Inverse Simulation as a Tool For Studying Helicopter Handling Qualities

Richard Dunlop*

University of Glasgow, Glasgow, G12 8QQ, Scotland

The aim of this project was to analyse helicopter handling qualities using inverse simulation. Two manoeuvres were developed based on Mission Task Elements described by ADS-33: the vertical manoeuvre and slalom. These manoeuvres were defined with the purpose of performing inverse simulations for two helicopter configurations, a baseline configuration based on the Westland Lynx (currently designated AgustaWestlend Lynx) and a degraded configuration. These were used in this research to find a way in which helicopter handling qualities could be assessed through the use of test cases. Two methods were employed, based on a previously developed parameter, referred to as the control quickness. The first method involved replicating the test cases performed in previous work, revising the parameter in order to be more flexible for certain manoeuvres, while the second method involved testing a new criterion for the control quickness, to compare results and decide on the best methodology for future studies. Both methods demonstrated satisfactory results in terms of showing a distinction between the handling qualities of the two helicopter configurations. The first method tested showed to be more conclusive.

Nomenclature

p, q, r	Helicopter angular velocities in body axes
Q_E	Engine torque output
t	Time
t_n	Time at time-point n
$\mathbf{u}$	Control vector
u, v, w	Translational velocities in body axes
V_f	Flight velocity
$\mathbf{x}$	State vector
x, y, z	Forward, lateral and vertical displacement
$\dot{x}, \dot{y}, \dot{z}$	Forwards, lateral and vertical velocity
$\ddot{x}, \ddot{y}, \ddot{z}$	Forward, lateral and vertical acceleration
$\dddot{y}, \dddot{z}$	Acceleration time-derivative
x_e, y_e, z_e	Earth fixed reference frame
x_b, y_b, z_b	Body fixed reference frame
$\mathbf{y}$	Output vector
$\mathbf{y_d}$	Desired output vector
y_{max}	Maximum y-displacement over slalom manoeuvre
ϕ, θ, ψ	Euler angles
θ_0	Main rotor collective pitch angle
θ_{1s}	Main rotor longitudinal cyclic pitch angle
θ_{1c}	Main rotor lateral cyclic pitch angle
$\theta_{0_{tr}}$	Tail rotor collective pitch angle
Θ_{1c}	Integral of lateral cyclic
Ω	Main rotor angular velocity

*Master's student, School of Aeronautical and Aerospace Engineering, r.dunlop.1@research.gla.ac.uk,

I. Introduction

Most helicopters have encountered delays during the development and certification stage while dealing with problems which had not been predicted in the design phases — especially those related with flying qualities and flight control.[1] Some of these problems might involve instability encountered by the helicopter in hover, a lack of agility while performing simple manoeuvres or an excessive workload required by the pilot in certain areas of the flight envelope.

The Aeronautical Design Standard Performance Specification for Handling Qualities Requirements for Military Rotorcraft (ADS-33-PRF),[2] known as ADS-33, was developed by the United States military for assigning Handling Quality Ratings to military helicopters. Many helicopter manufacturers worldwide have established their handling qualities design guide based on the methods introduced in this document. Using ADS-33, HQRs are awarded to an aircraft depending on how well it can perform Mission Task Elements (MTEs). The specification adopts the Cooper-Harper scale (Figure 1), which the pilot complies with by going through the decision tree, starting from the bottom left. By following this guideline, the pilot awards the aircraft a rating of 1 to 10 for the MTE in question, with a rating of 1 being Excellent and 10 indicating Major Deficiencies. The HQR for an aircraft is either Level 1 (pilot rating 1-3.5), Level 2 (3.5-6.5) or Level 3 (6.5-8.5), with a requirement for an overall Level 1 being that the aircraft must achieve a Level 1 rating for all MTEs. This, however, requires a helicopter to be flown, eliminating the opportunity of assessing its handling qualities and detecting issues regarding this before the manufacturing stage.

One of ADS-33's most important contributions is its inclusion of MTEs. These manoeuvres are fully determined, with adequate and desired performance specifications provided for different helicopter configurations, such as Scout/Attack or Cargo/Utility helicopter, for either Good Visual Environment (GVE) or Degraded Visual Environment (DVE). The MTEs also include the objectives for the manoeuvre and a description of the test course to be used by the pilot when performing the exercise. As ADS-33 clearly defines the MTEs to be used in the evaluation of handling qualities, a mathematical representation of each manoeuvre can be developed to be used in the inverse simulations.

