SURVEY PAPER

The tau of flight control

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ABSTRACT

With this survey paper, the author proposes a new 'tao' – a new way of understanding – of how pilots do what they do. Research into the control of purposeful action in the natural world suggests that very rapid, efficient and 'instinctive' techniques have evolved based on the time to close on a goal, or close a gap, $\tau(t)$, and its derivatives. Purposeful actions involve the closure of one or more physical gaps, each with its own time to close, varying with time. Maintaining a constant rate of change of $\tau(t)$ with time (< 1) during an approach will ensure a successful arresting when the gap is closed, but an animal's strategy can be adapted to the circumstances to achieve either a hard stop (aggressive action with $\dot{\tau} > 0{\cdot}5$), or a soft stop (gentle action with $\dot{\tau} < 0{\cdot}5$). Synchronous coupling of two motions, $x(t)$ and $y(t)$, such that the times to close are coupled, $\tau_x = k\tau_y$, results in the motion gaps $x(t)$ and $y(t)$ being related through a power law, $x = Cy^{1/k}$, and closing smoothly together; examples of such coupling in the form of pursuit tracking in the natural world abound. Research has also shown that gaps can be closed by following 'intrinsic' guides, or self-generated mental models of desired motion, that have particular forms; for example, constant deceleration or constant acceleration. The gathering evidence from research into animal behaviour in the natural-world forms a background for the exploration of flight control in the man-made world. The implications for control theory, flight control developments and flight handling qualities, are considered to be profound. τ-theory suggests that natural control has a particular non-linear, albeit very simple, time varying form and that pilots learn control strategy skills by developing mental models, or internalised schemata, in the form of what are described as 'τ guides'. In this context the author presents his perspective on flight control, briefly reviewing τ-theory and providing examples from research conducted at The University of Liverpool during the period 1999-2011, including the work of several PhD students. Concepts for guidance algorithms suitable for augmented manual or autonomous control are discussed and the implications for handling qualities developments, particularly relating to flight in degraded visual conditions, are presented. Some outstanding questions pointing directions for future research are raised.

NOMENCLATURE

$a(t)$	acceleration during stopping manoeuvre (m/sec^2, ft/sec^2)
C	a constant in power law relationship between two variables
c, n	constants in the relationship derived from the NASA approach test data
$d(t)$	distance to stopping point (m,ft)
$G(t)$	open-loop crossover model transfer function between response error and response
G_{CL}	closed-loop crossover model transfer function
g	gravitational acceleration (m/sec^2, ft/sec^2)
h	height above ground in flare manoeuvre (m, ft)
h_e	eye-height unit
K	pilot-aircraft gain in crossover model, gain in ball tracking dynamic model

Paper No. 3714. Manuscript received 3 May 2011, revised version received 13 July 2011, accepted 14 July 2011.
The latest in an occasional series of survey articles by leaders in their field focusing on a specific aspect of the aeronautical industry.

https://doi.org/10.1017/S0001924000006187 Published online by Cambridge University Press

K, K_m	pilot gains in Gray's model for boundary avoidance tracking
K_R, $K_{\dot{R}}$	proportional and rate R feedback gains in adaptive pilot model
K_x, $K_{\dot{x}}$	proportional and rate x feedback gains in adaptive pilot model
k	coupling constant between motion and guide
K_h, $K_{\dot{h}}$	proportional and derivative gains in pilot controller model in flare
n_v	number of distinct flight path changes in a manoeuvre
R, R_C	range and range command in adaptive pilot model of accel-decel manoeuvre
R^2	square of the correlation coefficient in a least squares fit
T	manoeuvre time (sec)
$T_{\theta_1}, T_{\theta_2}$	time lags in flight path and speed response to aircraft pitch angle changes
$\hat{t}$	time normalised by manoeuvre time T
t_w	aircraft heave dynamics time constant (sec)
U	aircraft flight speed (ms^{-1}, ft/sec)
$V, \dot{V}$	velocity and acceleration of aircraft within the conversion corridor (ms^{-1}, m/sec^2)
u,v,w	perturbations in velocity along aircraft x,y,z axes (ms^{-1}, ft/sec)
$v(t)$	velocity during deceleration (ms^{-1}, ft/sec)
X_u	drag derivative; rate of change of long. acceleration w.r.t. u perturbation (1/sec)
x,y	response and control input in ball tracking dynamics (inches)
$x,\dot{x},\ddot{x}$	distance to go, velocity and acceleration (m, ms^{-1}, m/sec^2)
x_a, x_f	aircraft distance to go in accel-decel manoeuvre (f – final)
$\hat{x}$	distance normalised by manoeuvre distance X
x', x''	first and second differentials of x with $\hat{t}$
X_a, $\ddot{X}_a$	lateral cyclic stick and acceleration (inches, inches/sec^2)
x_g, v_g, a_g	distance to go, velocity and acceleration for motion guide
x_{g0}, v_{g0}, a_{g0}	values of above at $t = 0$
Y	overall open-loop transfer function in the adaptive pilot model
Y_{PR}, Y_{P0}, Y_{A0}	transfer functions in adaptive pilot model
y	displacement across the runway (m, ft)
Z_w	heave damping derivative (1/sec)
ε_γ	error between flight path angle γ and motion of a guide (rad)
ε_τ	error between τ of motion and τ of a guide (sec)
δt	time increment for discrete visual information (sec)
$\delta\theta$	small change in looming angle (rad)
$\gamma, \gamma_a, \gamma_f$	flight path angles (a – aircraft, f – final) (rad)
$\dot{\gamma}_a$	rate of change of aircraft flight path angle (rad/sec)
θ, θ_c	aircraft pitch attitude and commanded pitch angle (rad)
θ_0	collective pitch angle (rad)
$\theta_1, \theta_2, \ldots\theta$	discrete looming angles when approaching an obstacle (rad)
$\theta_{1c}, \dot{\theta}_{1c}$	lateral cyclic pitch angle and acceleration (rad, rad/sec^2)
$\tau(t)$	instantaneous time to close on a goal or gap (sec)
$\dot{\tau}$	rate of change of $\tau(t)$ with time
τ_d	time delay in crossover model of pilot-aircraft system (sec)
τ_e	time to the runway edge in the BAT model (sec)
τ_g	time to close gaps for the guide (sec)
τ_h	time to close height gap (sec)
$\tau_b, \tau_{min}, \tau_{max}$	time to the boundary in the BAT and min and max values in pilot model (sec)
τ_p, τ_β	time constants for roll rate and rotor flapping dynamics (sec)
τ_s	safety margin for τ(sec) in UCE construct (sec)
τ_{vb}	time to reach the envelope protection boundary (sec)
τ_x, τ_y	time to close gaps x and y (sec)
τ_{x0}	time to close gap in x at $t = 0$ (sec)
τ_{x1}, τ_{x2}	times to reach x_1, x_2 in discrete formulation of τ model (sec)
τ_{xi}	time to reach x_i (sec)
τ_θ	time constant in pilot model of pitch response to pitch command (sec)
τ_γ, τ_ψ	time to close flight path and heading gaps (sec)
ψ, ψ_a, ψ_f	heading angle (a – aircraft, f – final) (rad)
$\dot{\psi}_a$	rate of change of aircraft heading angle (rad/sec)
ζ, ω_n	relative damping and natural frequency in ball tracking dynamics
ζ_{FL}, ω_{FL}	relative damping and natural frequency in flare manoeuvre dynamics
ζ_R, ω_R	relative damping and natural frequency of range dynamics in adaptive pilot model
ζ_x, ω_x	relative damping and natural frequency of x dynamics in adaptive pilot model
ω_p	frequency of phugiod motion
ω_ϕ, ω_t	roll axis and task bandwidths

List of Acronyms

ACAH, RCAH	attitude command attitude hold, rate command attitude hold
ADS-33PRF	aeronautical design standard – 33 (performance)
APCs	aircraft pilot couplings
APM	adaptive pilot model
ASRA	Advanced Systems Research Aircraft
BAT	boundary avoidance tracking
CAT I, II, III	categories of aircraft pilot couplings according to McRuer
DERA	Defence Evaluation and Research Agency
DVE, GVE	degraded visual environment, good visual environment
EPS	envelope protection system
ERICA	enhanced rotorcraft innovative concept achievement
FA, SA, SC	groups of flight and simulator trained pilots (e.g. Flight/Pilot A)
FGR	FLIGHTLAB Generic Rotorcraft
FRL	Flight Research Laboratory (Ottawa)
F-B412	FLIGHTLAB Bell 412 (ASRA)
F-UH60	FLIGHTLAB generic rotorcraft (UH60-like)
IMC, VMC	instrument meteorological conditions, visual meteorological conditions
MTE	mission task element
NASA (CP)	National Aeronautics and Space Administration (Conference Proceedings)
NRC	National Research Council (Canada)
OVCs	outside visual cues
PH	position hold
PIO, C-PIO	pilot induced oscillation, classical PIO in Cats I, II or III
RCDH, RCHH	rate command direction hold, rate command height hold
SIMDUCE	SIMulated Day UCE
SOP	Successive Organisation of Perception
T/D	touch down
TC	turn co-ordination
TRC	translational rate command
TTC	time to contact
UCE	usable cue environment
VCRs	visual cue ratings

1.0 INTRODUCTION – THE ESSENCE OF FLIGHT CONTROL

In a previous study conducted by the author, reported in Refs 1 and 2, pilot control activity during low level helicopter manoeuvring was shown to divide into two distinct patterns that could be interpreted in either the time domain (attack parameters or worklets, derived from the use of wavelet analysis) or the frequency domain (double peaks in the power spectra). A slower movement at the task frequency is modulated by higher frequency, smaller amplitude, 'corrective' activity. The distinct movements were described broadly as guidance

https://doi.org/10.1017/S0001924000006187 Published online by Cambridge University Press

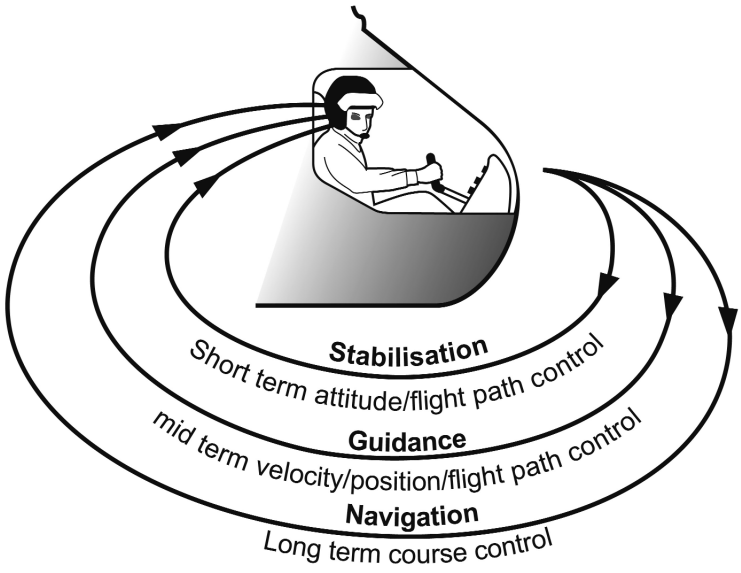


Figure 1. The three functions of flight management and control[7].

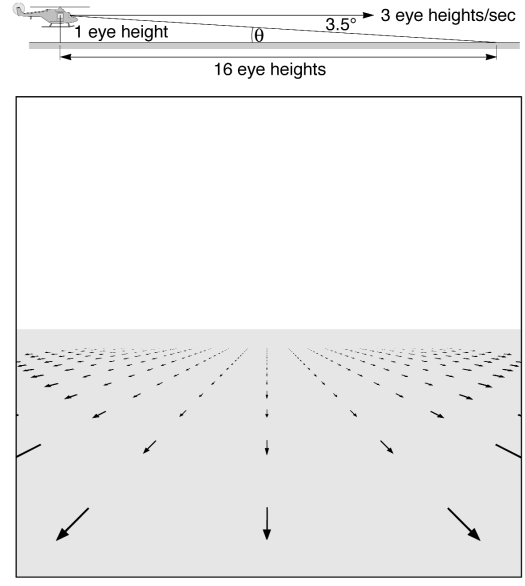


Figure 2. The optical flow field for helicopter flying over flat surface.

and stabilisation respectively. The frequency of the stabilisation was essentially a function of the aircraft dynamics and the level of pilot 'gain' adopted. The term corrective action was assumed to include all activity intended to cancel out small deviations from the commanded flight path or attitude. The research reported in Refs 1 and 2 attempted to provide a better understanding of situations where workload could increase rapidly as task demands increased and guidance and stabilisation frequencies approached some critical ratio, leading to pilot-induced-oscillations or, alternatively, task abandonment. The increased workload resulted from the pilot having to use smarter compensation than achievable by simply increasing feedback gains applied to motion errors; simple proportional feedback control is likely to drive some unconstrained aircraft motions unstable at relatively low pilot gain[3]. A by-product of the research was an increased interest in modelling the guidance strategy. The stabilisation strategy was considered to be reasonably well understood and the extensive developments, rooted in the so-called crossover model of pilot-aircraft behaviour[4,5], have led to a strong framework for tackling stabilisation problems and designing stability augmentation systems. In practice, pilots have to deal with guidance and stabilisation (and, in slower time, navigation)[1] at the same time of course and the roots of an integrated model of guidance and stabilisation can also be found more than 50 years ago with the successive organisation of perception theory[6].

