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Improving rotorcraft survivability to RPG attack using inverse methods

D. Anderson*, D. G. Thomson
Department of Aerospace Engineering, University of Glasgow, Glasgow, UK.

ABSTRACT

This paper presents the results of a preliminary investigation of optimal threat evasion strategies for improving the survivability of rotorcraft under attack by rocket propelled grenades (RPGs). The basis of this approach is the application of inverse simulation techniques pioneered for simulation of aggressive helicopter manoeuvres to the RPG engagement problem. In this research, improvements in survivability are achieved by computing effective evasive manoeuvres. The first step in this process uses the missile approach warning system camera (MAWS) on the aircraft to provide angular information of the threat. Estimates of the RPG trajectory and impact point are then estimated. For the current flight state an appropriate evasion response is selected then realised via inverse simulation of the platform dynamics. Results are presented for several representative engagements showing the efficacy of the approach.

Keywords: Rotorcraft, Inverse Simulation, Survivability, RPG

1. INTRODUCTION

Combat survivability is a function of the *susceptibility* of engagement by a threat in a hostile environment and the *vulnerability* of the platform once damage has occurred [1]. For an effective defensive system designed to maximize the protection of the platform and onboard assets, ideally you wish to reduce both the susceptibility and vulnerability of the platform which roughly translate to the simple maxim of "don't get hit, but if you do, don't get hit anywhere critical". Although many different threats exist on the modern battlefield, one of the most lethal engagements concerns an airborne platform under attack by highly agile or high velocity short-range threats. Typical scenarios of this type of engagement include IR countermeasures (IRCM) final phase, missile-to-missile engagement (eg. Patriot type system) and rocket propelled grenade (RPG) attack. This final threat in particular has been repeatedly highlighted during the ongoing conflict in West Asia, where rotorcraft have been shown to be particularly vulnerable, or alternatively to possess poor survivability to such an attack. As it is impractical to cover a helicopter in thick armour, the premise advocated here is that the best way to increase the survivability of a helicopter platform under RPG attack is to avoid detonation entirely – to reduce the susceptibility of the aircraft to a hit. Most currently deployed RPG's are impact (with time-fusing) devices, therefore the optimal strategy for evasion is to estimate/predict the trajectory of the incoming threat and compute the best platform manoeuvre to evade this threat.

While the proposed survivability strategy is conceptually simple, a number of significant scientific and technical challenges must be overcome. The nonlinear dynamics of the aircraft at the current flight condition and the operational environment (which may be highly cluttered or otherwise constrictive), must be known to establish which manoeuvres are feasible. The computed manoeuvre profile may be contrary to the pilot's natural instincts and so human factors may also become an important consideration – this approach does not presuppose a full-authority flight control implementation, but could equally well be applied to a pilot aid system. Traditionally, such problems have been handled using inverse simulation techniques [2, 3]. It is also reasonable to expect that the threat image tracking and/or geo-location errors will have to be extremely small to ensure high fidelity trajectory estimation, which implies the need for an advanced tracking algorithm. To the author's knowledge, no published work exists that documents the efficacy of modern tracking methods (EKF, UKF, IMM or particle filtering for example) to the RPG tracking problem, which is characterised by short engagement time and rapidly varying signal-to-noise ratio. As will be shown later, rapid accelerations following nonlinear trajectories is also a factor.

The focus of this paper is to present the preliminary results of an investigation into the dynamic modelling of an RPG attack on a helicopter using inverse methods. The inverse simulation technique developed for rotorcraft is described in

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section 2. The dynamic model of the RPG is discussed in section 3 and the results of the simulated engagement are presented in section 4. Conclusions and discussions regarding future work complete the paper.

2. ROTORCRAFT INVERSE SIMULATION

2.1 The Basic Principals of Helicopter Flight

There are two fundamental differences between helicopter flight and that of conventional fixed wing aircraft. Firstly the helicopter has the ability to fly at low speed and hover, the secondly, as a consequence of its low speed performance, the helicopter has the ability to follow precise trajectories and thereby manoeuvre close to obstacles such as trees, buildings and, of course, the ground. Given the radically different nature of the two aircraft it is perhaps no surprise that the method of flying them and the principles behind their operation are quite different. Although the principles and control of fixed wing aircraft may be familiar to many readers it is perhaps appropriate here to give some insight into these aspects of helicopter flight.