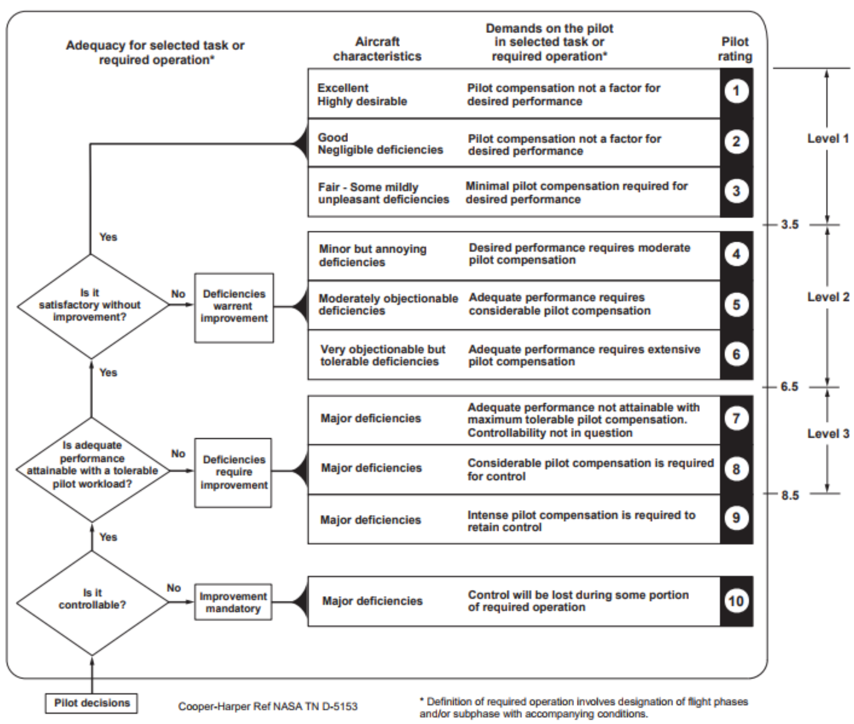

Figure 1: Cooper-Harper Scale

Inverse simulation uses a precisely defined manoeuvre to calculate the controls required for the aircraft to fly the manoeuvre. This makes it a suitable tool for studying flight dynamics as a time history of the control displacements and the aircraft's states are obtained as in an actual flight test. Inverse simulation is particularly useful for use with helicopters due to their extensive use in Nap-of-the Earth flight, which requires precise controls to be implemented by the pilot. Thomson and Bradley[3] developed a technique which can be used to analyse the data collected by the inverse simulations and utilise this to assess handling qualities in a similar manner to that from a real flight test. This research proposes a method, based on this technique, which could eventually enable manufacturers to assess the flying qualities of helicopters at the conceptual design stage. This has the potential of offering savings in terms of money and time, as well as improving flight safety from an early stage.

The main objectives for the current study were:

- Model MTEs in accordance with ADS-33 for use with inverse simulation
- Assess the current method in place for evaluating handling qualities through inverse simulation and propose changes if necessary
- Evaluate any proposed changes by applying them to a case study using two helicopter configurations: (a)baseline and (b)degraded
- Advice on future work based on the results obtained from the case study

II. Inverse Simulation

Inverse simulation was developed by Thomson[4] three decades ago as a simulation tool to measure the agility of helicopters. Various new techniques have been established since,[5] for use in fixed wing aircraft,[6] helicopter flight dynamics,[3,7–10] helicopter conceptual design[11] and more recently in designing a controller for an autonomous planetary rover.[12]

In a standard simulation for an aircraft, the controls are input to the mathematical model and the flight path is produced as an output. An inverse simulation inverts this process: taking a precisely defined manoeuvre in the form of the flight path as the input, the output from the simulation would be the necessary controls to achieve the manoeuvre.

The task of obtaining an aircraft's response to a series of control inputs may be generally described as the initial value problem:

$$\mathbf{y} = \mathbf{g}(\mathbf{x}) \tag{1}$$

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u});\ \mathbf{x}(\mathbf{0}) = \mathbf{x_0} \tag{2}$$

in which $\mathbf{x}$ represents the system state vector, $\mathbf{u}$ is the control vector and $\mathbf{y}$ is the output vector. Equation (1) shows how the mathematical model describes the evolution in time of $\mathbf{x}$ in response to an imposed time history for the control vector $\mathbf{u}$. Equation (2), or the output equation, demonstrates how the state vector is used to attain the output vector $\mathbf{y}$. In an inverse simulation, the control time histories $\mathbf{u}$ needed to produce $\mathbf{y}$ are calculated by using a desired output vector $\mathbf{y_d}$. In terms of helicopter flight, this means the flight path $\mathbf{y}$ is used as the input to obtain the necessary flight controls $\mathbf{u}$ as the output. Thomson and Bradley[13] demonstrated that Equation (2) can be differentiated to modify Equations (1) and (2) as a means of demonstrating the method:

$$\dot{\mathbf{y}} = \frac{\mathbf{dg}}{\mathbf{dx}}\dot{\mathbf{x}} = \frac{\mathbf{dg}}{\mathbf{dx}}\mathbf{f}(\mathbf{x}, \mathbf{u}) \tag{3}$$

If Equation (3) is invertible with respect to $\mathbf{u}$, it is possible to write:

$$\mathbf{u} = \mathbf{h}(\mathbf{x}, \dot{\mathbf{y}}_\mathbf{d}) \tag{4}$$

and substituting into Equation (1), gives:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{h}(\mathbf{x}, \dot{\mathbf{y}}_\mathbf{d})) = \mathbf{F}(\mathbf{x}, \dot{\mathbf{y}}_\mathbf{d}) \tag{5}$$

A complete statement of the inverse problem is represented by Equations (4) and (5), where $\mathbf{y_d}$ is the input vector and $\mathbf{u}$ is the output vector.

In the case of the helicopter, the state vector may be written as

$$\mathbf{x} = [u \quad v \quad w \quad p \quad q \quad r \quad \phi \quad \theta \quad \psi \quad \Omega \quad Q_E]^T$$

and the control vector is

$$\mathbf{u} = [\theta_0 \quad \theta_{1s} \quad \theta_{1c} \quad \theta_{0_{tr}}]^T$$

where u, v and w are the components of translational velocity relative to a body fixed reference frame (x_b, y_b, z_b); p, q and r are the angular velocities about x_b, y_b and z_b respectively; ϕ, θ and ψ are the attitude angles between the body fixed axes set and the earth fixed reference frame (x_e, y_e, z_e); Ω is the main rotor angular velocity and; Q_E is the torque produced by the engines. The control vector is made up of $\theta_0, \quad \theta_{1s}, \quad \theta_{1c}, \quad and \quad \theta_{0_{tr}}$; the main rotor collective, longitudinal cyclic, lateral cyclic and tail rotor collective pitch angles, respectively.

If Equation (3) is not invertible with respect to $\mathbf{u}$, then Equation (2) must be differentiated further in order to provide additional equations to obtain an inverse model. Due to this, higher order derivatives of $\mathbf{y}$ may appear as the forcing terms in the inverse formulation. In the case that higher order derivatives show up, extra care must be taken in achieving adequate smoothness in terms of the desired output vector $\dot{\mathbf{y}}_\mathbf{d}$, otherwise any calculated control response $\mathbf{u}$ will probably not be useful.