The description of flight control as a combination of short term closed-loop guidance and stabilisation and longer term navigation as illustrated in Fig. 1 is the starting point for the present paper. The research reported in a series of papers following Ref. 1 highlighted problems with the modelling of guidance strategies as a non-linear dynamic inversion problem[8,9]. Control activity, and residual motions estimated using current state information, often had unnatural or unrealistic features that a more prospective type of guidance strategy might iron out.

Fundamentally, flight control involves the pilot predicting where the aircraft needs to be in the future and manoeuvring to overlay the actual flight path over the desired flight path. Control is critical to any purposeful action and flight control needs to be prospective to achieve this overlaying. A dynamic projection of the flight path is available when an aircraft is flying close to the surface and a pilot can pick up information to make judgements of speed, rate of descent, turn rate etc. from these projections. Using this information, a pilot can thus take action to overlay the aircraft's flight path over that which is desired. The more obscured the visual information from the surface, the less accurate will be the overlaying, an obvious result that continues to provide a cause of aircraft accidents. James Gibson developed optical flow theory in response to his research into what kind of visual information was most useful to pilots during landings[10]. Gibson suggested that the '*...the psychology of aircraft landing does not consist of the classical problems of space perception and the cues to depth.*' Gibson was challenging conventional wisdom from the training community that piloting ability was determined by the sufficiency of linear/aerial perspective and parallax cues. Gibson went on to describe the visual information needed. '*Speaking in terms of visual sensations, there might be said to exist two distinct characteristics of flow in the visual field, one being the gradients of 'amount' of flow and the other being the radial patterns of 'directions' of flow. The former may be considered a cue for the perception of distance and the latter a cue for the perception of direction of locomotion relative to the surface.*' The cues for guidance, for distance and direction, are available in these changing optical flow patterns on the surfaces over and around which flight occurs. A simple example is presented in Fig. 2, from Ref. 11, showing the optical flow-field on a flat surface below a helicopter flying at three eye-heights per second, e.g. ~ 50kt at a height of 30ft. The eye-height measure for distance and velocity facilitates derivation of body or vehicle-scaled information when moving through an environment, providing a direct sense of subjective velocity, geared to a natural metric. Each flow vector in Fig. 2 represents the angular change of a point on the surface during a 0·25 second snapshot; the inter-point distance is one eye-height. The centre of optical expansion is the point where the extended flight trajectory meets the surface; on the horizon in the present case. In Fig. 2 the flow vectors are shown to disappear before this, to emphasise that the retina has a finite resolution and, in the figure, the information disappears at 16 eye-heights ahead of the aircraft. This 'typical' dynamic resolution[11] would give the pilot information about the trajectory about five seconds into the future, a crucial point to be developed in this paper. Note that looking ahead to the 16 eye-height point requires that the pilot's gaze line is depressed by about 3·5°.

The flow patterns change when the aircraft climbs, turns or decelerates, giving the pilot 'cues' about impending situations, and allowing prospective control of direction and velocity. Flow patterns also change when the surface shape changes or when obstacles appear in a cluttered environment. A helicopter pilot does not normally respond to these cues through direct control of velocity or

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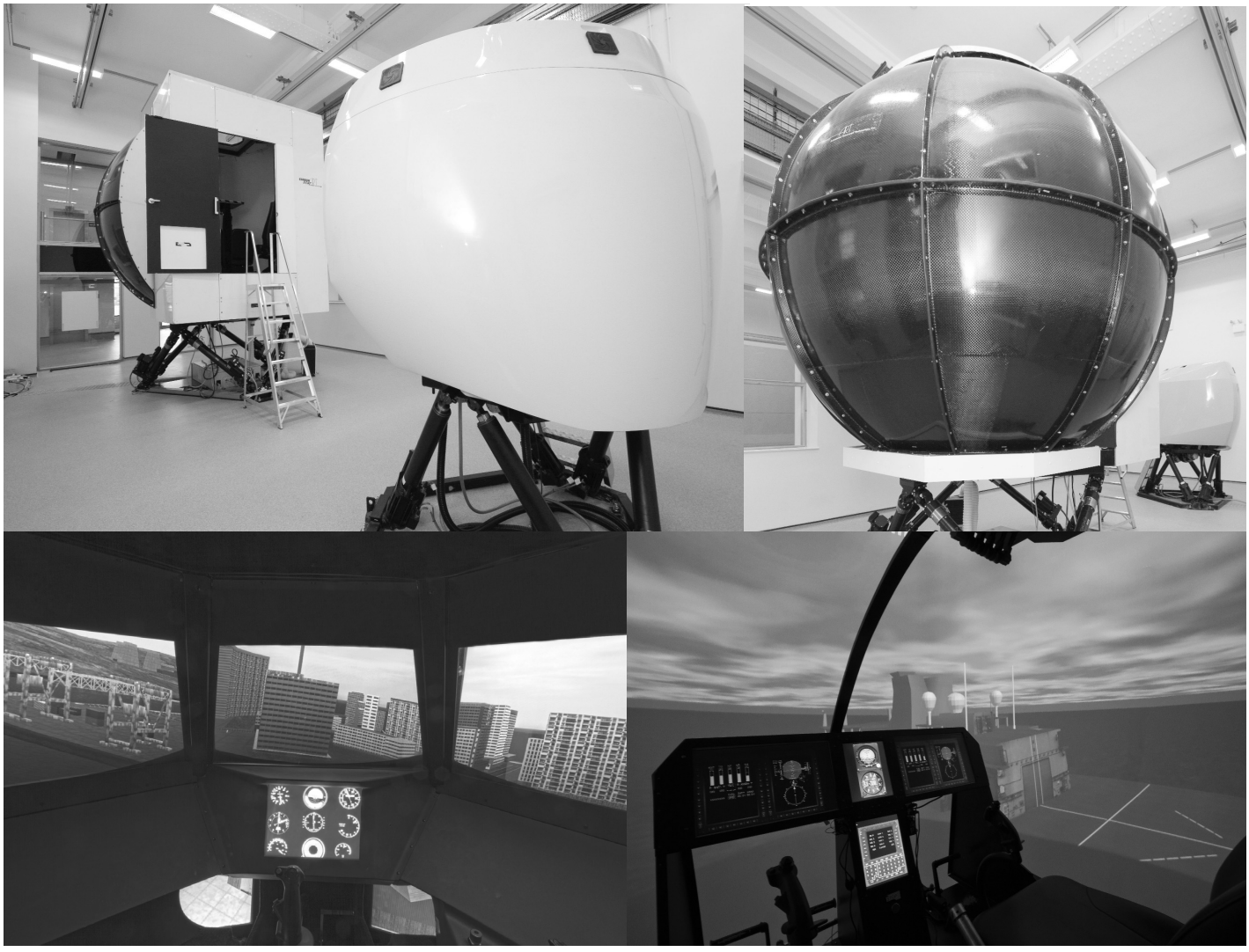


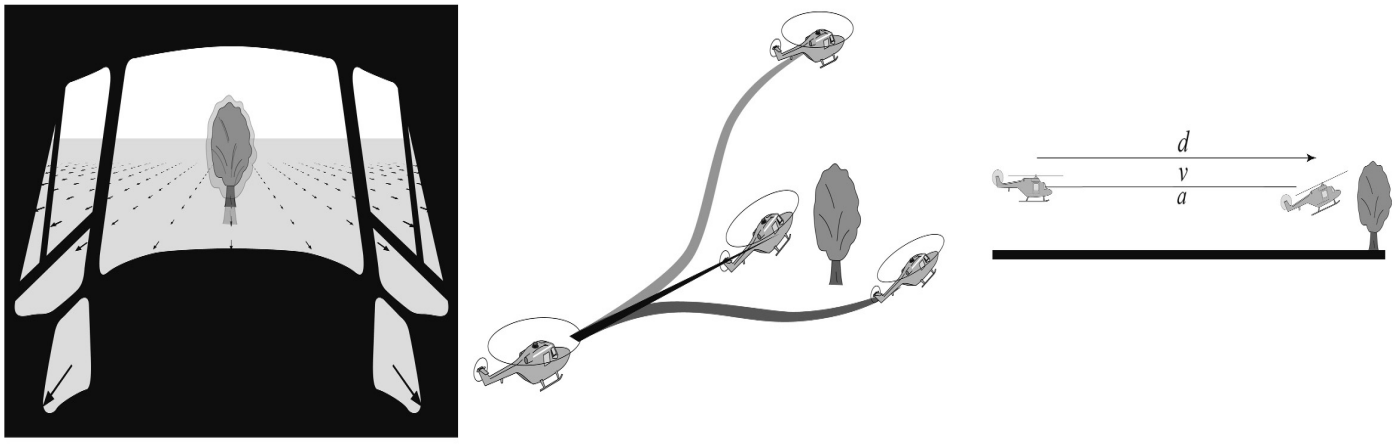
Figure 3. HELIFLIGHT and HELIFLIGHT-R in the Flight Simulation Laboratory at the University of Liverpool.

flight path angle. The normal response type, even with artificial stability augmentation, is attitude rate command about the three axes and height rate vertically, so the pilot has to first re-orient the aircraft attitude, and then make sense of the changes flow patterns, to derive flight path information. Superimposed on the changing global guidance patterns will be local fluctuations arising from stabilisation. For a pilot to manoeuvre an aircraft safely through a cluttered environment he or she requires information about what the aircraft is doing and where it will be in the future. An understanding of the feedback mechanisms at work in manual flight control can be informed by findings from research on movement control in the natural world. In Ref. 12, David Lee proposes general principles concerning the control of movement. First, movement is perceptually guided using, for example, stimuli from visual, proprioceptive and vestibular sources. Second, that movement requires intrinsic guidance, constructed from mental models of the future action. Third, that movement is prospectively guided, that allows action strategy to be modified based on some anticipated future state. These are underpinned by the principle that movement guidance must be simple and reliable, evolving as a universal mechanism for life on Earth.

These principles have an intuitive correctness to them. The ability to perform a task 'without thinking about it' resonates with the intrinsic guidance principle; thinking about a task will slow things down and is likely to result in degradation in performance. We have to learn to trust our direct perception-action system. The notion that purposeful motion is prospectively guided is also intuitively appealing. When operating close to the ground in a cluttered environment, a pilot will normally fly with a 'margin of safety' and it is crucial that this is sufficient to allow obstacle avoidance, ground clearance etc. That this margin of safety might be fundamentally temporal is also intuitive. Understanding the capability of your aircraft (or your own body in the natural world) a pilot should be able to judge if there is sufficient performance and thus time to manoeuvre around or over an obstacle for example.

Time to contact, to stop or to close a gap, defining the variable $\tau(t)$, is the topic of this paper. Often, manoeuvres are multi-axis, so the pilot might have to climb, turn and slow down, closing multiple gaps, at the same time. We will see that such multi-tasking in movement control is made easier when the motions are in some sense synchronised, or can be orchestrated in such a way by the pilot; the synchronised movements of our fingers on the guitar strings and frets provides a classic example of the simultaneous closure of multiple gaps. The degree of compensation required to manoeuvre successfully is a key ingredient in defining the flight handling qualities of an aircraft, which are part of the aircraft's performance capability. Linking prospective flight guidance with handling qualities is an underlying theme to this paper.

https://doi.org/10.1017/S0001924000006187 Published online by Cambridge University Press



(a) pilot's view with optical flow (b) options available (c) coming to a stop

Figure 4. Helicopter approaching an obstacle.

This paper presents a survey of research into the use of the optical flow variable, $\tau(t)$ in flight control, presenting the idea as a paradigm shift for the discipline, hence the unconventional but distinctive title to the paper '*the tau of flight control*'. The paper essentially presents an examination of $\tau(t)$ as a variable that models guidance in a wide range of circumstances. The author is not attempting to explain how the visual perception system functions, how sensory neurons transfer instructions to motor neurons, or to hypothesise a comprehensive theoretical model of guidance control. He is not claiming that τ-theory necessarily holds all the answers to the multitude of unanswered questions relating to man-machine control. The research has rather focussed on an examination of system dynamic behaviours that show a particularly successful transformation of inputs to outputs in flight control; example results will be presented. The paper describes aspects of τ-theory and concepts for motion control followed by applications to flight guidance, handling qualities and automatic control.