The basic control method is by varying the magnitude and direction of the main rotor thrust vector. The magnitude of the thrust is controlled by collectively altering the pitch (and hence lift) of all of the rotor blades together by means of the collective lever. This collective pitch displacement is given the symbol θ_0. As well as collective pitch control the pilot is also able to vary the pitch of individual blades cyclically around a complete revolution. When the pilot applies longitudinal cyclic pitch, denoted θ_{1s}, by pushing the cyclic stick forward, the blade travelling towards the back of the disc flaps upwards, whilst the blade travelling towards the front of the disc flaps downwards. The net effect is that the thrust vector is tilted forward simultaneously pitching the vehicle's nose down allowing accelerated flight in this direction. Similarly pushing the cyclic stick to one side (i.e. applying lateral cyclic pitch, denoted θ_{1c}) increases the pitch of the blades on the opposite side of the rotor (producing upwards flap) thereby producing a net thrust tilt in the direction of the stick motion. This can be used to produce sideways or banked flight. Finally, the torque transmitted by the engine to the main rotor is balanced by an opposing moment produced due to the offset of the tail rotor thrust from the centre of gravity. The tail rotor thrust is controlled through pedal displacements which alter the pitch of the blades (given the symbol θ_{0tr}) and by varying this thrust (and hence 'anti-torque' moment) it is possible to control the heading of the aircraft.

The coupling problem associated with helicopter control can be appreciated by considering the simple example of a pilot wishing to accelerate his aircraft without changing heading or altitude. The acceleration is achieved by application of forward longitudinal cyclic, θ_{1s}, which tilts the rotor disc forward. One effect of this is that the component of the thrust vector which balances the weight of the aircraft has been reduced, and hence if altitude is to be maintained the magnitude of the thrust vector must be increased by application of the collective pitch θ_0. The increased pitch causes increased blade drag and in order to maintain rotor speed, engine torque is also increased, and hence a tail rotor collective pitch, θ_{0tr}, input is required to maintain heading. If unopposed the change in side force due to the change in tail rotor thrust will cause the helicopter to drift to the side. To overcome this, an opposing input in lateral cyclic, θ_{1c} is required. In practise, the pilot's workload is kept at acceptable levels by introducing control mixing (via mechanical linkages or the flight control system), and equipping the helicopter with a rotor speed governor. This simple example where inputs to all four control channels are required to undertake a very basic manoeuvre demonstrates the complexity of the system being modelled – particularly so, when the example above has ignored the aerodynamic asymmetry of a helicopter in forward flight.

2.2 Inverse Simulation

The conventional approach to simulation has been to solve numerically the equations of motion to find the response of a system to a given control input or disturbance. In the context of aerospace applications this might typically involve calculating the flight trajectory resulting from a change in a control surface position. The inverse of this would be to determine the control displacement(s) required to achieve a particular trajectory or manoeuvre. The technique of inverse simulation is finding application in many and varied fields. The field of aircraft flight dynamics is particularly suited to this form of simulation as the question of what control actions must the pilot (or automatic flight control system) take for the aircraft to fly along a particular trajectory (a landing approach, for example) is often asked. A substantial body of work in this field exists and is summarised and reviewed by Thomson & Bradley [3].

The most widespread use in aerospace is for examining helicopter performance in manoeuvring flight [4]. The advantage the helicopter has over a fixed wing aircraft is its capability to hover and manoeuvre slowly around obstacles. It is therefore no surprise that many performance and handling criteria are specified in terms of aircraft capability in completing standard manoeuvres [4]. A prime example of this is the US Military Specifications for rotorcraft handling qualities [5]. This specifies a number of manoeuvre (or MTEs – Mission Task Elements) which should be flown in the assessment of handling qualities. The use of inverse simulation to analyse the performance helicopters flying MTEs was first proposed by Thomson and Bradley [6] and clearly has the great advantage of allowing the assessment of proposed new designs to be tested by simulation. Work on helicopter inverse simulation was pioneered at Glasgow and has led to the development of a number of widely used algorithms and well tested inverse simulation codes[2, 7].