The rotorcraft inverse simulation package (RISP) used in this research was developed by Bagiev[10] on MATLAB. This package uses an integration method for inverse simulation, first proposed by Hess et al,[14] where the desired flight path is discretised by dividing it into small time steps. The nonlinear equations of motion are integrated over the time step and a Newton-Raphson iterative scheme is used for minimising the error at each interval when compared with the desired flight path. The RISP software has within it a trim algorithm for calculating the states and controls of the rotorcraft at different flight velocities, a library of manoeuvres and a rotorcraft simulation model, RotorcraftSim. The helicopter model was based on HGS (Helicopter Generic Simulation),[15] a seven degree of freedom non-linear mathematical model developed for use with inverse simulation. The HGS model uses a multi-blade, disc-type representation for the main and tail rotor, assuming rigid blades with constant chord and linear twist. An engine model is included as well as look-up tables used for the fuselage and empennage of the aircraft. A main difference between HGS and RotocraftSim is the inflow model, as a Glauert model[16] is used for RISP to calculate the rotor induced velocity, rather than a dynamic inflow model. The HGS model has been previously validated against flight data[11,17] and RISP has been verified against the original HGS model.[10]

III. MTE Mathematical Models

In order to use inverse simulation for assessing handling qualities, MTEs must first be modelled mathematically for use by RISP. Thomson and Bradley[11] demonstrated a method using polynomials to model manoeuvres which are regularly performed by helicopters. This method was used to model two MTEs defined by ADS-33: the Vertical Manoeuvre and Slalom.

A. The Vertical Manoeuvre

This manoeuvre is defined in ADS-33 as follows:

"from a stabilised hover at an altitude of 15 ft., initiate a vertical ascent of 25 ft., stabilise for two seconds, then descend back to the initial hover position."

Desired Performance Requirements for Utility Helicopter:

- Maintain the longitudinal and lateral position within 3 ft
- Maintain start/finish altitude within 3 ft
- Maintain heading within 5 deg
- Complete the manoeuvre within 13 sec

Mathematical Model

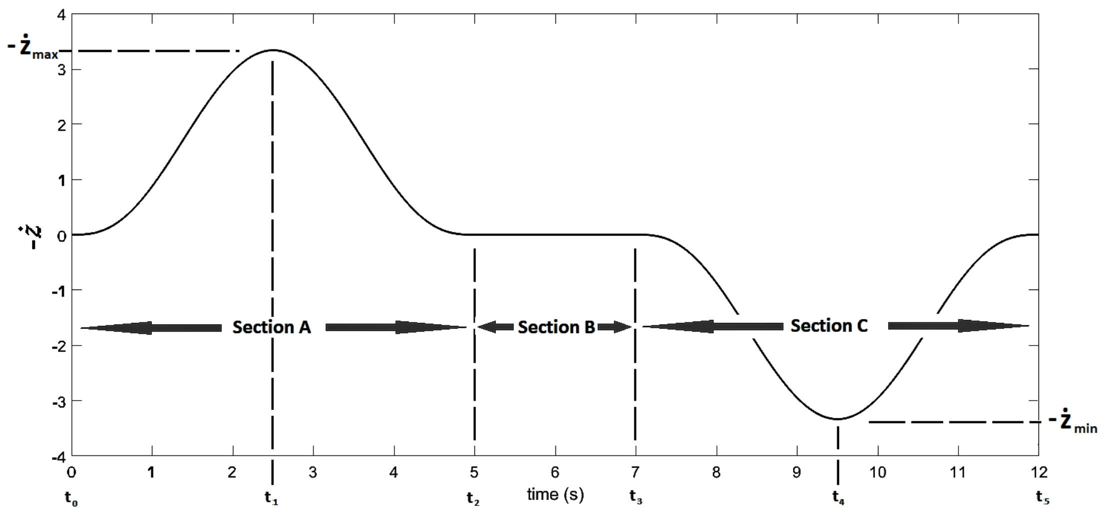

Figure 2: Vertical Manoeuvre MTE: time vs. z-velocity

A piecewise polynomial consisting of three sections (A, B, C) was used to model this manoeuvre. Vertical velocity $\dot{z}$ was used as the lowest order derivative (Figure 2), in order to ensure a smooth transition with no initial acceleration, as the manoeuvre commences from trim. Since this whole manoeuvre occurs in the z-axis alone:

$$x = \dot{x} = \ddot{x} = y = \dot{y} = \ddot{y} = \psi = \dot{\psi} = \ddot{\psi} = 0 \tag{6}$$

Section A was divided into three time-points: t_0, t_1 and t_2, where $t_0 = 0$. As the position is to be held for section B, $t_3 - t_2 = 2$ seconds, all velocities and accelerations equate to zero and the positions remain constant throughout this section. Section C, similarly to A, was separated into three time-points: t_3, t_4 and t_5.

At t_0 and t_2, all velocities and accelerations equate to zero. With the helicopter rising in a smooth motion, the z-velocity increases until it reaches a maximum velocity, $\dot{z}_{max}$, halfway up, at t_1. The boundary conditions used to model section A are as follows:

$$\text{At } t = t_0: \quad \dot{z} = 0; \quad \ddot{z} = 0; \quad \dddot{z} = 0 \tag{7}$$

$$\text{At } t = t_1: \quad \dot{z} = -\dot{z}_{max}; \tag{8}$$

$$\text{At } t = t_2: \quad \dot{z} = 0; \quad \ddot{z} = 0; \quad \dddot{z} = 0 \tag{9}$$

The seven boundary conditions can be represented by a 6^{th} order polynomial in $\dot{z}$ and its two derivatives, $\ddot{z}$ and $\dddot{z}$:

$$\dot{z} = at^6 + bt^5 + ct^4 + dt^3 + et^2 + ft + g \tag{10}$$

$$\ddot{z} = 6at^5 + 5bt^4 + 4ct^3 + 3dt^2 + 2et + f \tag{11}$$

$$\dddot{z} = 30at^4 + 20bt^3 + 12ct^2 + 6dt + 2e \tag{12}$$

Substituting $t_0 = 0$ into the above equations, it is clear that $g = f = e = 0$. The four remaining coefficients can be solved with the aid of symbolic algebra by writing the above equations in matrix form.