Research into flight control and pilot behaviour can only be properly conducted using test aircraft or flight simulators of sufficient fidelity. The Flight Simulation Laboratory at the University of Liverpool includes the HELIFLIGHT[13] and HELIFLIGHT-R[14] simulators[3] that have been used extensively in support of flight handling qualities and control developments over the last decade and the results from this research form the core of the review.

With the title of this paper, the author has taken a liberty by transposing tao with tau, suggesting that the introduction of tau within flight control theory points to a new 'way' of understanding pilot control behaviour. Based on the limited evidence to date, whether a 'neat and tidy story' of the new way has properly formed is left to the reader to judge, and certainly further research is considered necessary to consolidate the story. In this context, a short discussion on some of the ongoing research challenges for the tau of flight control completes the paper.

2.0 TAU CONCEPTS AND THEORY

Research into the motion control in flying animals, undertaken over the last few decades, has provided evidence that a common feature of the approach trajectory, prior to landing or reaching a target, is that the trajectory gap is closed by keeping constant the rate of change of the instantaneous time to contact[15-21]. These works build on the seminal work of David Lee, who first introduced the concept of optical τ and its relevance to motion control in Refs 22 and 23, rooting the new theory firmly within the soil of Gibson's ecological optical flow concept[24,25]. David Lee went on to extend the theory to address guided motions in Refs 26, with applications as wide ranging as control during somersaulting[27], musical instrument playing[28], understanding brain damage[29], fell running[30], psychomotor developments in infants[31] and suckling babies[32]. This astonishing range of application is perhaps not so surprising if τ and its role in motion control is a fundamental phenomenon of evolution. When living things move with purposeful action, those with eyes can perceive the changing patterns of optical flow on the surfaces amongst which they are moving, and are able to control actions with varying levels of agility and precision, sometimes closing several gaps and completing several tasks successfully at, apparently, the same time. Pilots close gaps in manoeuvring flight, and to do so safely they have to avoid colliding with the terrain, other aircraft and obstacles, while staying within the flight envelope of the aircraft. Pilots also perform precision manoeuvres as in aerial re-fuelling, positioning an under-slung load, aiming a weapon or manoeuvring in a confined area. Pilots are surrounded by the structure of the machine they are piloting, which might be one to two orders of magnitude larger than themselves, their view of the outside world often severely restricted, and yet they learn to fly and position this structure with human-size accuracies and precise timings. This is testimony to the skill of pilots of course, but also, by implication, to the workings of the natural perception system and, according to the ecological school of perception, to the ability of this system to pick up information about τ and its derivatives directly.

A description of τ-theory can begin by examining the situation of a helicopter approaching an obstacle. The pilot might have the option of pulling up and climbing over the obstacle, turning and finding a way around the obstacle or coming to a stop before reaching the obstacle (Fig. 4). All of these options will be explored later in the paper, but the deceleration-to-stop is selected to serve the illustration.

To stop safely before the obstacle the pilot must first make a judgement when to initiate the deceleration and then regulate this during the approach. Let $d(t)$ be the distance to the stopping point just in front of the obstacle, $v(t)$ the velocity and $a(t)$ the acceleration of the aircraft, all functions of time. At any point during the deceleration, the instantaneous distance to stop can be derived from simple kinematics to be,

$$d = \frac{v^2}{2a} \qquad \ldots (1)$$

So, for a given instantaneous v and a, if d is larger than the distance to the obstacle, the pilot has to increase the deceleration; if smaller,

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the pilot knows that he can safely ease off the deceleration. If the pilot maintains the deceleration constant from this point, the aircraft will stop at the desired point in space. The pilot will have some idea of the maximum possible deceleration of the aircraft as a function of speed (i.e. the flight envelope). One might argue that Equation (1) is the basis of the visual perception and motion control system – the pilot somehow knows the velocity and acceleration and can compute the distance to stop, or any other combination of these three. After all, this is how a man-made flight controller might work. However, although apparently simple, the calculation in Equation (1) is prone to errors (square and divide) and is actually difficult to do quickly. For example, if the instantaneous velocity, given by the airspeed indicator, was 30kt and the pilot could somehow perceive a deceleration of 0·25g and maintain this constant, how long would it take to compute that the aircraft would stop in about 45m? This took the author several seconds to compute so it is clearly not practical for 'real-time' manual control. The kinematics of the above situation can be transformed into the more general form,

$$x = \frac{\dot{x}^2}{2\ddot{x}} \qquad \ldots (2)$$

and, based on the above analysis, to avoid a collision,

$$\frac{x\ddot{x}}{\dot{x}^2} > 0{\cdot}5 \qquad \ldots (3)$$

it has become convention in τ-theory to consider $x(t)$ as negative, so the negative gap $x(t)$ is closing to zero, with $\dot{x}$ positive and $\ddot{x}$ negative during a deceleration. The instantaneous time to stop can be written as the ratio of distance to go and velocity,

$$\tau(t) = \frac{x(t)}{\dot{x}(t)} \qquad \ldots (4)$$

for the decelerating helicopter discussed above, $\tau(t)$ to stop is just three seconds, less time than it took to perform the mental computation. The actual time to stop is longer than this of course; in fact, for a constant deceleration, the time to stop is exactly twice the value of $\tau(0)$; where $t = 0$ is the instant that the deceleration was initiated. The pilot perceives the looming of the obstacle as an expansion of the image on his/her retina. In fact, any element in the visual world becomes an optical texture element and flows and grows relative to a moving observer. The rate of expansion provides direct information on the τ of that element[23]. Knowing τ is crucial for decision making but it is the rate of change of tau with time, $\dot{\tau}$, that is particularly useful for motion control.

$$\dot{\tau} = 1 - \frac{x\ddot{x}}{\dot{x}^2} \qquad \ldots (5)$$

or

$$1 - \dot{\tau} = \frac{x\ddot{x}}{\dot{x}^2} \qquad \ldots (6)$$

The fundamental hypothesis of τ-theory is that the perception system directly picks up the τ and $\dot{\tau}$ of a motion gap as the basic inputs to the natural movement control system. Maintaining $\dot{\tau}$ constant during a decelerating approach can be interpreted as keeping the τ's of the gap and the gap closure rate in a constant ratio, i.e., using Equation (6),

$$\tau_x = k\tau_{\dot{x}} \qquad \ldots (7)$$

The coupling constant $k = 1 - \dot{\tau}$ can vary between zero and unity,

a) $k = 0$, $\dot{\tau} = 1$, $\ddot{x} = 0$, the helicopter will approach and collide with the obstacle at constant velocity,

b) $k = 0{\cdot}5$, $\dot{\tau} = 0{\cdot}5$, the helicopter will approach and stop in front of the obstacle with constant deceleration,

c) $k = 1$, $\dot{\tau} = 0$, the helicopter will approach the stopping point exponentially, in theory never arriving.

Equation (7) brings us to the concept of coupling with, or following, motion guides. The coupled motions involved above are displacement and velocity but the development of τ-coupling has been based on actions where it is necessary to couple two motions together to achieve a successful goal, e.g. interceptive actions[33], where two or more gaps are being closed. In many situations however, the action being performed is not visually guided by an extrinsic motion, but rather is reliant on internalised motion 'programmes or schemata' that correspond in some way to the desired movement. These mental guides have been learned or 'programmed', either in early development or when developing a new psycho-motor skill (e.g. learning to fly a helicopter). To be effective in a range of different living organisms, such guides need to be biologically simple while being fit for purpose. The most naturally occurring motions are free falls or rises under gravity, a ubiquitous experience for animal life. Decelerating with constant $\dot{\tau}$ is equivalent to following a motion guide that has a constant deceleration form. More generally, a motion that starts and ends at rest, involving acceleration, followed by deceleration, can be accomplished successfully by following a constant acceleration guide. These remarkably simple motions form the guides that have been explored extensively by the author and colleagues in flight control research and warrant a closer examination.

2.1 A Closer Look at τ guides

When two variables, x and y, are τ-coupled in the form,

$$\tau_x = k\tau_y \qquad \ldots (8)$$

it can be shown that these variables are also related through a power law[33],

$$x = Cy^{1/k} \qquad \ldots (9)$$

C is an arbitrary constant and $0 \le k \le 1$. A power law relationship between two variables allows dilation/expansion in time and space and fits several natural sensory-perceptual relationships. Table 1 provides the derivation of the equations for the motion $x(t)$ when $y(t)$ is either a constant deceleration or a constant acceleration motion guide, both written as x_g. The accompanying Figs 5 and 6 illustrate the variations of motions and τ´s for various values of the coupling constant k; although the same parameter k is used for both types of coupling, the reader should note that the significance of the numerical values is different. Time and distances have been normalised by the manoeuvre time and distance, T and X. Some straightforward observations from these relationships can usefully be made at this point.

Motions following a constant deceleration guide:

(*i*) Motions begin with an abrupt deceleration which gradually eases off as the gap is closed. The larger the coupling k, the more the profile approaches the limiting case of constant deceleration ($k = 1$). In practice the initial deceleration will take a finite time to build up as will the reduction of $\dot{\tau}$ to the selected constant value.

(*ii*) Following the guide results in $\dot{\tau}_x = k/2$ and, in theory, values of $k > 1$ are possible but result in infinite deceleration at the stop, which in practice means a collision will occur e.g. the $k = 1{\cdot}2$ case shown to illustrate such a hard-stop case.

(*iii*) At the time the deceleration is initiated ($t = 0$), the overall time required to stop $T = -2\tau_x(0)/k$; e.g. if $k = 1{\cdot}0$, then the manoeuvre time will be double the perceived τ_x at $t = 0$·

Motions following a constant acceleration guide:

(*i*) Motions begin with an abrupt acceleration, which then subsides, with maximum velocity occurring further into the manoeuvre as k is increased. When $k = 0{\cdot}4$, the maximum velocity occurs mid way, in time, through the manoeuvre.

https://doi.org/10.1017/S0001924000006187 Published online by Cambridge University Press

Table 1
Equations for the guide-following motions

constant deceleration guide	constant acceleration guide
x_g motion	
$a_g = a_{g0}$	$a_g = a_{g0}$
$v_g = v_{g0} + a_{g0}\,t$	$v_g = v_{g0} + a_{g0}\,t$
$x_g = x_{g0} + v_{g0}\,t + \frac{a_{g0}}{2}t^2$	$x_g = x_{g0} + v_{g0}\,t + \frac{a_{g0}}{2}t^2$
$v_g(T) = 0$	$v_{g0} = 0$
$x_g = x_{g0}(1-\hat{t})^2$	$x_g = x_{g0}(1-\hat{t}^2)$
$v_g = -\frac{2x_{g0}}{T}(1-\hat{t})\quad v_{g0} = -\frac{2x_{g0}}{T}$	$v_g = -\frac{2x_{g0}}{T}\,\hat{t}$
$a_{g0} = \frac{2x_{g0}}{T^2}$	$a_g = a_{g0} = -\frac{2x_{g0}}{T^2}$
$\tau_g = -\frac{1}{2}(T-t) = \tau_{g0} + \frac{t}{2}$	$\tau_g = -\frac{T}{2}(\frac{1}{\hat{t}} - \hat{t})$
$\hat{\tau}_g = -\frac{1}{2}(1-\hat{t})$	$\hat{\tau}_g = -\frac{1}{2}(\frac{1}{\hat{t}} - \hat{t})$
$\tau'_g = \hat{\tau}'_g = 1$	$\tau'_g = \hat{\tau}'_g = \frac{1}{2}(1+\frac{1}{\hat{t}^2})$
x motion	
$\tau_x = k\,\tau_g$	$x = C\,x_g^{1/k}$
	$\hat{x} = -(1-\hat{t}^2)^{1/k}$
$\hat{x} = -(1-\hat{t})^{2/k}$	$\hat{x}' = \frac{2\hat{t}}{k}(1-\hat{t}^2)^{(\frac{1}{k}-1)}$
$\hat{x}' = \frac{2}{k}(1-\hat{t})^{(\frac{2}{k}-1)}$	$\hat{x}'' = -\frac{2}{k}\left(\left(\frac{2}{k}-1\right)\hat{t}^2 - 1\right)(1-\hat{t}^2)^{(\frac{1}{k}-2)}$
$\hat{x}'' = -\frac{2}{k}(\frac{2}{k}-1)(1-\hat{t})^{2(\frac{1}{k}-1)}$	$\hat{\tau}_{\hat{x}} = \frac{k}{2}\left(\hat{t} - \left(\frac{1}{\hat{t}}\right)\right)$
$\hat{\tau}_{\hat{x}} = -\frac{k}{2}(1-\hat{t})$	$\hat{\tau}_{\hat{x}} = \frac{k}{2}\left(1 + \left(\frac{1}{\hat{t}}\right)^2\right)$
$\hat{\tau}'_{\hat{x}} = \dot{\tau}_x = \frac{k}{2}$	$\hat{x}''(0) = \frac{2}{k}$
$\hat{x}''(0) = -\frac{2}{k}(\frac{2}{k}-1)$	$T = -\sqrt{\frac{2x(0)}{k\,\ddot{x}(0)}}$
$T = -\frac{2\tau_{x0}}{k}$	

(*ii*) When $k = 0{\cdot}5$, there is a finite deceleration at the end of the manoeuvre; when $k > 0{\cdot}5$, an infinite deceleration is required to close the gap, which, in practice, means a collision will occur.