2.3 The Helicopter Mathematical Model

Use has been made of the helicopter mathematical model, HGS (Helicopter Generic Simulation), developed by Thomson [8]. HGS is a non-linear, seven degree of freedom, generic mathematical model, and was developed to be suitable for use in an inverse simulation. Multi-blade representations of the main and tail rotor was used, each blade being assumed rigid and to have constant chord and profile. The flow around the blades was assumed to be steady and incompressible, thus allowing two-dimensional aerodynamic theory to be applied in calculating the blade aerodynamic loads. Other significant features of the HGS include a dynamic inflow model, an engine model and look-up tables for fuselage, tailplane and fin aerodynamic forces and moments. The mathematical model used in both simulations is of a fairly standard generic form for rotorcraft. There are seven equations of motion, the six Euler rigid body equations:

$$m\dot{U} = -m(WQ - VR) + X - mg\sin\Theta \tag{1}$$

$$m\dot{V} = -m(UR - WP) + Y + mg\cos\Theta\sin\Phi \tag{2}$$

$$m\dot{W} = -m(VP - UQ) + Z = mg\cos\Theta\cos\Phi \tag{3}$$

$$I_{xx}\dot{P} = (I_{yy} - I_{zz})QR + I_{xz}(\dot{R} + PQ) + L \tag{4}$$

$$I_{yy}\dot{Q} = (I_{zz} - I_{xx})RP + I_{xz}(R^2 - P^2) + M \tag{5}$$

$$I_{zz}\dot{R} = (I_{xx} - I_{yy})PQ + I_{xz}(\dot{P} - QR) + N \tag{6}$$

and the engine torque equation:

$$\ddot{Q}_E = \frac{1}{\tau_{e_1}\tau_{e_2}}\left[-\left(\tau_{e_1} + \tau_{e_3}\right)\dot{Q}_E - Q_E + K_3\left(\Omega - \Omega_{idle} + \tau_{e_2}\dot{\Omega}\right)\right] \tag{7}$$

where τ_{e1}, τ_{e2}, τ_{e3}, K_3 are the time constants and gain of the governor, and Ω_{idle} is the angular velocity of the rotor in idle. The engine model is discussed in more detail by Padfield [9].

Of course, these are general equations and the feature which distinguishes them as helicopter equations of motion is the composition of the external forces and moments X, Y, Z, L, M and N (and the engine torque QE). These forces and moments are periodic due to the once per revolution flapping/lag/pitch motions of a main rotor blade. The HGS model however is simplified by disregarding the lag and blade pitch dynamics and assuming that the flap dynamics can be treated as quasi-steady. This is an acceptable assumption as firstly, blade flap motion is much more influential in terms of predicting blade loads (hence lag and pitch motion can be ignored) and the blade dynamics are much faster than those of the body modes. As discussed by Padfield [9], this assumption allows a multi-blade disc representation of the main rotor to be formed which is time-invariant in trim. More comprehensive models include full dynamic representation of the dynamics of each blade separately.

The question of the validity of the results is also important - if any meaningful information is to be derived then the mathematical model must replicate the actions of the real aircraft. In the case of HGS, inverse simulation has been used whereby trajectory data from manoeuvres flown by real helicopters is used to drive the inverse simulation. The states and controls computed by HGS (in its inverse formulation) are compared with those recorded in the flight tests to establish the validity of the simulation, and results have demonstrated acceptable correlation for a range of manoeuvres [3, 4]. The HGS model is generic in structure, representing single main and tail rotor helicopters by a series of basic configuration parameters. It is then possible to simulate a wide range of different rotorcraft by developing appropriate data files for specific types.

3. RPG DYNAMIC MODEL

The RPG-7 is a soviet-made antitank grenade launcher first introduced in 1962 [10]. Since then this weapon has proven to be both lethal and versatile in all of the main conflicts of the latter part of the 20th century, from Vietnam and Northern Ireland [10] to Iraq and Afghanistan. Part of this popularity is due to the mobility offered to the artilleryman and the rugged construction of the weapon. Essentially, the weapon consists of a launcher that is used by the artilleryman to aim the weapon through an optical sight and an explosive projectile – normally a HEAT (High Explosive Anti-Tank) round. The engagement is divided into two main sections; the initial ejection from the launcher by a small strip of powder charge, accelerating the projectile to 117m/s, followed approximately 11m from the launcher by a sustainer rocket ignition to boost the rocket to a maximum velocity of 294m/s. This two-stage launch reduces backblast and protects the gunner. The launch sequence is shown in figure 1.