Substituting the coefficients $(a - d)$ into Equation (10), the polynomial for velocity $\dot{z}(t)$ takes the following form:

$$\dot{z} = (t^6 - 3t_2t^5 + 3t_2^2t^4 - t_2^2t^3(\frac{-\dot{z}_{max}}{t_1^3(t_1 - t_2)^3}) \tag{13}$$

Similarly, for acceleration:

$$\ddot{z} = (6t^5 - 15t_2t^4 + 12t_2^2t^3 - 3t_2^2t^2(\frac{-\dot{z}_{max}}{t_1^3(t_1 - t_2)^3}) \tag{14}$$

Throughout section B of the manoeuvre, $\dot{z}(t) = \ddot{z}(t) = \dddot{z} = 0$

The position z(t) can be obtained by integrating Equation (14) with respect to time. Section C was modelled in a similar fashion to section A, with the coefficients for Equation (10) taking the following form:

Table 1: Section C coefficients

a	H
b	$-3(t_3 + t_5)H$
c	$3(t_3^2 + 3t_3t_5 + t_5^2)H$
d	$-(t_3^3 + 9t_3^2t_5 + 9t_3t_5^2 + t_5^3)H$
e	$3t_3(t_3^2t_5 + 3t_3t_5^2 + t_5^3)H$
f	$3t_3(t_3^2t_5 + 3t_3t_5^2 + t_5^3)H$
g	$-3t_3^2(t_5^3 + t_3t_5^2)H$
h	$t_3^3t_5^3H$

Where

$$H = \frac{\dot{z}_{max}}{(t_4 - t_5)^3(t_3^3 - 3t_3^2t_4 + 3t_3t_4^2 - t_4^3)}$$

Results

Combining the three sections of the piecewise polynomials and plotting them against time, a 10-second vertical manoeuvre in terms of position, velocity and acceleration is shown in Figure 3. Note the position time-history fulfils the requirements set in ADS-33: the vehicle climbs up to an altitude of 40 ft (12.192 m) and remains stabilised for two seconds before descending back to its initial altitude.

Figure 4 shows the control inputs required to perform the vertical manoeuvre over 12 seconds, using a 0.05 second time-step. Once the move commences, a collective control input is applied to start the ascent. As the collective is increased, a tail rotor collective control input is necessary to counteract the added torque produced. When the helicopter is reaching the maximum vertical velocity defined by the model, the collective is decreased to begin decelerating, the tail rotor collective follows as a lower anti-torque force is now required. As the vehicle nears its destination in terms of altitude, a final correction is made by the collective control to reach a halt, again followed by the tail rotor collective. The process is then reversed to descend after the 2 seconds in hover. The cyclic control inputs (longitudinal and lateral) only encounter a slight change (<5%) throughout the whole manoeuvre, as no lateral, forward or backward movement is required. These small cyclic inputs are used for minor corrections throughout the length of the manoeuvre.

Figure 5 shows the flight path provided after completing the manoeuvre, showing negligible movement in the x and y direction, with all the ADS-33 requirements met in the z direction. The time-history of the states show the heading was maintained within 10^{-3} degrees.

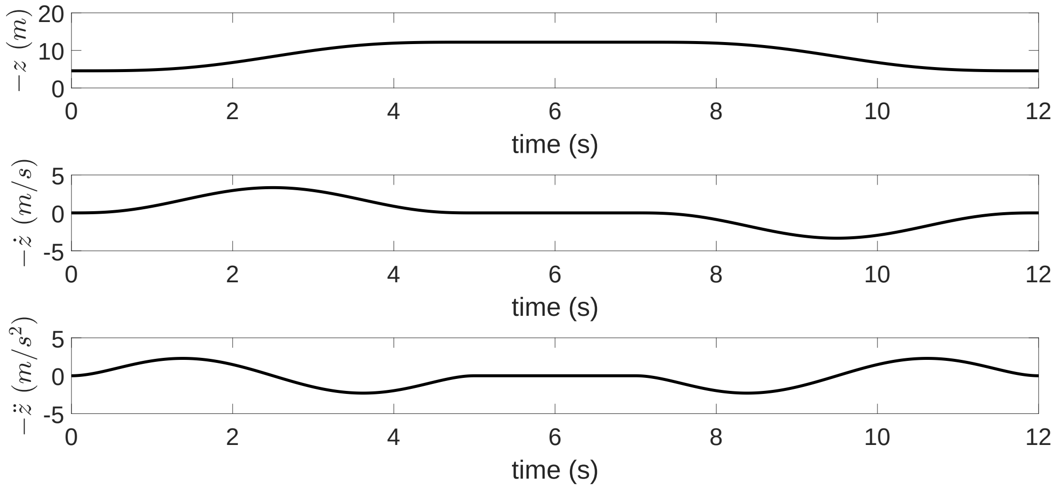

Figure 3: Vertical Manoeuvre MTE

B. The Slalom Manoeuvre

This Mission Task Element is defined in ADS-33 as follows:

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

Requirements for Desired Performance:

- Maintain an airspeed of at least 60 knots throughout the course
- Accomplish manoeuvre below reference altitude of 100 ft.

The suggested test course for the Slalom MTE, from ADS-33, is shown in Figure 6. The manoeuvre is to take place at a constant velocity throughout. Since there is no change in altitude, it is to be performed in the x-y plane only, so the flight velocity

$$V_f = \sqrt{\dot{x}^2 + \dot{y}^2} \tag{15}$$

This manoeuvre was modelled using a piecewise polynomial made up of five sections (A-E), each consisting of two boundary time points. The first section begins at the manoeuvre starting point and ends midway through the first turn (figure 7), at the first marker. The next three sections begin with the second half of the turn and end midway through the following turn. The final section commences on the second half of the final turn and ends at the end of the manoeuvre along the centreline.