(*iii*) As the manoeuvre comes to a close $\hat{t} \to 1$, $\hat{\tau}' \to k$, asymptotic to the constant deceleration guided motion, noting that k (const acceleration) is actually half of k (const deceleration).

In practice, we would expect a transient engagement with the guide so that the transition from constant velocity to deceleration in the one case, and stillness to acceleration in the other, will take a finite time, long enough for the information to generate τ to be acquired and the coupling to be activated. Once engaged with the self-generated guide, provided the target does not move, and provided that disturbances do not deflect the aircraft or animal off the trajectory, the guidance is very straightforward, requiring no cognitive processing[12] to control the motion. In many circumstances, particularly relating to flight and pursuit tracking, the target does move and atmospheric disturbances require additional corrective action. These corrections can, in principle, be made by adjustments to k or even the manoeuvre time T although, as seen with motions following the constant deceleration guide, T itself can be predicted through the instantaneous τ. Many helicopter manoeuvres require an acceleration followed by a deceleration, e.g. hover to hover re-positioning. If the manoeuvre is continuous, with the deceleration following smoothly from the acceleration, tracking the constant acceleration guide will ensure that the manoeuvre is flown successfully. We might assume that practising to fly manoeuvres, or any other purposeful action in life for that matter, will reinforce the mental schemata and refine the consequent skill. If the manoeuvre includes a constant velocity phase, then the pilot can switch from the constant acceleration guide to maintaining $\dot{\tau} = 1$, and then on to follow the constant deceleration guide to close the gap. We see this in some acceleration-deceleration or lateral-sidestep manoeuvres, where the pilot prefers to minimise the task time by accelerating to the maximum speed as quickly as possible (large k), hold this constant as long as possible before decelerating to stop with $\dot{\tau}$ constant. During the deceleration phase, it can be shown that following a constant deceleration guide in x is equivalent to following a constant acceleration guide in $\dot{x}$, an aspect that will be returned to in the next section.

3.0 HOW DO PILOTS KNOW WHEN TO STOP, TURN OR PULL UP? τ AS A PRIMARY GUIDANCE CUE

Returning to the problem, a pilot approaching a hill or a barrier has to decide whether to stop, turn or pull up. Normally there will be other factors influencing the choice but, having 'decided' (a cognitive process), the pilot will judge when to initiate the manoeuvre. Figure 7, taken from Ref. 34, shows results from flight simulation experiments designed to develop an improved understanding of how pilots 'use' τ in terrain-following flight. The flight speed was 35kt ($\approx 17{\cdot}5\text{ms}^{-1}$) and the height above ground about 30ft ($\approx$ 10m; speed $\approx 1{\cdot}8$ eye-heights/second).

In handling qualities test manoeuvres, adequate and desired boundaries are set to enable the pilot to judge task performance achieved. The adequate performance boundary was set at 50% of nominal height above ground, and the desired boundary at 25%, relative to the nominal trajectory. The flight path of the aircraft (height *vs* range) is shown in the left figure, including the trajectory tangents at two-second intervals; the circles indicate the crossings of the desired and adequate boundaries and, further ahead, the surface collision point. The right figure shows the instantaneous τ's to the boundaries and surface. Therefore, at each point in the manoeuvre as the hill in approached, three projected τ's can be derived. In the case shown, as the aircraft approached the hill, the pilot allowed the time to contact the surface to reduce to about 6 seconds, corresponding to a distance of approximately 12 eye-heights. Note that half this distance was actually on the slope of the hill. The first three (triple) points in Fig. 7 show the pilot maintaining approximately constant velocity ($\dot{\tau} = 1$). The desired performance boundary was within a fraction of a second of being breached as the climb was initiated. On some occasions there are fewer than three τ values on the chart, corresponding to situations where the aircraft is climbing away from the surface, and on other occasions more than three, when the aircraft is above the upper desired boundary and descending.

A hypothesis from this analysis is that typically the pilot in the simulation used visual information about 12 eye-heights ahead to 'pickup' τ information, electing to fly at about 2 eye-heights/sec (h_e/sec). When the looming information changed, e.g. when this point moved up the slope, the pilot continued in level flight for about three seconds (6 eye-heights distance) before initiating the climb. The 12 eye-height point was then directly ahead and the pilot knew that the base of the hill was halfway between the aircraft and the viewing point. These points are illustrated in Figs 8(a) and 8(b). In Fig. 8(a), the 12 eye-height point is shown at the base of the hill. As the aircraft climbs, both the optical flow centre of expansion, and 12 eye-height point, move up the hill as illustrated in Fig. 8(b).

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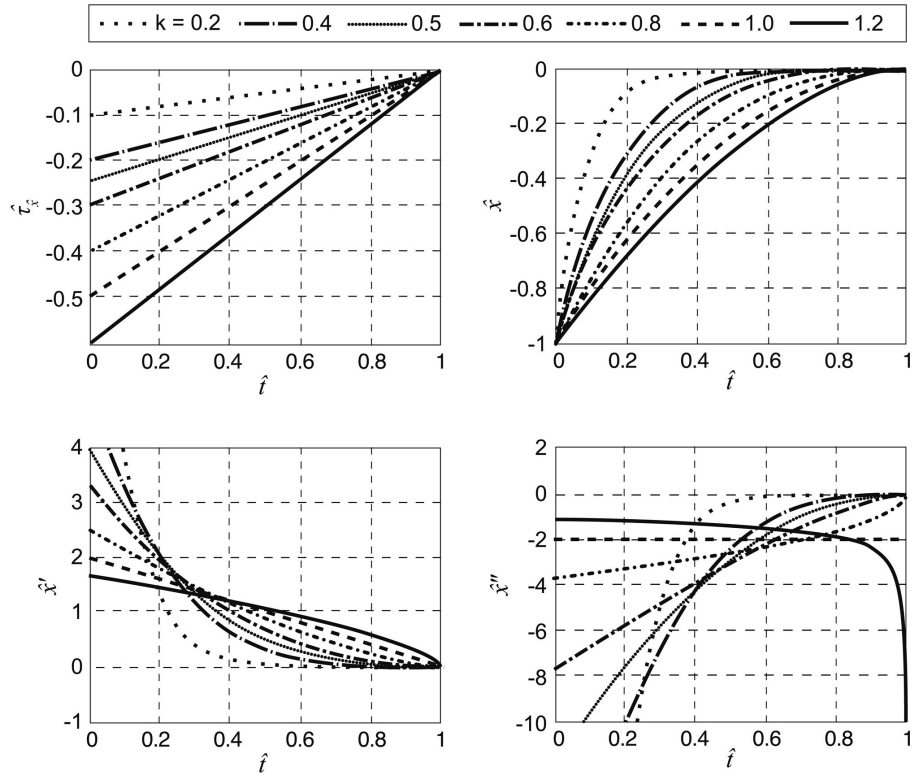


Figure 5. Motion τ, gap distance, closure rate and acceleration when following a constant deceleration guide such that $\tau_x = k\tau_{xg}$.

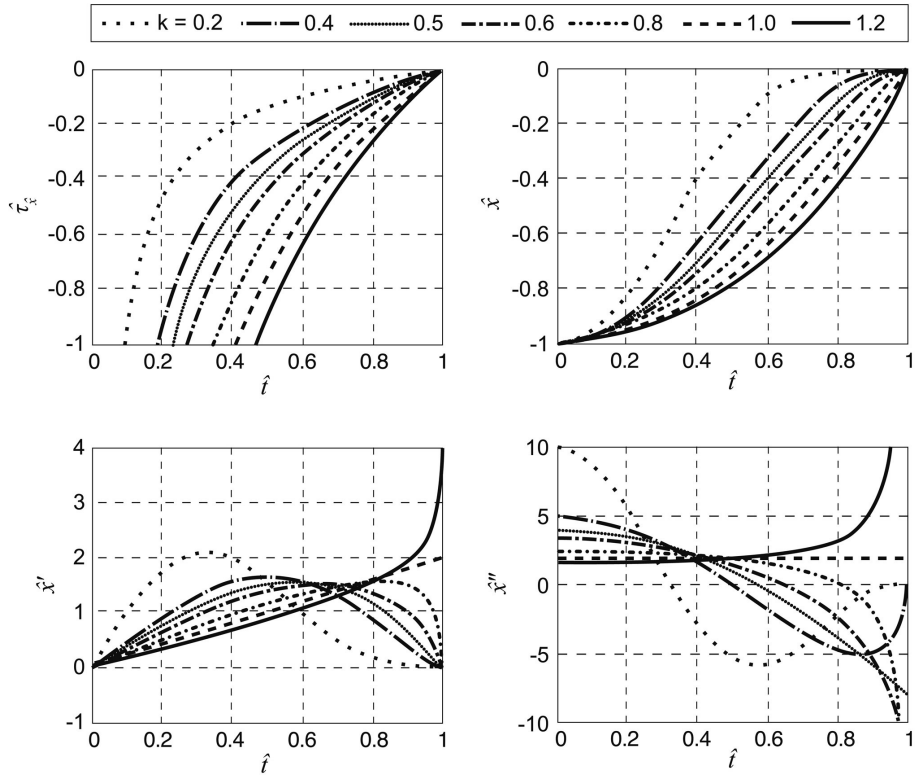


Figure 6. Motion τ, gap distance, closure rate and acceleration when following a constant acceleration guide such that $\tau_x = k\tau_{xg}$.

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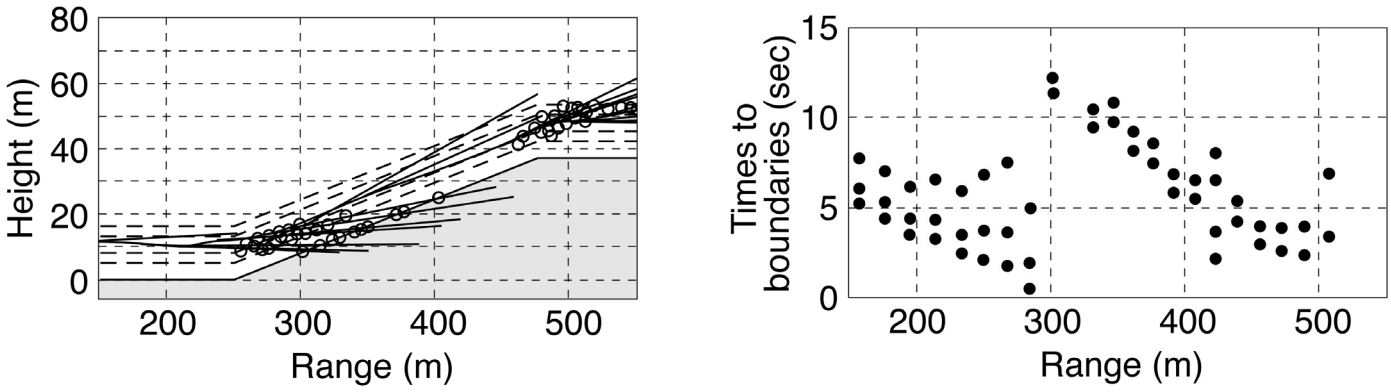
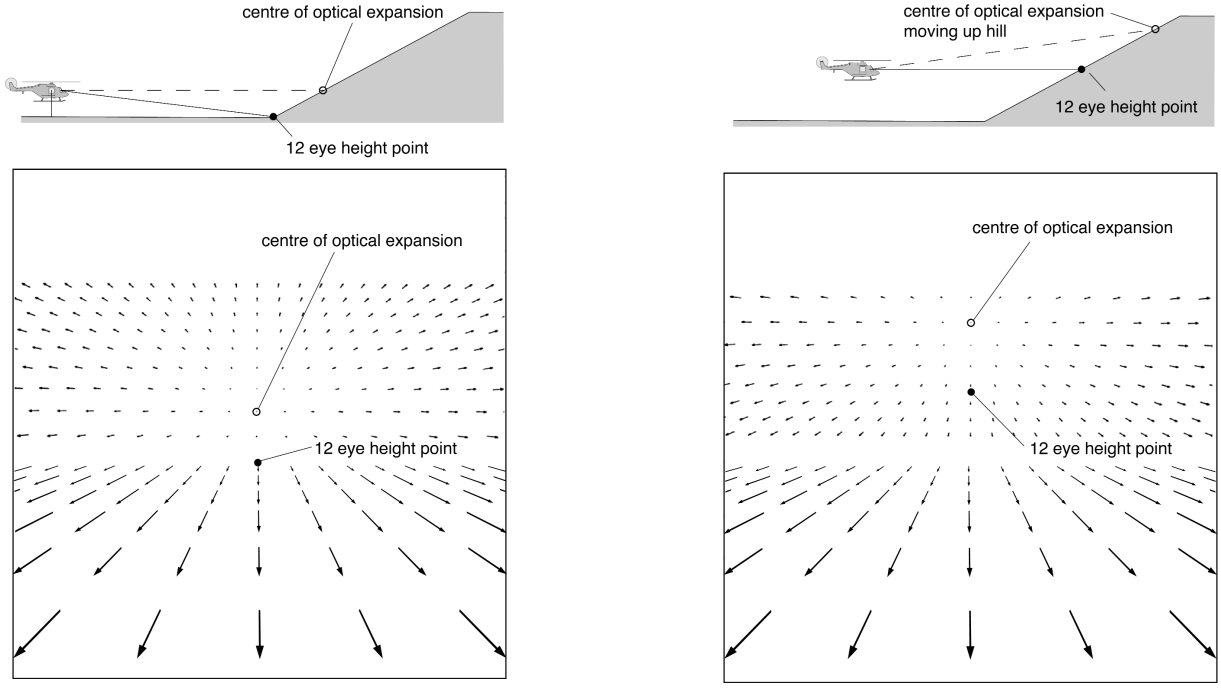


