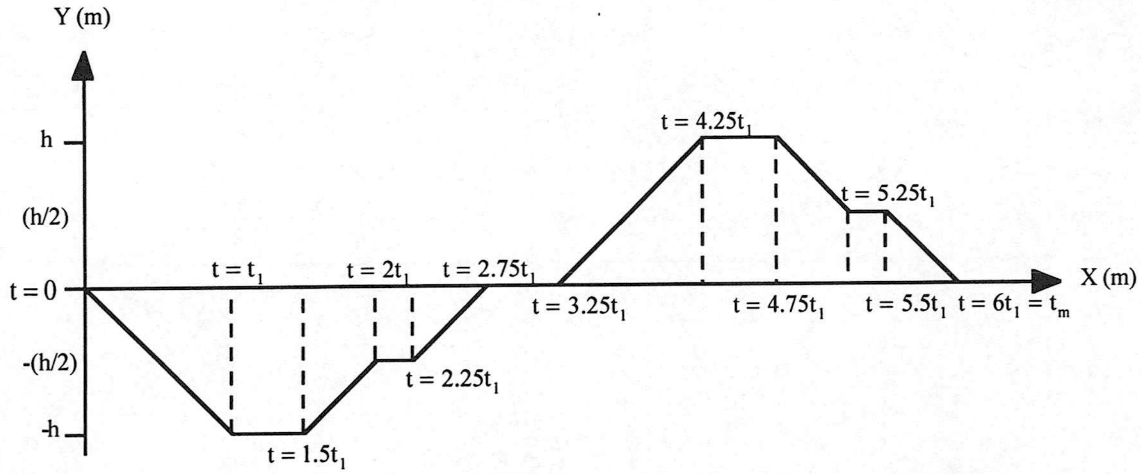

Figure 6: Schematic of idealised DLR Slalom (with linear sections)

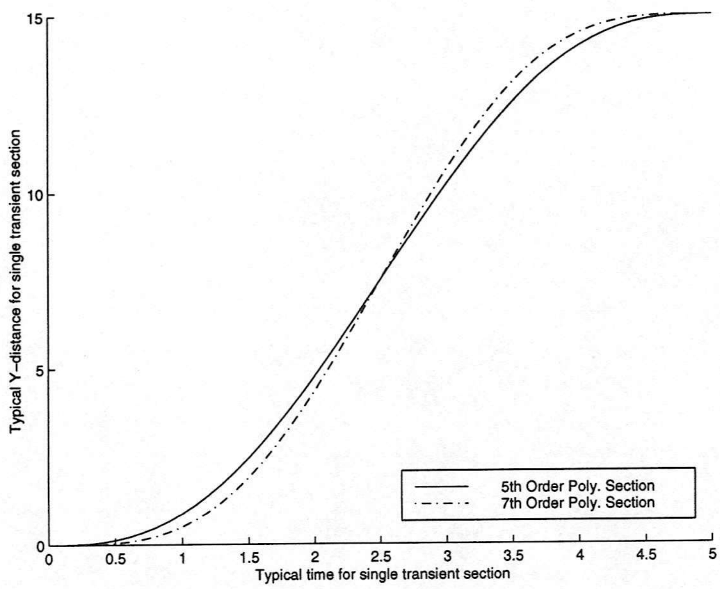

Figure 7: Illustration of the difference between 5^{th} and 7^{th} order polynomial sections