There are four boundary conditions at each boundary point ($y, \dot{y}, \ddot{y}$ and $\dddot{y}$), adding up to eight boundary conditions per section. For section A, at t_0: $y = 0$, $\dot{y} = 0$, $\ddot{y} = 0$ and $\dddot{y} = 0$, while at t_1: $y = -y_{max}$, $\dot{y} = 0$, $\ddot{y} = 0$ and $\dddot{y} = 0$. This allows for a 7th order polynomial to be used in the modelling of each sector:

$$\dddot{y} = Ax^7 + Bx^6 + Cx^5 + Dx^4 + Ex^3 + Fx^2 + Gx + H \tag{16}$$

The integrals of the above polynomial define the acceleration, velocity and position of the aircraft in the y-direction, in terms of x, allowing for the time of the manoeuvre to be calculated once the length and flight velocity have been selected. The above expression may then be stated in terms of time to determine the

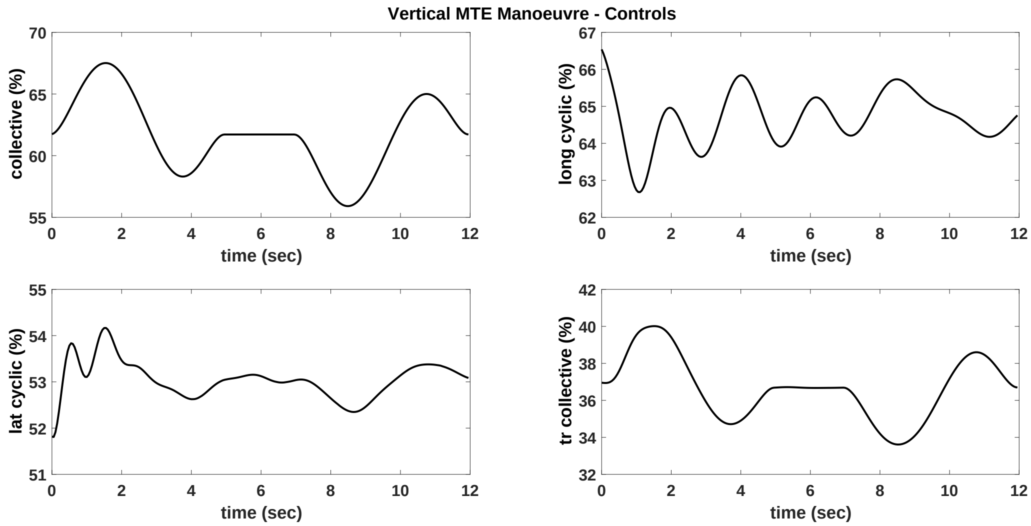

Figure 4: Vertical Manoeuvre Control Time-History

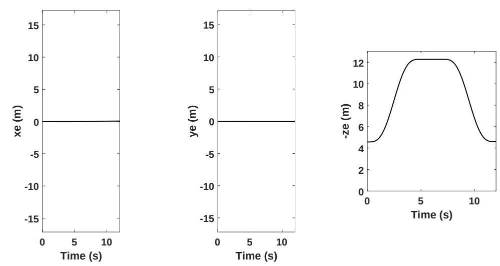

Figure 5: Vertical Manoeuvre Flight Path

desired flight path:

$$\ddot{y} = at^7 + bt^6 + ct^5 + dt^4 + et^3 + ft^2 + gt + h \tag{17}$$

The coefficients are calculated following the same method used for the vertical manoeuvre, producing the flight-path shown in Figure 8, with the solid line displaying the flight path achieved through an inverse simulation at 60 knots. This model complies with the manoeuvre as described by ADS-33, deeming it appropriate for the present study.

IV. Analysing Handling Qualities Using Inverse Simulation

ADS-33 includes criteria such as the attitude quickness parameter for flight tests (Figure 9). This allows handling qualities to be assigned on the aircraft based on time histories of the helicopter's states throughout a manoeuvre. By using the time-histories for the helicopter's states while performing the manoeuvre, a HQR rating may be awarded to the aircraft based on this parameter. Thomson and Bradley[3] developed a technique to analyse the handling qualities of helicopters using inverse simulation, through a parameter akin to the attitude quickness.

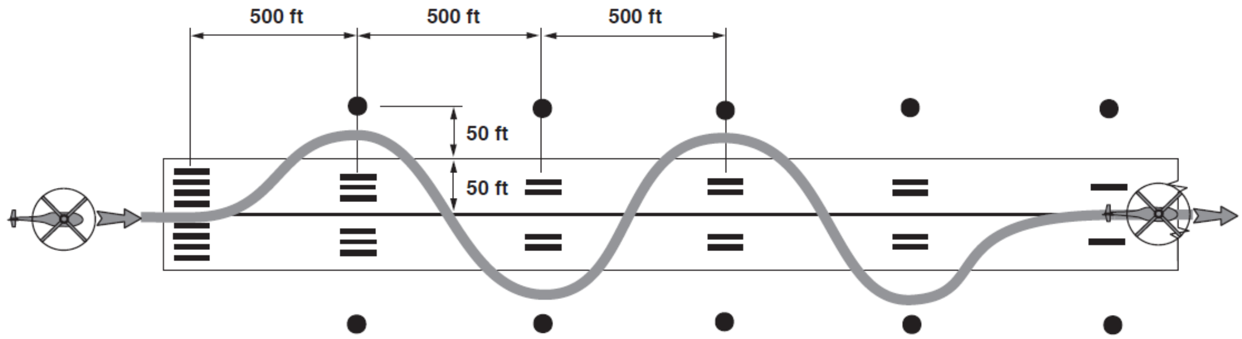

Figure 6: Slalom Manoeuvre Test Course (Extract from ADS-33)[2]