Figure 7. Flight trajectory and times to boundary during a hill climbing manoeuvre.



(a) Optical flow-field before of the climb

(b) Optical flow-field during the climb

Figure 8. Optical flow field as a helicopter approaches rising ground.

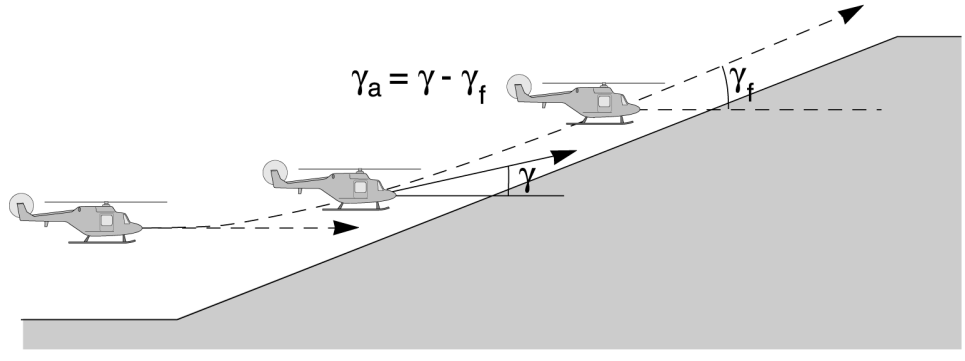


Figure 9. Definition of flight path angle gap during climb manoeuvre.

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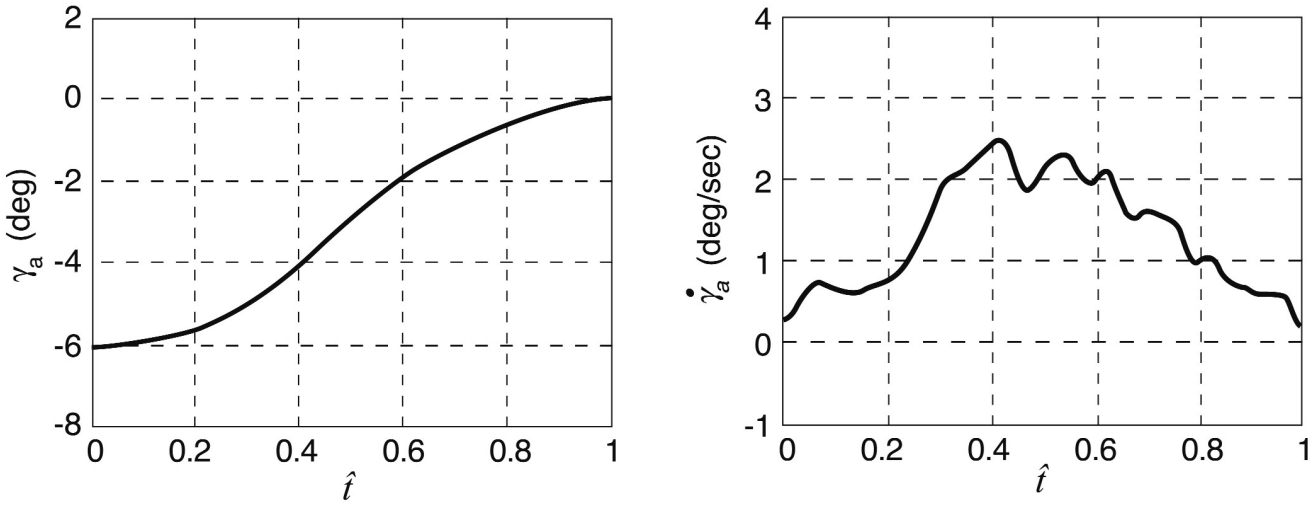


Figure 10. Flight path angle and rate during the climb manoeuvre (F-UH60 with fog at 720m).

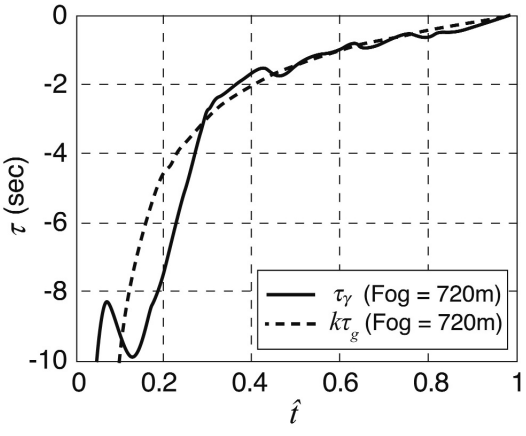


Figure 11. Flight path angle $\tau_{\gamma a}$ and motion guide τ_g during climb manoeuvre, k = 0·41.

Did the pilot use a motion guide as the basis of guidance strategy in the manoeuvre? To answer this question we can create a model of the manoeuvre using the flight path angle as the motion variable under control. This example formed an element of the PhD study by Gary Clark[34,35] who was particularly interested in applying τ-theory to gain improved understanding of the dynamics of helicopter flight and associated piloting problems in a degraded visual environment.

3.1 Prospective guidance in a hill-climb manoeuvre

Figure 9 shows the flight path variable γ_a as the gap to be closed being the difference between the instantaneous (γ_a) and final (γ_f) flight path angles. This formulation results in the gap closing from a negative value to zero, following the convention in τ analysis.

The piloted simulation experiments included a range of different visual obscuration, including surface micro-texture,

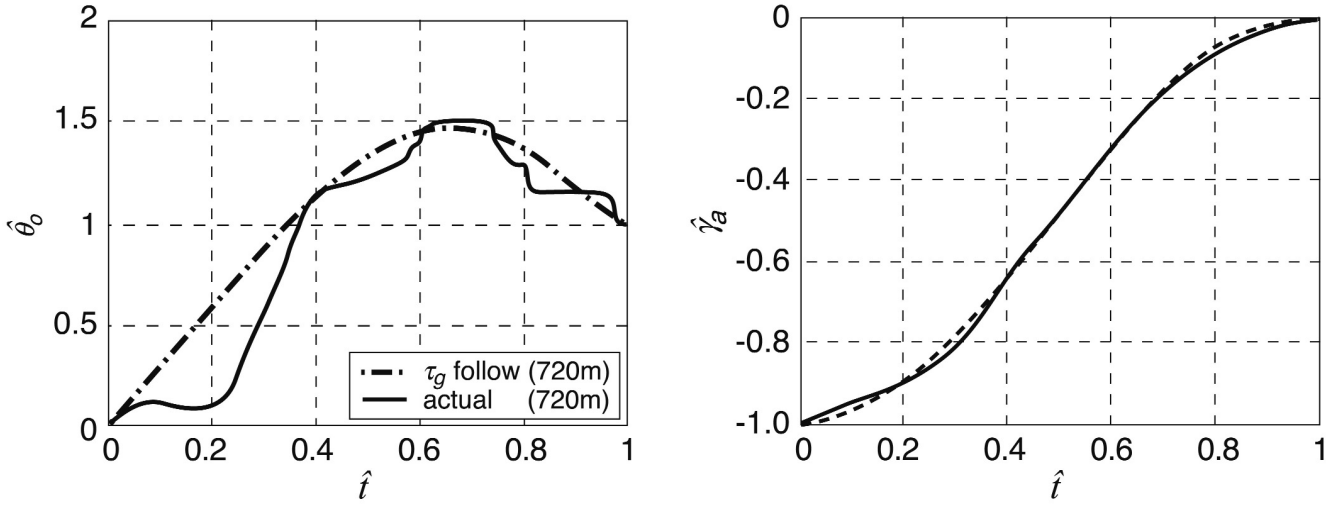


Figure 12. Normalised collective pitch and flight path angle during climb manoeuvre; $\hat{t}_w$ = 0·5, k = 0·4.

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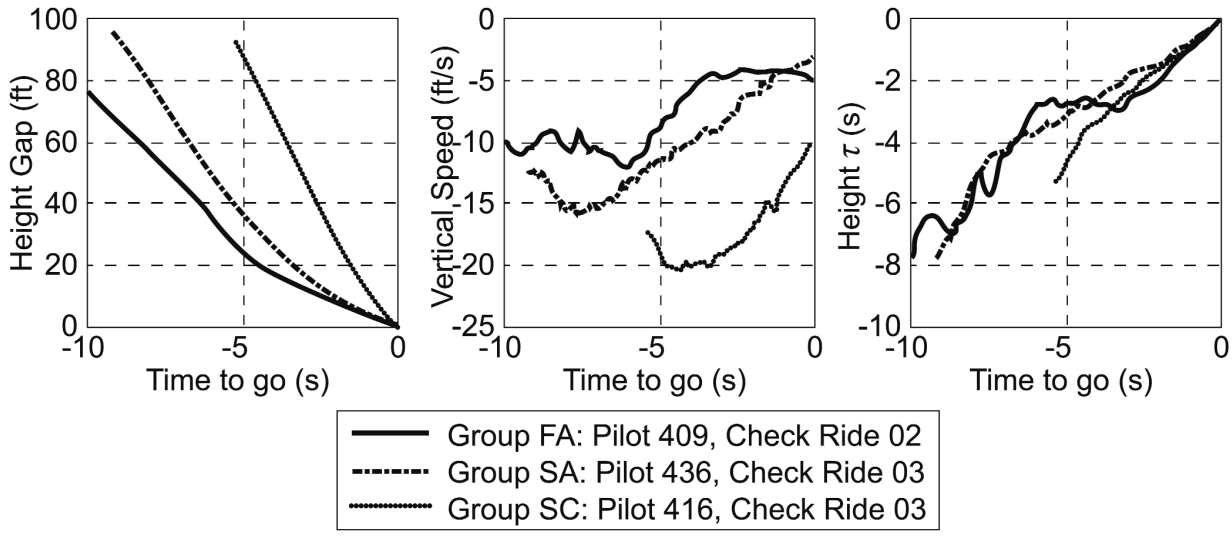


Figure 13. Height, vertical speed and τ_h as a function of time to touch down[37].

obstacle macro-texture and fog level[35]. The aircraft flown was the FLIGHTLAB F-UH60. Figure 10 shows typical results for the flight path gap and gap closure rate as a function of normalised time; results are shown for a fog range of 720m. The slope of the hill was 6°.