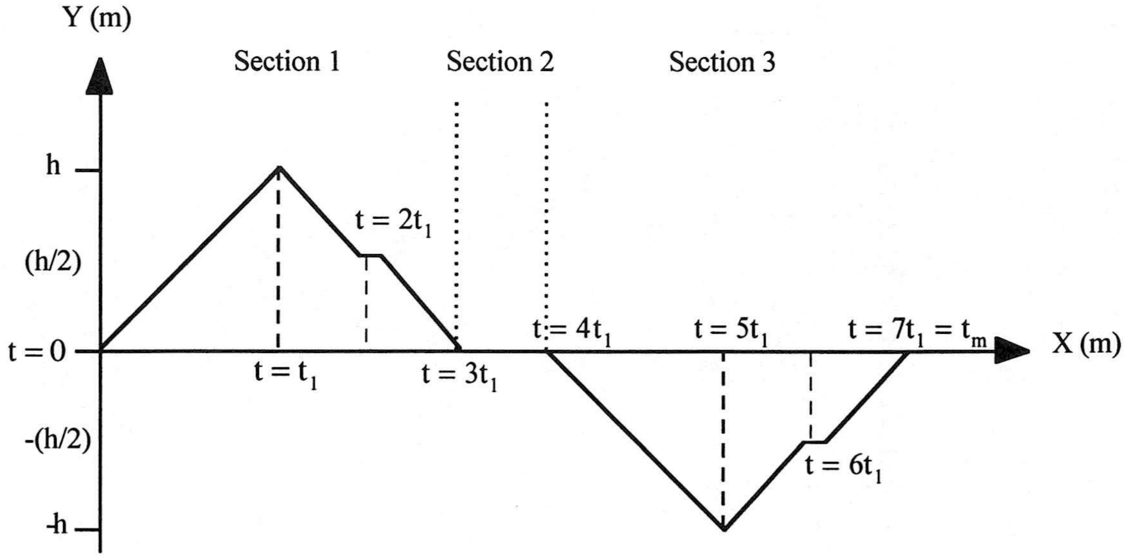

Figure 8: Schematic of idealised DLR Slalom (without linear sections)