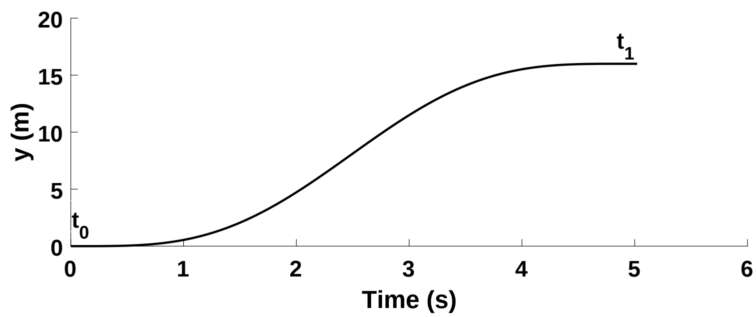

Figure 7: Slalom Section A

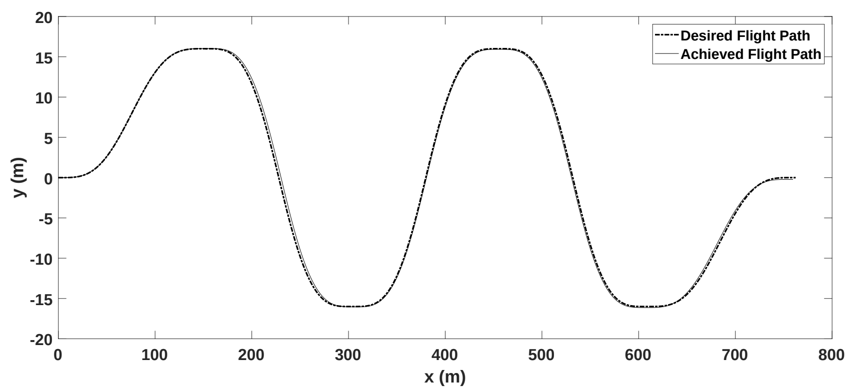

Figure 8: Slalom Manoeuvre Flight Path

A. The Control Quickness Parameter

Using inverse simulation, the attitude quickness is not an appropriate method of calculating the handling qualities of a helicopter configuration, as the states of the aircraft will have been defined in the modelling of the manoeuvre. This means that two helicopters of different configurations, flying the same manoeuvre, will exhibit very similar, if not identical, angular rates and attitude changes. For example, if a pilot were to fly a manoeuvre using a light and agile helicopter, and then follow the exact same path using one of a degraded configuration, the states encountered by the helicopter would be very similar but the pilot's workload would clearly be increased. This increase in workload may be viewed through inverse simulation results, as shown in Figure 10 for the longitudinal cyclic time-history of two configurations of the Lynx flying the slalom MTE at 60 knots.

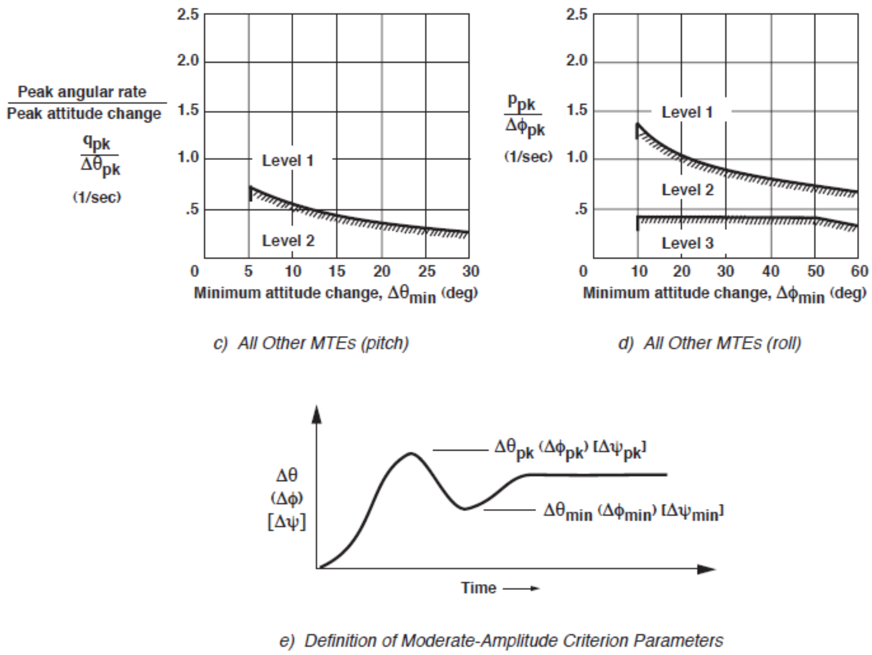

Figure 9: Attitude Quickness Parameter (Extract from ADS-33)[2]

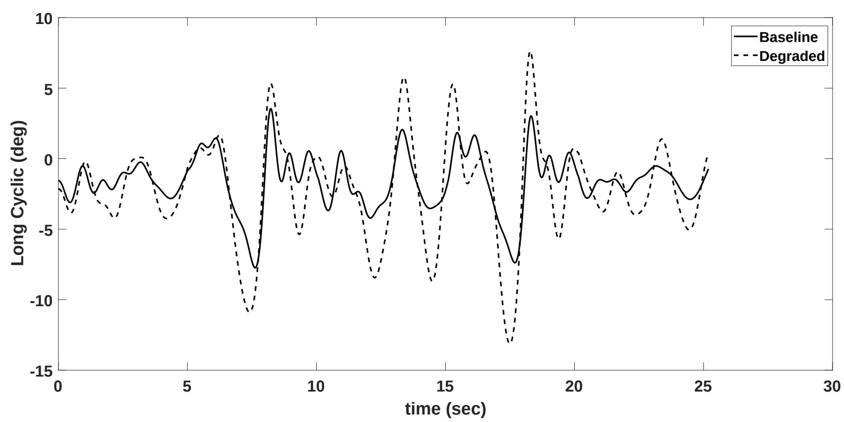

Figure 10: Longitudinal Cyclic Time Histories for Two Helicopter Configurations

Thomson and Bradley suggested using a control quickness parameter (CQP) rather than ADS-33's attitude quickness, to compare the handling qualities of different helicopters flying MTEs, using inverse simulation. Using the similarity exhibited by the pulses of longitudinal cyclic away from the trim position to the pulses of roll rate, p, the roll angle may be related to the integral of the lateral cyclic: Θ_{1_c}. This allows for the attitude quickness parameter to be replaced by the control quickness parameter: $\frac{\theta_{1_{c_{pk}}}}{\Delta\Theta_{1_c}}$. Figure 11 shows the time-history of the lateral cyclic for a helicopter flying the slalom manoeuvre at 60 knots, with the dashed line displaying the trim position at this flight speed. There are several pulses which are fully formed, after which more pulses are formed before the control returns to the trim position. Using the method described above, these pulses may not be taken into consideration when calculating the control quickness parameter. Therefore, two methods of calculating this parameter have been proposed: the pulse method and the full control rise method.