The gap γ_a is smoothly closed by the pilot but $\dot{\gamma}_a$ reveals higher frequency (stabilisation) content, particularly in the second half of the manoeuvre, an order of magnitude higher than the task frequency. The τ-guide followed can either be expressed in terms of the height gap (constant deceleration) or height rate/flight path angle gap (constant acceleration). For a motion that follows a constant acceleration guide, from the analysis in the previous section, we can write,

$$\hat{\gamma}_a = -(1-\hat{t}^2)^{\frac{1}{k}} \quad \ldots (10)$$

$$\dot{\hat{\gamma}}_a = \frac{2\hat{t}}{k}(1-\hat{t}^2)^{(\frac{1}{k}-1)} \quad \ldots (11)$$

and therefore,

$$\hat{\tau}_{\gamma_a} = \frac{\hat{\gamma}_a}{\dot{\hat{\gamma}}_a} = -\frac{k}{2}\left(\frac{1}{\hat{t}} - \hat{t}\right) \quad \ldots (12)$$

The method adopted to derive the extent to which the guide is followed involves performing a least-squares fit of τ_{γ_a} to τ_g, working back from the $t = 1$ point, until the correlation coefficient (squared) R^2 reduced below some pre-defined value. The resulting value of k was then used to make the fit. The case shown in Fig. 11 resulted in $k = 0{\cdot}41$ with R^2 dropping below 0·99 at $\approx \hat{t} = 0{\cdot}5$. The fit is still credible at $\approx \hat{t} = 0{\cdot}3$, before the deceleration was initiated. The simulation runs reported in Ref. 35 resulted in variations of k in the range, $0{\cdot}3 < k < 0{\cdot}45$, for the hill climb manoeuvre, suggesting the maximum climb rate occurred during the second quarter of the manoeuvre.

Assuming a first order response model for flight path angle to collective pitch, the pilot control command required to perform the guidance manoeuvre can be predicted. The control is a function of the time constant of heave response t_w, the negative inverse of the stability derivative Z_w, which can be normalised by the manoeuvre time T to give $\hat{t}_w$. Z_w varies between –0·25 in low speed flight to about –1·0 in high speed flight. The approximation for collective control takes the form[34],

$$\hat{\theta}_0 = \left(1-(1-\hat{t}^2)^{1/k}\left[1-\frac{2\hat{t}_w\hat{t}}{k(1-\hat{t}^2)}\right]\right) \quad \ldots (13)$$

Figure 12 shows a comparison of the perturbation from trim collective pitch, $\hat{\theta}_0$, normalised by the final steady state value, and flight path angle gap $\hat{\gamma}_a$ in a typical run, with that predicted by the response of the first order model guided by τ_g. The results correspond to a normalised heave response time constant of 0·5. The higher frequency 'corrective' control activity is absent from the model prediction but a noticeable feature is the 50% overshoot in the control perturbation prior to settling at the new steady state value. The longer the response time constant, the larger the collective overshoot required but, in practice, the pilot will be inhibited by control limits or the risk of an over-torque in the power-train. The predicted control appears from Equation (13) to be open-loop but the pilot is actually working to minimise the error between the motion and the τ-guide, which can be written in the τ-domain as,

$$\varepsilon_\tau = \tau_\gamma - k\tau_g \quad \ldots (14)$$

or in the spatial-domain as,

$$\varepsilon_\gamma = \gamma_a - Cx_g^{1/k} \quad \ldots (15)$$

The first order approximation predicts the flight path angle very well, reinforcing the hypothesis that the pilot is following the constant acceleration guide during the manoeuvre. Later in the paper results are shown from a study into the design of a closed-loop feedback system designed to minimise the error function given in Equation (15).

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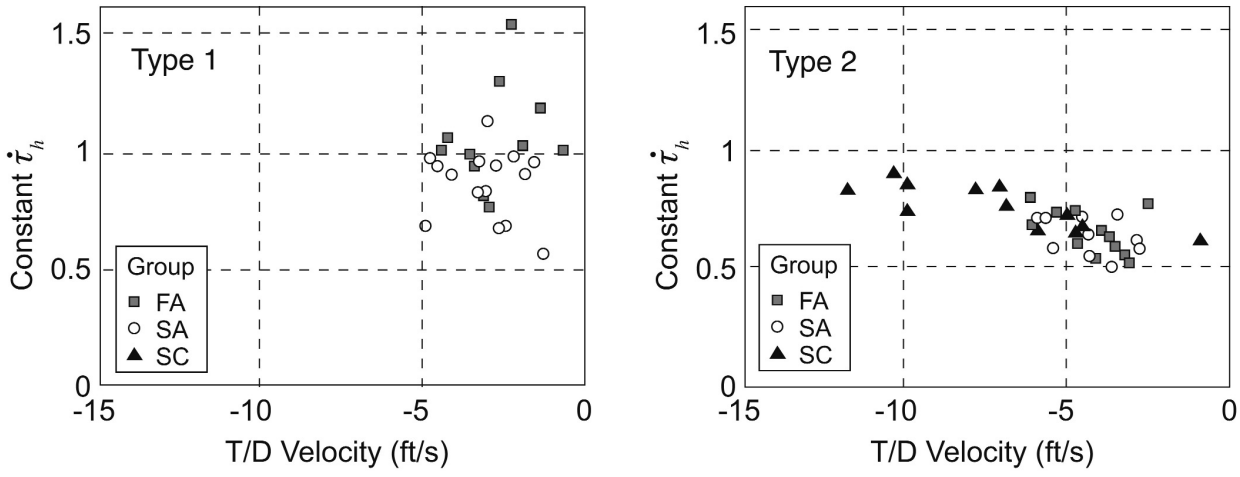


Figure 14. Variations in $\dot{\tau}$ during flare with touch-down velocity[37].

Figure 11 shows that the $\tau_{\gamma a}$ profile is approximately linear during the final 20-30% of the manoeuvre, reflecting the approximation to a constant $\dot{\tau}$ motion. In fact, the whole manoeuvre could have been analysed as one following the constant deceleration guide for height. The manoeuvre closely resembles the final moments of the approach and landing phase in a fixed-wing aircraft. This, and other fixed-wing aircraft manoeuvres, were examined by Mike Jump[36-39] in his PhD study at Liverpool.

3.2 Prospective guidance in a fixed-wing aircraft flare manoeuvre

The flare manoeuvre lasts a similar length of time to the hill climb manoeuvre, about 3-4 seconds, and is usually initiated from a final approach with a flight path angle of 3-4°. For a large civil airliner, the descent rates prior to the flare will be more than 4ms^{-1} (≈12ft/sec), so the pilot aims to reduce this rate by as much as 80% to result in a safe but firm touchdown (*T/D*) to ensure the aircraft neither floats, balloons or incurs damage to the undercarriage. In his research, Mike Jump examined the use of τ as a 'cue' for flare initiation and also the extent of τ-guide following during the manoeuvre. A series of simulation trials were conducted to provide data for developing pilot models and τ-based pilot vision aids. A study more than three decades previously into the effectiveness of simulators for training in landing skills reported differences in landings performed in flight and in a simulator[40,41]; the differences were quantified in terms of parameters in pilot-vehicle dynamic models. This work formed one of the starting points for Mike Jump's research. Figure 13, showing results from flight tests with a DC-10 airliner, illustrates the problem.

The figure shows typical results for variations in height, height rate and τ_h from three pilot groups. FA refers to flight trained pilots who were consistently able to achieve touch-downs at < 5ft/sec during check-rides. SA refers to simulator trained pilots, again consistently able to achieve touch-downs at < 5ft/sec during check-rides. SC refers to pilots who displayed inconsistent performance and hard landings with no discernable improvement during check-rides. In Ref. 41 the authors report that, when transitioning from simulator to flight, pilots made substantial adjustments (reflected in pilot model parameters), the nature of these adjustments being different between the different pilot groups. This topic is returned to in the later section on pilot-vehicle modelling. A major conclusion in Ref. 41 was that training simulator fidelity was not adequate to perform the landing manoeuvre correctly. Simulator trained pilots consistently exhibited longer time lags during the manoeuvre transitions, attributed partly to inadequate spatial perception near the surface. Another conclusion was that good landing performance did not appear to depend on initiating the flare from a narrow range of altitude – there were different 'cues' that triggered the pilot. The three 'typical' trajectories illustrated in Fig. 13 have interesting characteristics when viewed in the τ domain. SA and SC both feature an approximately constant $\dot{\tau}$ during the last stage of the flare, while FA features a 'pause', with constant τ from 6-3 seconds 'time to go'. Constant τ implies an exponential reduction in the height and the pilot holding controls fixed following a step input. Mike Jump classified the two landing techniques as Type 1 (including the pause) and Type 2 (no discernable pause). The flare data were analysed to determine the gradient of the τ variation during the flare and Fig. 14 shows the $\dot{\tau}$ results for both Type 1 and Type 2 landings.

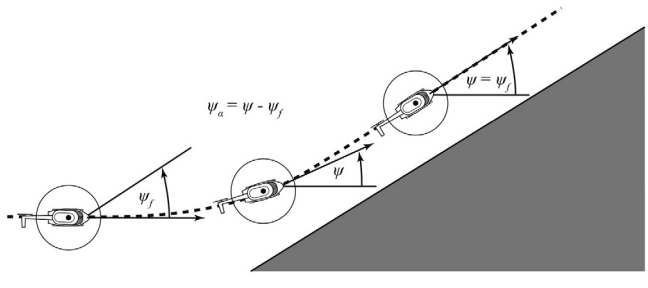


Figure 15. Definition of heading angle gap during the turn manoeuvre.

For the Type 1 landings, particularly for group FA, the constant $\dot{\tau}$ motion following the constant τ pause, can involve a final downward acceleration ($\dot{\tau}$ >1), possibly resulting from the pilot preferring to command a final push onto the surface. For the wholly constant $\dot{\tau}$ flare in Type 2 landings, most successful landings (*T/D* vertical velocity < 5ft/sec) occurred with 0·5 < $\dot{\tau}$ < 0·75, equivalent to 1·0 < *k* < 1·5, where *k* is the coupling constant when following the constant deceleration guide (Fig. 5). According to Fig. 14, the less successful the landing, the larger the value of $\dot{\tau}$. These results were replicated in the simulation trials conducted by Mike Jump and reported in Ref. 37. An important development in this research was the exploration of the impact of degradations in visual conditions on the landing performance and $\dot{\tau}$ coupling. As expected, degrading the visibility resulted in harder landings and a reduction in the extent of τ-coupling. Mike Jump advanced this research with the design of τ-based guidance displays[39] to aid landings in low – zero visibility. The display concepts were evaluated in piloted simulation and compared with state-of-the-art head-up-displays that were just entering civil airline service. The results showed

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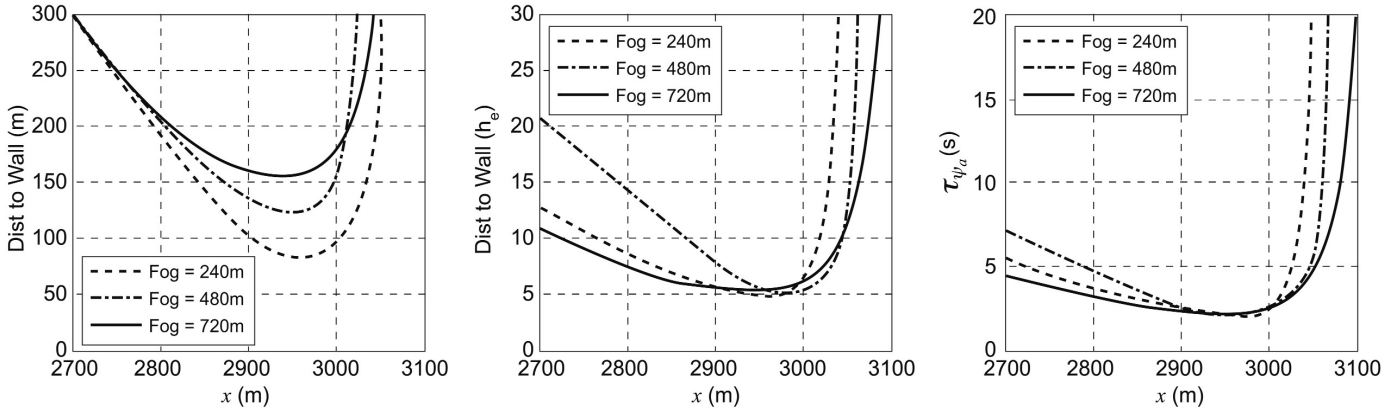


Figure 16. Distance to the wall in metres and eye-heights and time to contact the wall in turn manoeuvre.

equivalent and, in some cases, improved landing performance in low-zero visibility with the τ-display, reinforcing the premise that τ information is an effective source of motion cueing.