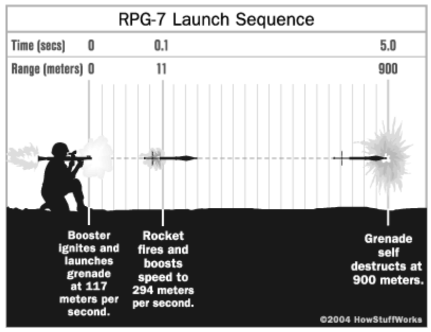

Figure 1: RPG-7 Launch sequence (figure reproduced from http://www.howstuffworks.com/rpg.htm).

Additional stabilisation in flight is achieved via the deployment of four fins at the rear of the projectile, fig 2. These fins provide two functions. First, the drag induced by the fin aerodynamics provides a stabilising moment to the projective trajectory and second the fins induce a stabilising spin around the roll axis.

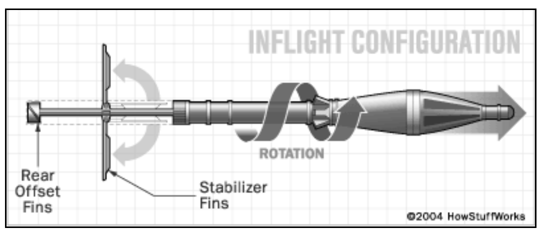

Figure 2: RPG-7 in-flight configuration (figure reproduced from http://www.howstuffworks.com/rpg.htm).

When simulating the RPG-7 grenade precisely, both aerodynamic effects should be modelled. For the current problem the output required is the kinematic trajectory expressed in inertial axes. If we assume that the grenade is spin-stabilised, then in a vacuum the trajectory will become that of a simple point-mass subject to a time-varying thrust in a gravitational field – a ballistic problem. However, in [10] the rocket trajectory is shown to be sensitive to a cross-wind, which means that some aerodynamic calculations are required. The modelling strategy used here was to simplify the projectile into a centre-of-mass and a centre-of-pressure, fig 3.

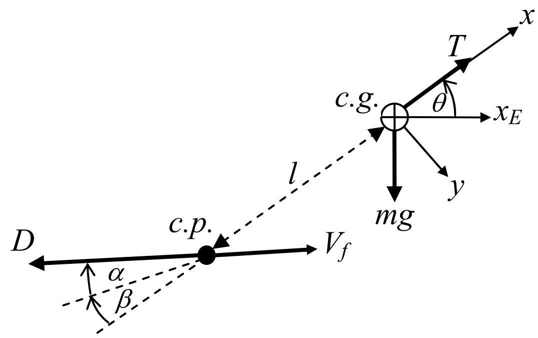

Fig 3: Simplified RPG free-body diagram.

Of all the variables and parameters in figure 3, only the velocity profile and the rocket mass are known. However, by careful manipulation of the equations of motion for a rigid-body flight vehicle (equations 1-6), a representative dynamic model can be developed. Exact validation of this model is impossible without access to range firing reports but verification against the published velocity profiles is possible, figure 4.