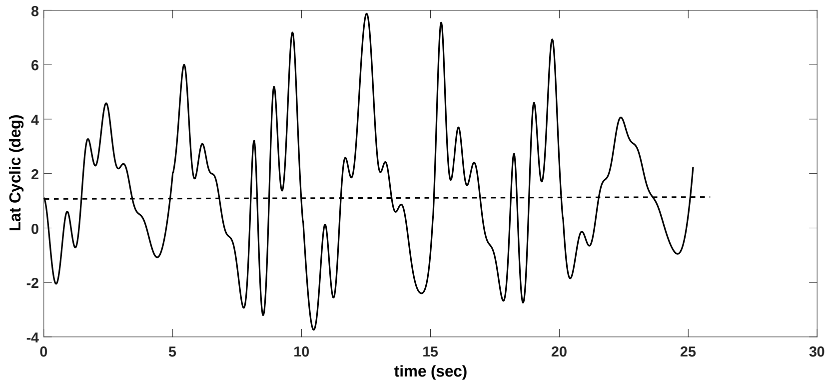

Figure 11: Lateral Cyclic Control from Trim

The pulse method, Figure 12 (a), considers a full pulse, ignoring any control input applied before the pulse commences. In the example below, the pulse peaks at 5.64 from its start, and the integral of θ_{1_c}, which is the area of the shaded section, is 1.76, giving a CQP of $\frac{\theta_{1_{c_{pk}}}}{\Delta\Theta_{1_c}} = 3.21$. This method is very much like the approach proposed by Thomson and Bradley, without the need for the pulse to begin from or return to the trim position. This allows for each pulse produced to be considered in the handling qualities assessment, accounting for each time the pilot moves a control back and forth.

The full control input method, Figure 12 (b), analyses the full control input, from one peak to the next, where $\Delta\Theta_{1_c}$ is now the integral of the lateral cyclic only up to the peak, again representing the area of the shaded region under the section being considered. Using this method, in the example below, the change in lateral cyclic is 9.94 and its integral for the section considered is 2.65, giving a CQP of 3.81. Using this approach, the entire effort by the pilot for each section is accounted for. If a large control input is applied over a shorter amount of time, exhibiting more effort required by the pilot, the control quickness parameter will be calculated at a higher value accordingly.

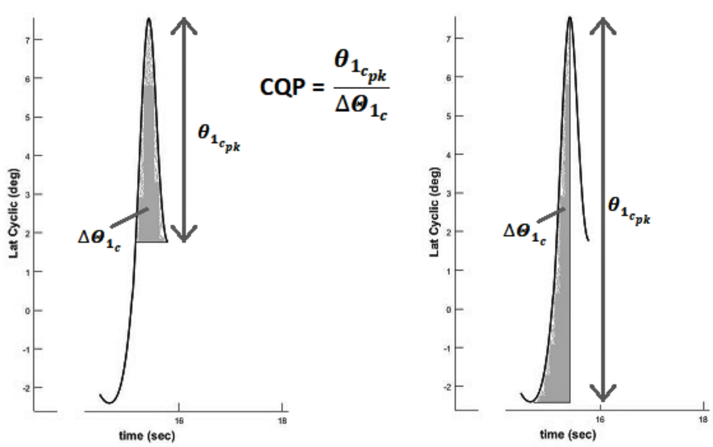

Figure 12: (a) Method 1

Figure 12: (b) Method 2

B. Case Study

A case-study using two helicopter configurations, based on the Westland Lynx, was performed to assess the use of the control quickness parameter using the two methods. The baseline configuration has a mass of

3300kg, a rigid rotor and a rotor solidity of 0.078. The poor helicopter configuration is 1000 kg heavier, with a fully articulated rotor and lower rotor solidity at 0.056. These configurations were applied so to assess the handling qualities of similar helicopters which are expected to be graded at different levels of handling qualities.

Figure 13 presents the control quickness parameters for the two configurations using the pulse method (Method 1), for the cyclic control histories of the slalom manoeuvre at 60 knots. A clear distinction may be seen at the points where the different configurations are pushed closer to the limits, with the degraded configuration displaying various points beyond 40% of the full control limits (the limit being 15°, from negative limit to positive limit). This clearly shows the effectiveness of the method in distinguishing the two configurations, allowing for their handling qualities to be compared.

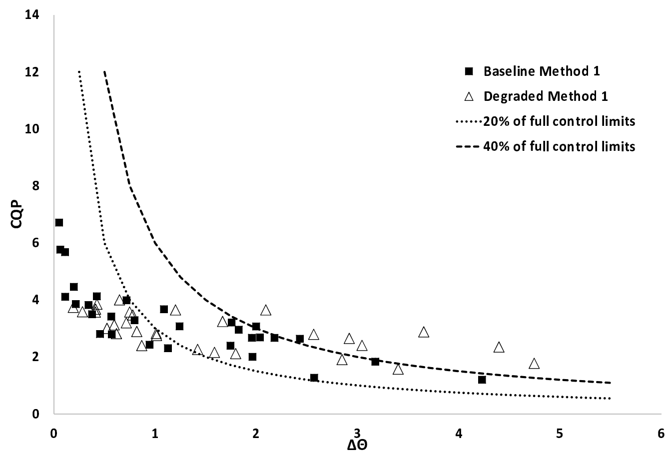

Figure 13: Slalom Control Quickness Parameters Using Method 1

Figure 14 shows the control quickness parameters for the same cyclic control inputs as above, this time employing the full control input method (Method 2). The upper curve now sets the boundary at 60% of the full control limits, as a larger section of the control input is considered for this criterion. This curve once again shows the distinction between both helicopter configurations, with the degraded configuration requiring larger control inputs at the most demanding sections of the manoeuvre. There are, however, a couple of points from the baseline configuration which have exceeded the 60% of limit boundary, which point to the most aggressive lateral cyclic control inputs (starting at t=9.6s and t=14.6s). This may be a sign of this method not being as accurate as the pulse method for this study, although it clearly outlines the portions of the manoeuvre which require rapid movements by the pilot.

Both methods of calculating the control quickness parameter have proven to be adequate, as from the results displayed it is clear which of the two sets of results represents the helicopter which would obtain a higher handling quality rating. In order to use this approach adequately, the manoeuvre must be modelled in a way which complies with ADS-33. That is, the attitude quickness parameters obtained should represent that of an aircraft with Level 1 handling qualities. Once this has been established, the manoeuvre may be used for studying handling qualities with the use of inverse simulation.