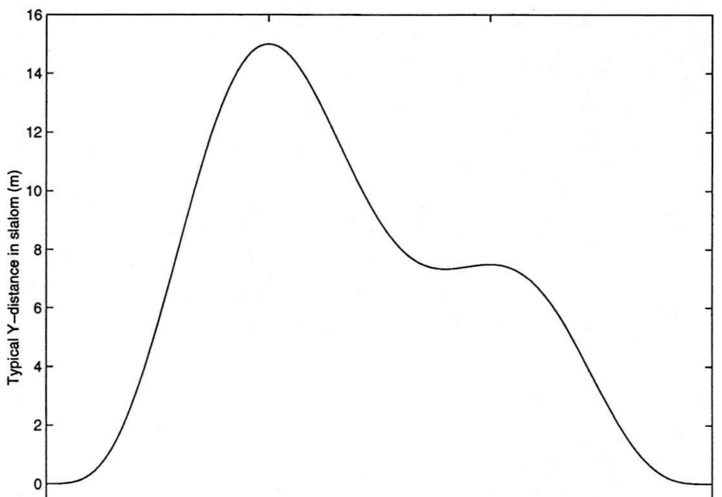

Figure 9: Plot of polynomial developed for DLR (without linear sections) MTE

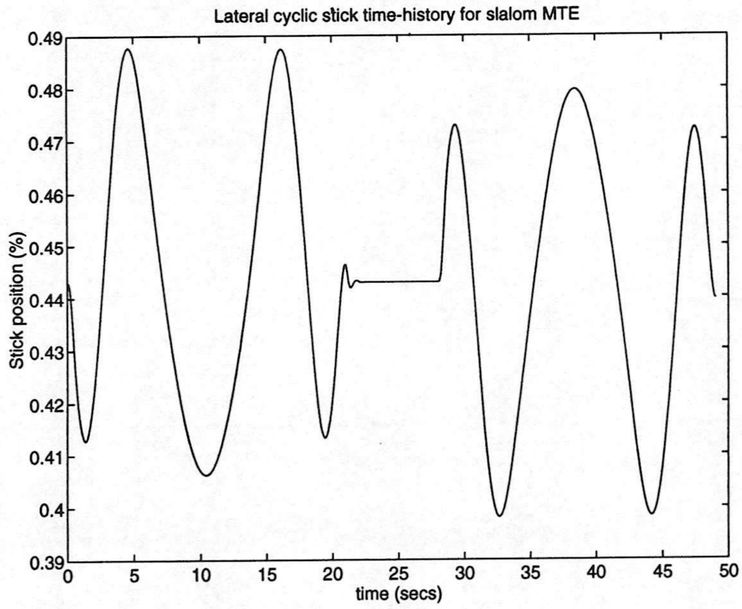

Figure 10: Time-history of lateral cyclic stick for DERA slalom MTE

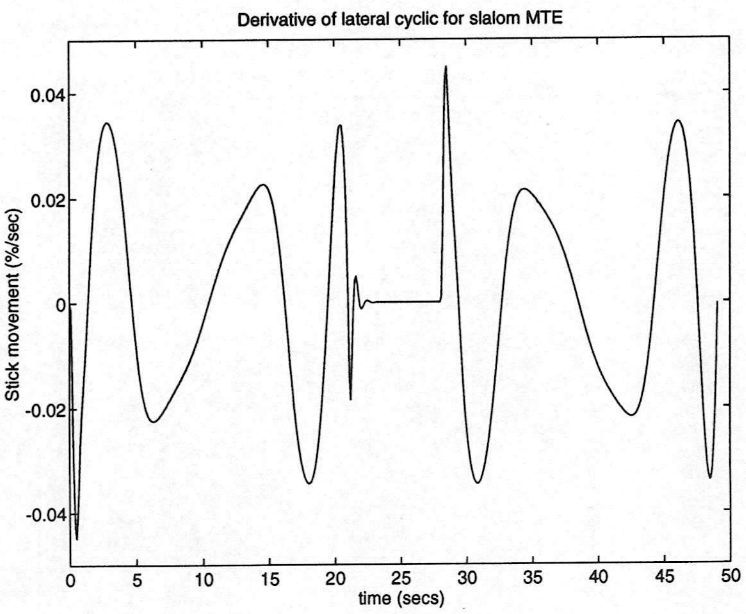

Figure 11: Time-history of derivative of lateral cyclic stick for DERA slalom MTE

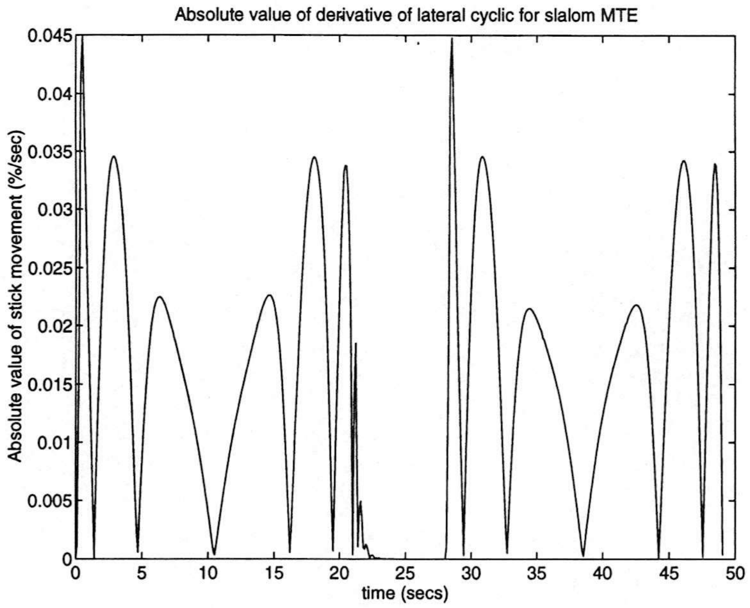

Figure 12: Time-history of absolute value of derivative of lateral cyclic stick for DERA slalom MTE