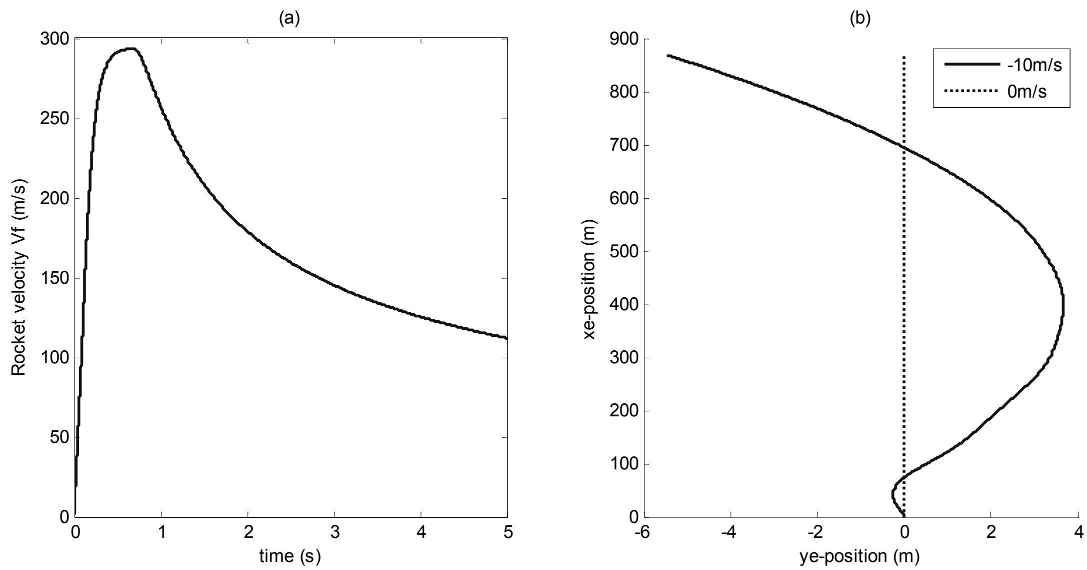

Fig 4: Example RPG Kinematics. (a) shows the velocity profile as a function of time and (b) the impact of a 10m/s crosswind on lateral position.

As shown in Fig.4 (a) the velocity profile matches the launch sequence described in Fig 1. The main uncertainty here is the time constant governing the transition from the launcher exit velocity of 117m/s until the final velocity of 294m/s, which cannot be accurately specified without detailed information of the temporal thrust profile and drag characteristics of the projectile. The sensitivity of the rocket to a crosswind is shown in fig. 4 (b).

Precise information regarding the dynamic response of the RPG-7 class of rocket-propelled grenades is, unsurprisingly, not available in the public domain. Therefore, the modelling activity undertaken employed a significant degree of engineering judgement combined with previous airborne dynamic system modelling expertise and some limited performance metrics. The RPG-7 dynamic model is qualitative rather than precise, but this is perfectly acceptable for the current investigation.

4. ENGAGEMENT MODELLING

To investigate the efficiency of candidate evasion strategies a simulation containing the RPG model and the helicopter inverse simulation was constructed. Several assumptions were made regarding the engagement:

- the RPG was launched from the port side of the aircraft,
- only a single MAWS system (port side) is considered,
- the MAWS camera has a 120deg field-of-view (FoV),
- the MAWS sensor is a 1024x1024 focal plane array,
- the RPG gunner assumes that the helicopter will maintain the same flight path after launch.

The engagement geometry is shown in figure 5. The simulation was written in MATLAB as a series of functions with a GUI interface. The user provides initial conditions in NED coordinates for both helicopter and RPG gunner. An optimisation routine then calculates the necessary gunners' launch angles to minimise the miss distance (in inertial coordinates) at the end of the non-evasive engagement.

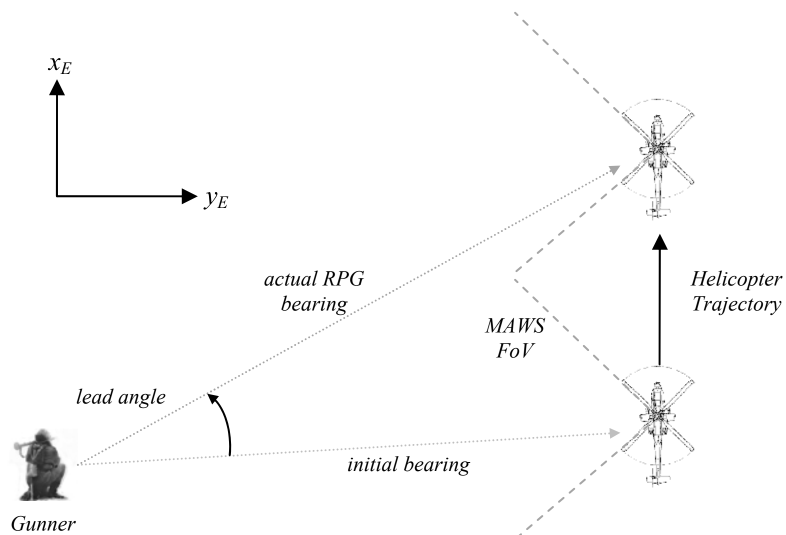

Figure 5: Engagement geometry.

The main outputs of the simulation are two plots, one containing the RPG position in camera coordinates and the other a 3-D plot of the trajectories of both systems. An example plot is shown in figure 6 for the helicopter travelling due north at an altitude of 50m and velocity of 30m/s, RPG gunner located 300m west at sea level. The bearing and elevation angles for the RPG are 10.6deg & 82.32deg respectively and these give a miss distance of 0.08m. The interesting result of this plot is that the RPG position does not deviate significantly from the initial location in camera axes during the engagement. The trajectory is similar to that of a missile flown using proportional navigation guidance [11, 12], as used in most MANPAD (man-portable air defence) systems. This technique is based upon maintaining a constant-bearing trajectory throughout the engagement which, from figure 5, is a similar requirement for the RPG to hit target. Another output of the model is the standard deviation of the RPG coordinates in the image plane. Table 1 below illustrates the target standard deviations for a few representative firing engagements.