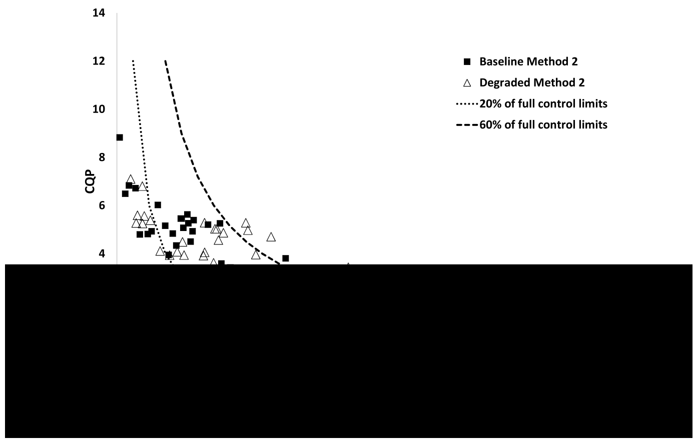

Figure 14: Slalom Control Quickness Parameters Using Method 2

V. Conclusion

The main aim of this investigation was to analyse the handling qualities of helicopters using inverse simulation.

It has been demonstrated that inverse simulation may be used in the study of helicopter handling qualities and, once fully developed, may offer the possibility of performing these studies for helicopters at an early stage of development. Based on the objectives set out for this research:

- The piecewise polynomial method for modelling manoeuvres has been demonstrated in detail for the vertical MTE, followed by a brief description of the model for the slalom MTE manoeuvre, both complying with the requirements set by ADS-33.
- Thomson and Bradley's method to measure the workload encountered by the pilot was introduced and the question addressed as to how to proceed with calculating the control quickness parameter if the control displacements do not return to the trim position once a pulse has fully developed.
- Two methods were proposed for measuring the CQP in this situation:
  - The pulse method, in which a full pulse is considered with no regards as to where it begins in comparison with the control trim value.
  - The full control input method, which examines the entire control displacement from turn to turn, not requiring the control input to return to its initial position.
- A case study was used, using a baseline helicopter configuration and a degraded configuration, to test these methods. They both proved to be useful in distinguishing between the different configurations, although the pulse method seemed to depict a clearer distinction.
- The author recommends the following to be employed for future work on the topic:
  - Validating RISP using flight test data for various helicopters
  - Populating the manoeuvre library with more MTEs and assess the methods used in this research
  - Employing the methods described in this research in an attempt to find the Levels 1-2 and 2-3 boundaries for known helicopter configurations

Acknowledgments

The author would like to thank Dr Douglas Thomson for his help and guidance throughout this project.

References

[1]Gareth Padfield. Theoretical modelling for helicopter flight dynamics - development and validation. *ICAS*, 1:165–177, 1988.

[2]Anon. Aeronautical design standard, performance specification handling qualities requirements for military rotorcraft. Technical report, US Army Aviation and Missile Command, 2000.

[3]D.G. Thomson and R.Bradley. The contribution of inverse simulation to the assessment of helicopter handling qualities. In *In:Proceedings of the 19th ICAS Conference*, number 7.3.2, Anaheim, USA, September 1994. ICAS.

[4]D.G. Thomson. *Evaluation of Helicopter Agility Through Inverse Solution of the Helicopter Equations of Motion*. PhD thesis, Department of Aeronautics and Fluid Mechanics, University of Glasgow, May 1987.

[5]David J. Murray-Smith. A review of inverse simulation methods and their application. *International Journal of Modelling and Simulation*, 34(3), 2014.

[6]O. Kato and I. Siguira. An interpretation ofairplane general motion and control as inverse problem. *Journal of Guidance, Control, and Dynamics*, 9(1):198–204, 1986.

[7]R.A. Hess and C. Gao. A generalized algorithm for inverse simulation applied to helicopter maneuvering flight. *Journal of the American Helicopter Society*, 16(5), October 1993.

[8]S. Rutherford and D.G. Thomson. Improved methodologies for inverse simulation. *ICAS*, September 1996.

[9]D.G Thomson and R. Bradley. Inverse simulation as a tool for flight dynamics research - principles and applications. *Progress in Aerospace Sciences*, 42:174–210, 2006.

[10]M. Bagiev, D.G. Thomson, D. Anderson, and D. Murray-Smith. Predictive inverse simulation of helicopters in aggressive manoeuvring flight. *The Aeronautical Journal*, 116(1175):87–98, January 2012.

[11]D.G. Thomson and R. Bradley. Development and verification of an algorithm for helicopter inverse simulation. *Vertica*, 14(2), May 1990.

[12]K. Worrall, D.G. Thomson, E. McGookin, and T. Flessa. Autonomous planetary rover control using inverse simulation. In *In: 13th Symposium on Advanced Space Technologies in Robotics and Automation*, Noordwijk, May 2015.

[13]D.G. Thomson and R. Bradley. The principles and practical application of helicopter inverse simulation. *Simulation Practice and Theory*, 6:47–70, 1998.

[14]R.A. Hess, C. Gao, and S.H. Wang. A generalized technique for inverse simulation applied to aircraft maneuvers. *Journal of Guidance, Control and Dynamics*, 14(5):920–926, 1991.

[15]D.G. Thomson. Development of a generic helicopter mathematical model for application to inverse simulation. Technical report, University of Glasgow, 1992.

[16]H. Glauert. A general theory of the autogyro. *Reports and Memoranda No. 1111*, November 1926.

[17]D.G. Thomson and R. Bradley. Validation of helicopter mathematical models by comparison of data from nap-of-the-earth flight tests and inverse simulations. In *Proceedings of the 14th European Rotorcraft Forum*, number 87, Milan, Italy, September 1988.

[18]Mayne Johnson, Benton H. Lau, and Jeffrey V. Bowles. Calculated performance, stability, and manouvrability of high-speed tilting-prop-rotor aircraft. Technical report, NASA, September 1986.