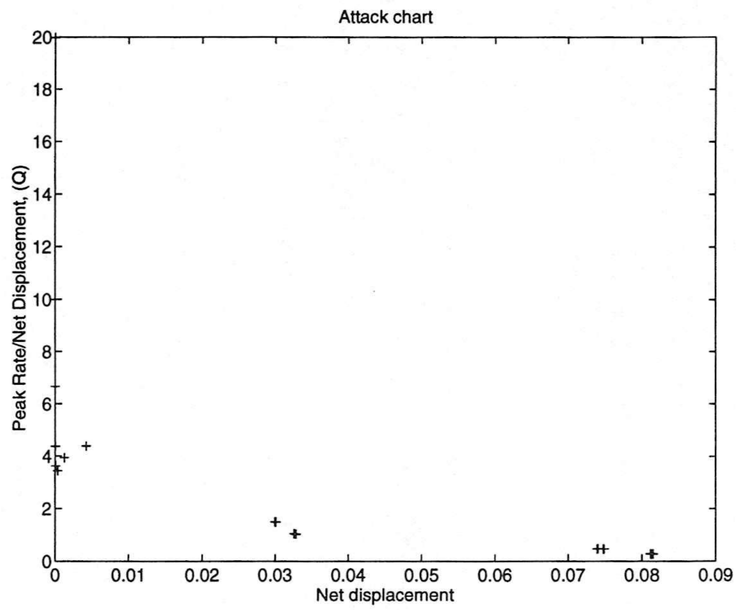

Figure 13: Attack chart obtained using Figure 10 and Figure 11 time-histories

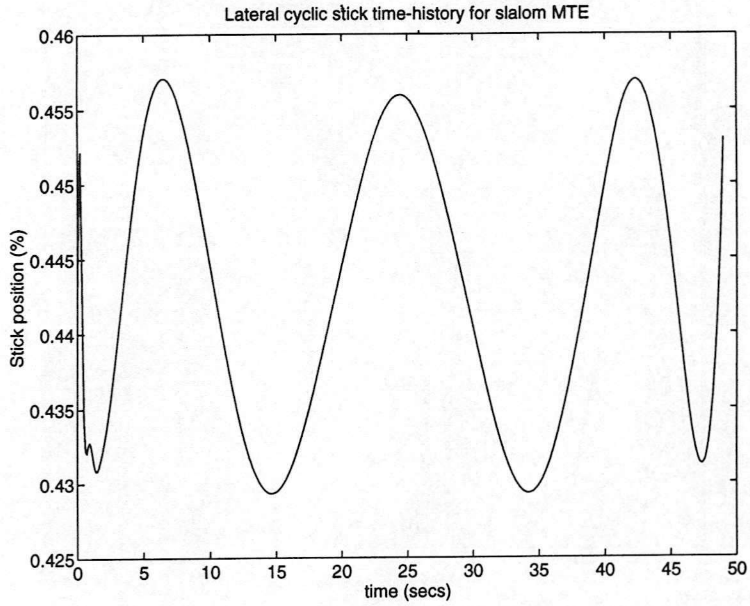

Figure 14: Time-history of lateral cyclic stick for ADS-33D slalom MTE

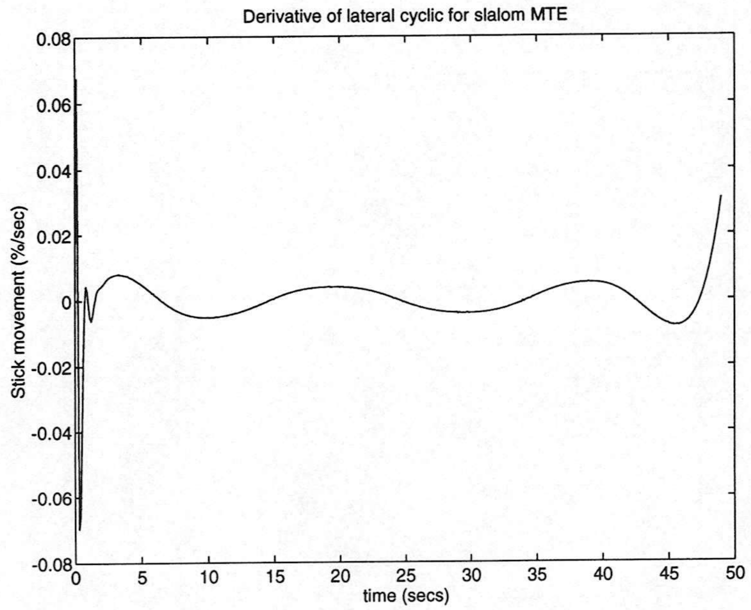

Figure 15: Time-history of derivative of lateral cyclic stick for ADS-33D slalom MTE