The hypothesis that τ is used to trigger the flare initiation, or any manoeuvre that involves closing on and stopping at a goal from an approach velocity, is supported by the analysis in Table 1, where the manoeuvre time T is expressed in terms of the value of τ at the moment the deceleration is initiated (τ_{x0}).

$$T = -\frac{2\tau_{x0}}{k} \qquad \ldots (16)$$

Through practice and training, a pilot can learn about the capability of the aircraft and how to pick up visual gap and related τ cues from the dynamic 'picture' seen through the cockpit windows. Based on τ perception the pilot can, within limits, select k (level of manoeuvre aggressiveness) to match the achievable T. For example, if the flare is flown with a constant vertical deceleration, then $k = 1$ ($\tau = 0{\cdot}5$) and the manoeuvre time will be double the perceived τ_{x0}. There will be a transient as $\dot{\tau}$ reduces from 1 to 0·5, again a function of the aircraft dynamics, in this case the heave damping, and the pilot may then elect to reduce $\dot{\tau}$ to zero (Type 1 strategy) before finally 'pushing' the aircraft firmly onto the runway. Pilots need to learn techniques for different heave dynamics and also different visual information available through the cockpit windows.

3.3 Prospective guidance in a turn manoeuvre

In Ref. 35, Gary Clark examined the turn manoeuvre with the same methodology used for the hill climb manoeuvre described in Ref. 34. In this case the pilot approached a vertical surface (wall) inclined at 30° to the flight path. The task was simply to turn and fly parallel with the wall with ψ as the instantaneous yaw angle, ψ_f the final heading change and ψ_a the heading gap being closed (Fig. 15).

As with the vertical manoeuvre, tests were carried out with different levels of simulated fog obscuration. The results from the turn manoeuvre are chosen to illustrate an aspect that was common to all manoeuvres. In all cases the pilot initiated the manoeuvre in a low hover and was required to accelerate into forward flight and establish a trim forward speed and height appropriate to the visual conditions and the task ahead. Figure 16 shows typical results for the manoeuvre flown in three different visual conditions (fog obscuration beginning at 720m, 480m and 240m).

Results are shown for the distance to the wall in physical units, in eye-heights (h_e) and $\tau_{\psi a}$ in seconds. The striking feature of the distance to the wall curves is the way they coalesce when transformed into the eye-height variable. This natural scaling also occurs in the velocity, such that in all three cases the forward speed is about 2·5 eye-heights/sec; the actual flight velocities varied between 40 and 60kt, increasing as visibility increased. The turn is initiated before the minimum distance is reached of course, the latter being about 5 eye-heights in all cases, with $\tau_{\psi a}$ reducing to a minimum of

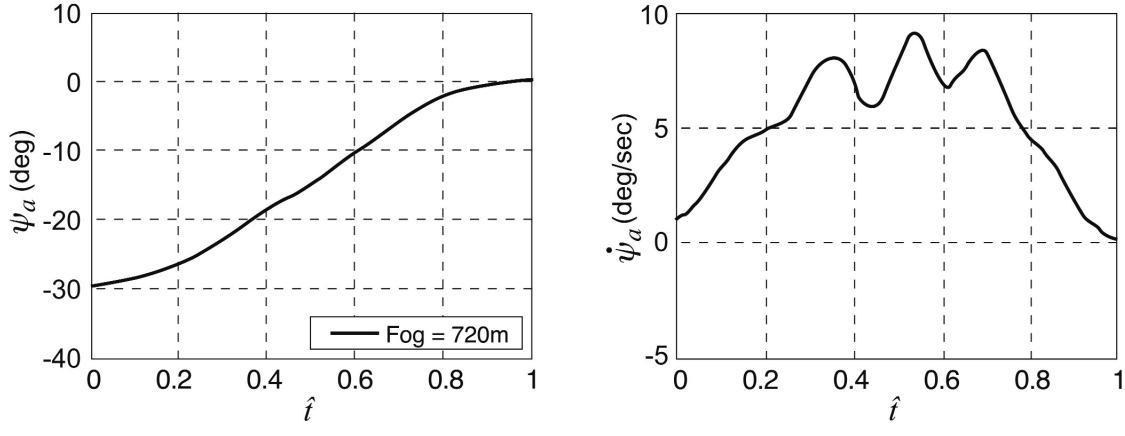


Figure 17. Heading angle and rate during the turn manoeuvre.

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just over two seconds. This theme of invariance in motion control will be re-visited when discussing handling qualities and the usable cue environment in the next section.

Figure 17 shows a typical variation with normalised time $\hat{t}$ of the heading gap ψ_a and closure rate $\dot{\psi}_a$ for the 720m fog case. For the turn manoeuvre the pilot uses lateral cyclic as the primary control but pedal is also used to balance the turn, which contribute to the higher frequency stabilisation component in the yaw rate. The manoeuvre duration (T) was about 6·5 seconds, and the stabilisation activity occurred at a frequency of about 1Hz. These variations cannot, of course, be modelled by τ-guidance with constant coupling k.

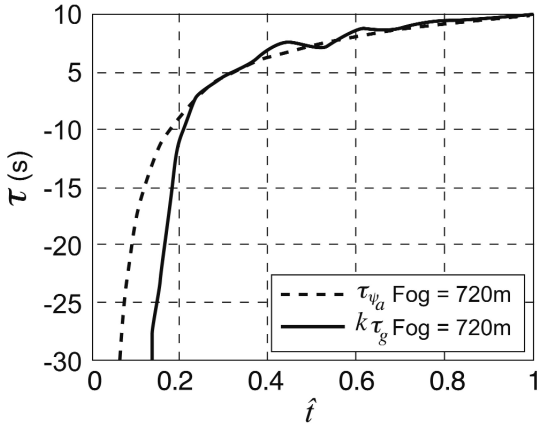


Figure 18. Variation of $\tau_{\psi a}$ during the turn manoeuvre.

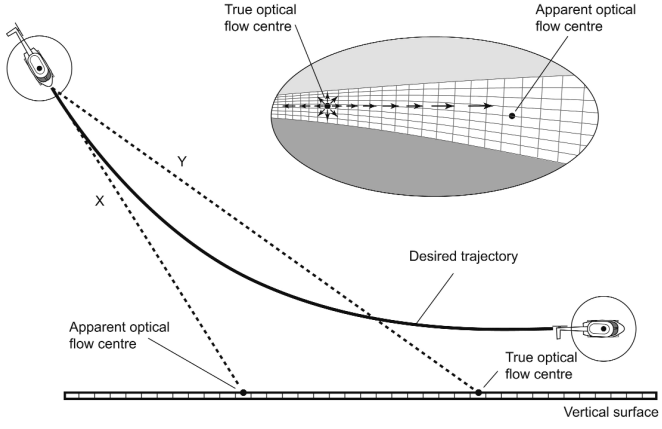


Figure 19. Helicopter trajectory during a turn showing optical flow vectors.

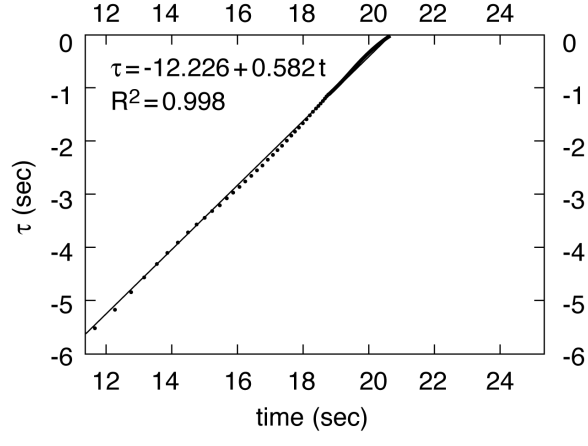


Figure 20. τ in the deceleration phase of an acceleration-deceleration MTE[43].

Figure 18 presents the correlation of the motion gap $\tau_{\gamma a}$ with $k\tau_g$ where, as with the hill climb manoeuvre, τ_g is the constant acceleration guide. The stabilisation fluctuations can be seen in $\tau_{\gamma a}$ and these lead to a correlation coefficient, R^2 reducing to 0·92 early in the fitting but staying at this level for 75% of the turn. The value of k for the case shown was 0·59 and k varied across the range $0{\cdot}5 < k < 0{\cdot}7$, the maximum turn rate occurring in the third quarter of the manoeuvre. The pilot does not reduce the bank angle and hence turn rate until late in the manoeuvre.

The turn manoeuvre introduces a new dimension to the optical flow on the surfaces – rotation. The centre of optical expansion is no longer where the extended flight path vector impinges on the wall. The flow vectors now have a lateral component due to the aircraft's turn rate and the centre of expansion shifts ahead of the point due purely to forward translation (the apparent centre of expansion), as shown in Fig. 19. A pilot will need to know that this flow centre, effectively the instantaneous collision point, is at a safe distance or, in τ terms, a safe time ahead. The minimum value of $\tau_{\gamma a}$(≈–2 seconds) shown in Fig. 16 is therefore not strictly the time to the surface; the aircraft has a yaw rate of about 8 deg/sec (Fig. 17) and, at a distance to 160m (Fig. 16), this gives an optical flow vector with magnitude of 22ms^{-1} ahead (hence zero when the optical flow is –22ms^{-1}). The true centre of expansion moves into the turn and the pilot's task is to maintain this situation, presumably picking up $\tau_{\gamma a}$ information from the flow between the apparent and true centres. For the case shown in Fig. 16, after reaching a minimum $\tau_{\gamma a}$ the pilot completes the turn in a further two seconds, flying parallel with the surface. The sufficiency of visual information to maintain a margin between the aircraft and impending hazards is critical to flight safety. In the development of helicopter handling qualities engineering during the 1980s, this sufficiency was described by a concept called the usable-cue-environment, developed to assist in establishing stability and guidance augmentation system requirements. This topic, and its relationship with τ-theory, will be returned to in the following section. Before this, the third manoeuvre studied by Gary Clark in his research is examined – the deceleration-to-stop.

3.4 Prospective guidance in a stopping manoeuvre

The acceleration-deceleration manoeuvre, a handling qualities mission-task-element (MTE) in the ADS-33 family[42], featured in the first of the author's journal publications on τ in flight guidance[43]. The results of the simulation trials, conducted both in flight and on the Advanced Flight Simulator at DERA (Bedford) with a Lynx helicopter, showed strong evidence of τ-guide following. This manoeuvre shows how different interpretations can be made of the guide-following used by the pilot. Figure 20 presents the first part of an example, showing τ of the distance to stop during the deceleration phase of the MTE.

A very tight correlation results and τ = 0·58, corresponding to k = 1·16 (Table 1; coupling constant in the constant deceleration guide). The pilot initiates the deceleration when τ ≈ –5·5 seconds, the stop taking nearly 10 seconds to complete (note from Table 1, $T = 2\tau_{x0}/k$). For the whole accel-decel, (Fig. 21), the fit to the constant acceleration guide is less tight though still good with k = 0·28, indicating that the maximum velocity and transition to the deceleration occurs during the second quarter of MTE. Gary Clark turned his attention to the examination of situations where the visual cues were degraded, either through reductions in micro/macro-texture or through foggy obscuration. As before, the manoeuvre was analysed as a one-dimensional, in this case longitudinal, motion, as shown in Fig. 22. Gary focussed on the deceleration phase of the manoeuvre as in some cases the pilots had established a steady translational velocity before beginning the deceleration.

The motion gap variable selected for analysis was the translational velocity, $\dot{x}_a = \dot{x}_f - \dot{x}$ and typical variations of the velocity gap and acceleration are shown in Fig. 23, for the three different fog levels. The increasing fog obscuration resulted in the pilot reducing velocity as shown in the Figure.

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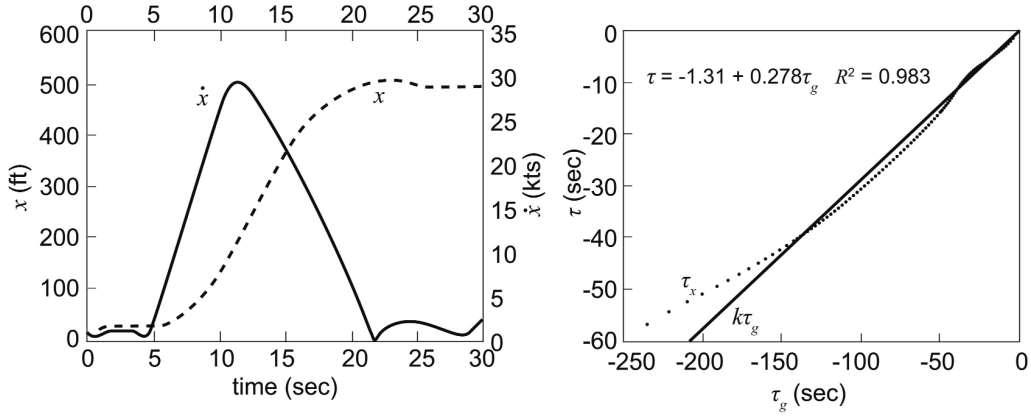


Figure 21. Following a constant acceleration guide during an accel-decel[43].