	Helicopter Flight Speed			
RPG Location (NED)	Hover	20knots	40knots	60knots
[0 -300 0]	[0.32 1.44]	[0.39 1.44]	[1.60 1.44]	[2.30 1.45]
[100 -300 0]	[1.84 1.51]	[0.36 1.51]	[1.68 1.48]	[0.27 1.65]
[-100 -200 0]	[0.35 1.43]	[0.21 1.42]	[2.17 1.35]	[0.39 1.55]
[50 -200 0]	[0.29 1.08]	[1.02 1.06]	[2.05 4.28]	[0.71 1.13]
[-50 -100 0]	[0.74 0.96]	[1.58 0.49]	[0.67 1.04]	[1.21 1.08]

Table 1: Standard deviations of the (u,v) image coordinates in pixels.

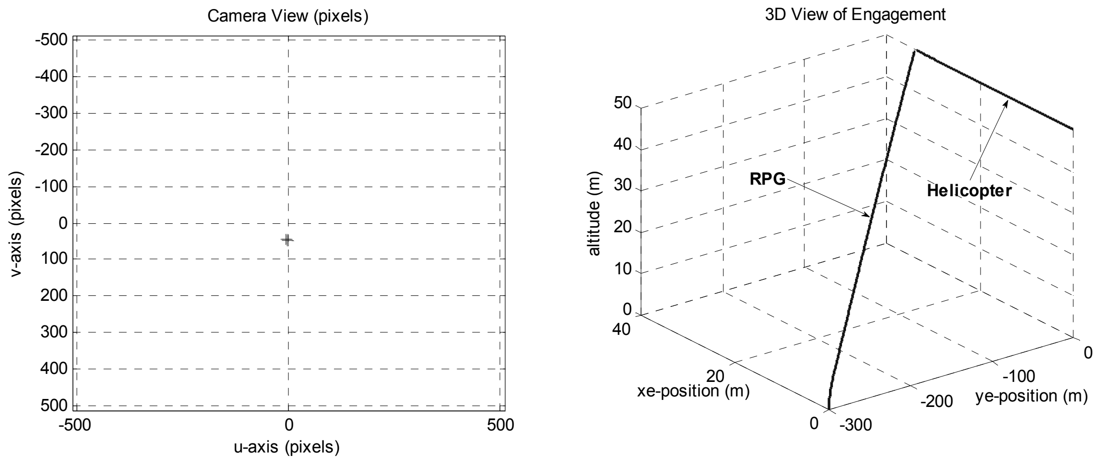

Fig 6: (a) RPG position as seen by the camera (+ denoted RPG position). (b) 3D representation of the engagement trajectories.

It is apparent from table 1 that the standard deviations of the image coordinates are pretty small for all engagement geometries. This result may be used to a significant advantage as it suggests that, in the simplest case, any planar motion of the aircraft (x_E-z_E plane) that causes the RPG to move drastically in the image will induce a miss. The simplest such motion and the one employed by many pilots in combat situations is a sharp increase in collective pitch to 'bunt' the aircraft out of the path of the incoming projectile. To test the efficiency of this response, four test cases were created in the helicopter inverse simulation – hover, 20knots, 40knots and 60knots – each one with a step increase in collective pitch as the control input. The trajectories in image coordinates for each test case are shown in figure 7.