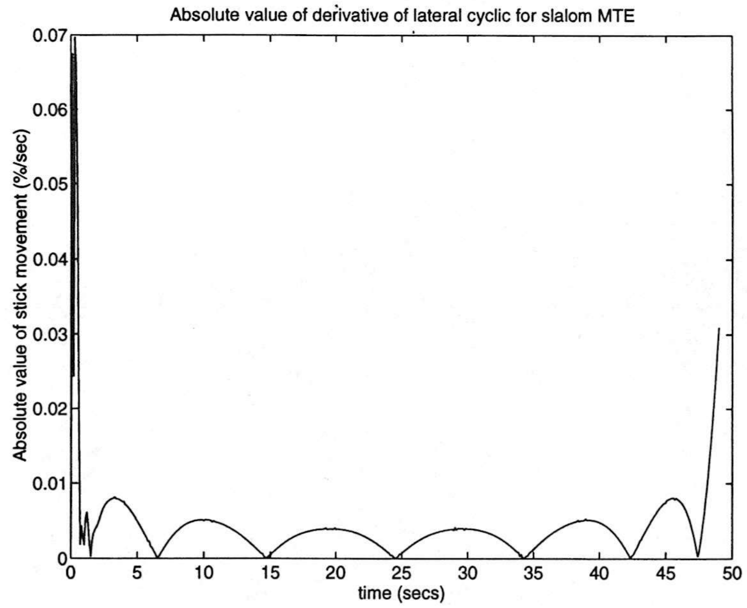

Figure 16: Time-history of absolute value of derivative of lateral cyclic stick for ADS-33D slalom MTE

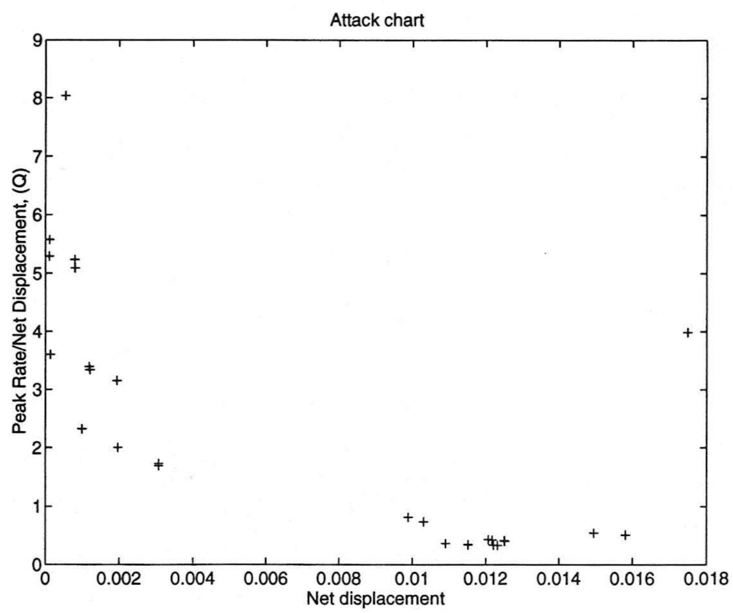

Figure 17: Attack chart obtained using Figure 14 and Figure 15 time-histories

References

1. Thomson, D. G. and R. Bradley. "Development And Verification Of An Algorithm For Helicopter Inverse Simulation." Vertica, Vol. 14, No. 2. 1990.

2. Anon. "Aeronautical Design Standard, (ADS-33C): Handling Qualities For Military Rotorcraft. United States Army And Troop Command. 1989.

3. Anon. "Aeronautical Design Standard, (ADS-33D): Handling Qualities For Military Rotorcraft. United States Army And Troop Command. 1994.

4. Howell, S.E. "Preliminary Results From Flight And Simulation Trials To Investigate Pilot Control Workload In Slalom Manoeuvres". Defence Research Agency. 1995.

5. MacDonald, C.A. and R. Bradley. "An Initial Investigation Of Helicopter Pilot Workload Rating Using Rule Induction Techniques. Department Of Mathematics. Glasgow Caledonian University.