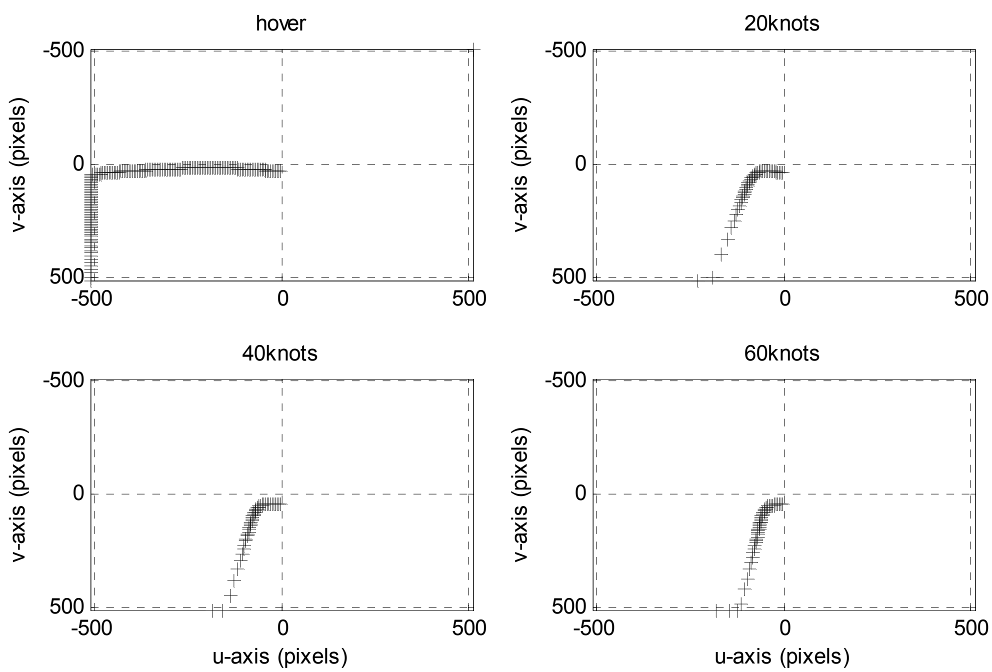

Fig 7: Camera axes view of the RPG trajectory for helicopter undergoing step increase in collective pitch.

As expected, the increase in collective pitch forces the RPG trajectory to move to the bottom of the image. This happens in all four test cases eventually but in the hover case, the initial trend is for the RPG track to move to the left of the image plot. The reason is the yaw rate of the helicopter during the manoeuvre. As the collective pitch is increased, the aerodynamic drag acting on each rotor blade increases considerably - yielding a steep increase in combined aerodynamic torque acting on the rotor shaft. The engine governor detects this increase and applies more torque to maintain rotor speed. From Newton's third law, the helicopter body will then rotate in the opposite direction unless the pilot applies additional tail-rotor collective to counteract this yaw. Although it is simple to add an additional heading constraint to the inverse simulation algorithm, this effect is included here to illustrate the need for an inverse approach to move complex manoeuvres.

	Hover	*20knots*	*40knots*	*60knots*
Optimisation error (m)	0.03	0.01	0.03	0.1
Evasion Error (m)	6.95	1.9	2.27	2.64

Table 2: Computed miss distances for trim and evasion engagements.

How effective the bunt manoeuvre is in avoiding the RPG is shown by the data in table 2. Here, the miss distance from the optimisation is given alongside the miss distance computed at the end of the evasive manoeuvre. The optimisation error give a measure of the numerical error induced by the assumptions made in the simulation and the optimisation termination criteria. Ignoring the hover case for the moment, a clear trend is apparent in the forward-speed cases as the miss distance increases with increasing airspeed. This is to be expected as the aerodynamic forces used to accelerate the aircraft out of trouble are proportional to the square of the airspeed. However, when one looks at the hover case it is clear that the aircraft manages to pull clear by almost 7m – a considerable improvement over all other flight conditions. One possible reason for this is that although the available aerodynamic loads at hover are weaker, the rotor thrust vector is almost aligned with the inertial z-axis. For low elevation launch angles this direction is aligned with the (near) optimal agility vector, found by projecting the RPG velocity vector at intercept onto the x-z plane.

5. CONCLUSIONS & FUTURE WORK

A number of conclusions can be drawn from the work presented here. The first conclusion is that the authors have shown that rotorcraft inverse simulation techniques can be applied to the RPG engagement scenario. Although restricted to current practice evasive manoeuvres, the simulation model developed can be used to predict the efficiency of more complex evasion strategies. Another important result was that the RPG engagement obeys geometry very similar to a MANPAD attack from a missile guided by proportional navigation. The key result here is that the RPG remains close to stationary in image axes if the platform is going to be hit. This implies that it would be possible to select an evasive manoeuvre by commanding a desired RPG position in the image space. Finally, it has been shown that the simple bunt manoeuvre will not be sufficient for many engagement scenarios due to the deficiencies in in-plane acceleration capabilities of the platform. More complex manoeuvres involving aircraft rotations will be required to increase platform survivability to acceptable levels.

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