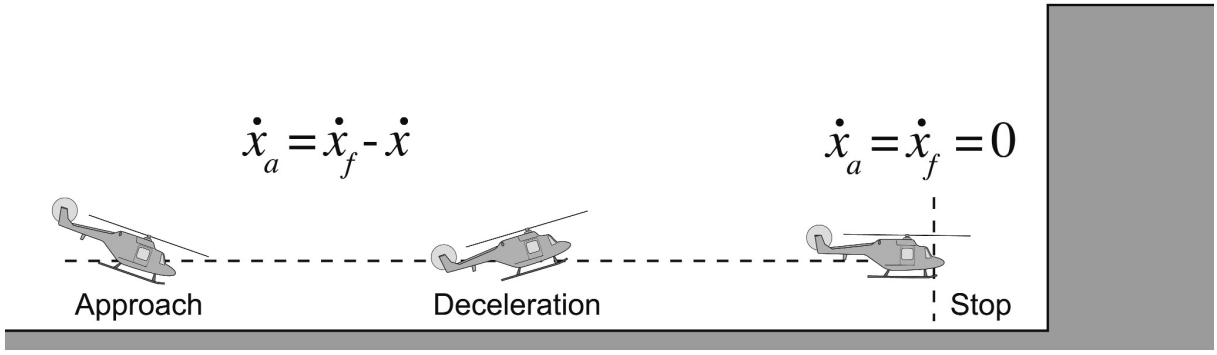


Figure 22. Definition of longitudinal velocity gap during the accel-decel manoeuvre[35].

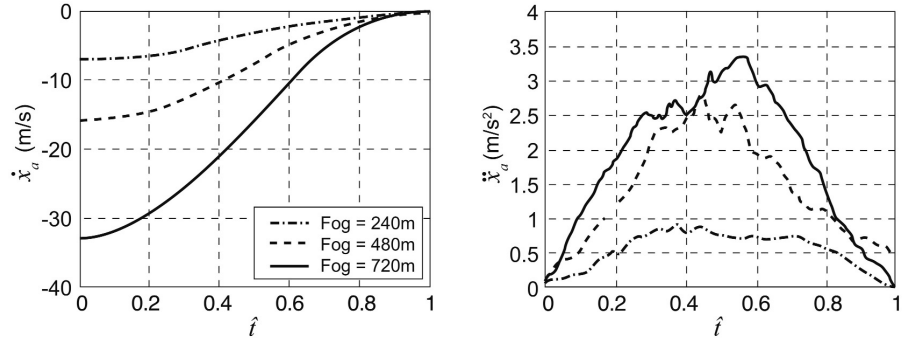


Figure 23. Velocity gap and acceleration during the deceleration-to-stop manoeuvre[35].

The initial velocity varied from more than 30ms^{-1} for the 720m fog case to less than 10ms^{-1} in the 240m fog case; the decelerations (shown positive in Fig. 23 reflecting the reducing negative velocity) reduced accordingly. The stabilisation content in the manoeuvre features in the variation of acceleration as the pilot modulates the pitch attitude of the aircraft; a deceleration of 3ms^{-1} corresponds to a pitch attitude of about 20°, a practical limit in the Bibby HELIFLIGHT simulator at Liverpool as, above this value, the horizon disappears below the cockpit coaming. In all cases the pilot initiated the deceleration with $\tau_{\dot{x}}$ between (-)6-8 seconds, the deceleration itself lasting between 11 and 17 seconds, depending on the initial flight speed. Variations in $\tau_{\dot{x}}$ during the deceleration and the correlation with motion following the constant acceleration guide are shown in Fig. 24, with coupling constants varying between 0·37 and 0·43 – the maximum deceleration occurring approximately in the middle of the stopping manoeuvre.

Earlier in this paper it was shown that approaching a stop with a constant $\dot{\tau}_x$ implied the relationship $\tau_x = k\tau_{\dot{x}}$ (Equation (7)) and consequently that $\dot{\tau}_{\dot{x}}$ is constant, a result confirmed by Fig. 24 at least for the final 60-70% of the deceleration. In each case the pilot initiated the deceleration when $\tau_{\dot{x}}$ was about 7 seconds, with $\dot{\tau}_{\dot{x}}$ taking a similar form to the flight path angle displacements in the climb and turn manoeuvres. As the fog obscuration increased, the pilot slowed down to maintain a safe τ_x and $\tau_{\dot{x}}$ to the fog so that he could make a decision whether to stop, turn or climb if an obstacle or sloping ground lay ahead.

The deceleration profile selected by pilots during approaches to hover was the subject of a study undertaken by NASA Langley during the 1970s to understand better the control requirements of flight directors on the one hand and air traffic management on the other[44]. A review of the results of this work was conducted by Heath Lockett as part of his PhD research at Liverpool[45]. The NASA study had involved a large number

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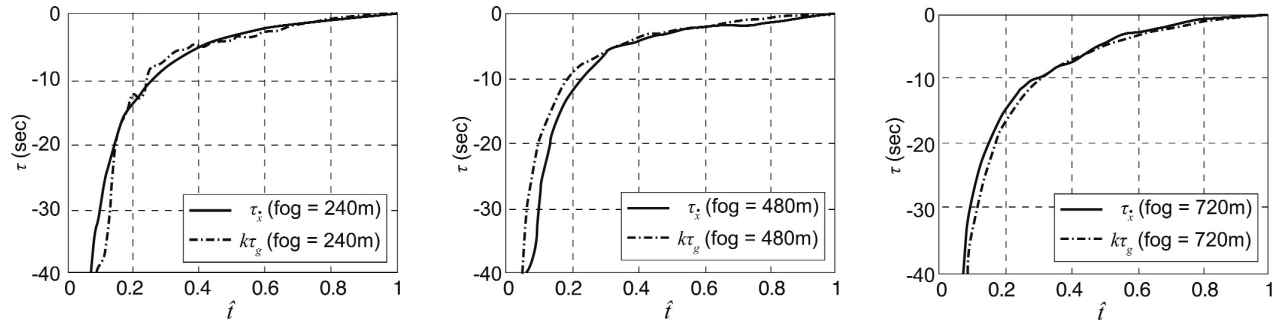


Figure 24. Typical variations of $\tau_{\dot{x}}$ with $\hat{t}$ for three fog cases and correlation with $k\tau_g$[35]
(240m fog, k = 0·43 (R^2 = 0·92); 480m fog, k = 0·37 (R^2 = 0·9); 720m fog, k = 0·42 (R^2 = 0·9)).

of flights tests conducted to determine the optimum deceleration profile. The analysis indicated that approach trajectories, initiated at a range of about 2,800 feet, could be modelled by the relationship,

$$\frac{x^n \ddot{x}}{\dot{x}^2} = c \qquad \ldots (17)$$

Where c is a constant and n varied between 1·7 and 1·3 as the initial velocity increased from 50kt to 100kt. Note that n = 1 corresponds to the classic $\dot{\tau}$ constant profile. In his research, Heath tried to replicate the NASA flight trials in simulation but did not find the implied variation of $\dot{\tau}$ guidance with range shown in Equation (17). Rather, a similar range of approach and final 'flare' strategies to those discovered by Mike Jump were identified, including the τ-pause, prior to stopping. Heath extended the study to examine helicopter approaches in degraded visual environments to raised helipads. In addition to visual degradation through fog, Heath reduced the level of surface micro-texture, creating conditions of usable cue environment (UCE) 1 to 3 (the UCE is described in more detail in the next section). Not unexpectedly, as the surface texture degraded pilots experienced difficulties establishing consistent approach strategies. Heath performed an incremental τ analysis on the data, computing a best $\dot{\tau}$ estimate by using increasing amounts of data (with τ = 0 as the start point), range at which R^2 reduced to 0·95. Fig. 25 shows the general trends of the results, with estimated $\dot{\tau}$ shown as a function of the range at which reduced to 0·95. The limiting case of $\dot{\tau}$ approaching 0·5 occurs at the initial range of 2,800ft only in UCE 1. Values of $\dot{\tau} > 0{\cdot}5$, or hard stops, and even close to unity (passing the helipad with residual constant velocity) were computed in the degraded conditions.

The suggested role of τ in establishing safe margins for flight in the clutter near the Earth's surface is intuitively strong and forms a stepping stone to take us to the next main topic in this paper.

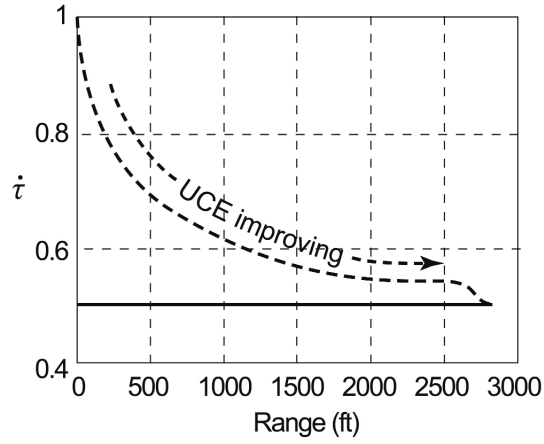


Figure 25. Trend variation of estimated $\dot{\tau}$
with range for $R^2 > 0{\cdot}95$ during decelerating approaches.

4.0 τ IN THE DEVELOPMENT OF HANDLING QUALITIES

Handling qualities are, in paraphrased form, '*those aircraft characteristics that govern the ease and precision with which a pilot is able to perform tasks, in support of an aircraft role*'[46]. The emphasis on role in the definition is important because the flying task, except perhaps for display pilots, is secondary to the role. In this definition, George Cooper and Robert Harper were referring to the characteristics such as the shape and speed of the response to controls, or the natural stability, the ability to trim or the susceptibility to gusts. For example, it is actually difficult to maintain a precise flight path, with simple control movements, particularly in gusty atmospheric conditions and particularly with an aircraft that has weak longitudinal or directional stability. The level of difficulty depends on the aircraft dynamics and the available task cues. Flying up and away, a pilot normally has no information on the aircraft's flight path with which to judge accuracy, but in many situations this is not critical; flying with reference to the, more readily available, attitude cues is sufficient; the flight path response then lags behind the attitude response. It is testimony to the adaptability of humans that we can transfer the gap-closing skills developed for motion control in the natural world, to the task of interpreting or following moving needles and symbology from electro-mechanical devices on the cockpit instrument panel.

Flying at low level, near the surface, the flight path can be inferred from the optical flow on the surface, and precision becomes critical to safety, as in the flare or obstacle avoidance manoeuvres analysed in the previous section. It would be very easy to design an aircraft that made these tasks almost impossible to perform safely. Fortunately, handling qualities engineering has developed, particularly over the last 40 years since the publication of Ref. 46, into a mature discipline supported by a substantial database of lessons learned in the honing of good practice[47,48]. With the publication of ADS-33PRF[42], rotorcraft flight handling qualities became a recognised measure of an aircraft's performance. Good handling qualities are not just 'nice to have', nor are they attributes that can be left to flight test to discover and fix. Unless good handling qualities are designed in, there will always be a risk that in some region of the operational flight envelope, the pilot may be exposed to characteristics that require extensive compensation, or even characteristics that risk loss of control. But it is not enough to follow the best design practice. The flight handling of a new or upgrade aircraft need to be thoroughly flight-tested to ensure that the operational pilot does not find himself or herself in the role of test pilot during service, having to work out some new control strategy to fly the aircraft safely out of hazardous conditions. The author has taken the opportunity to reinforce these points about good design and development practice in several of his publications[7,49,50].

Until relatively recently, however, there has been little published on the role of τ as a variable that pilots use to fly tasks and hence its utility in support of handling qualities engineering. A likely reason for this is that engineers are more used to working with, and measuring, spatial

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gap variables of distance, velocity and acceleration; translational and rotational. Pilots also can make sense of their motion, and articulate what they experience, in terms of these spatial variables. But τ-theory suggests that the sensing of temporal variables is fundamental to perception. If this is true then it follows that we have been working, albeit with considerable success, with a higher level transformation of the fundamental measurement in the development of handling qualities theory and associated stability and control augmentation. In the following, four areas where some progress in working with τ has been achieved will be discussed. The first relates to handling requirements specific to flight in poor visibility.

4.1 τ in the usable cue environment

During the development of Aeronautical Design Standard 33[42], a requirement called for criteria that would set new standards to assist designers in determining both the 'stability and control' and 'visual cue' augmentation necessary to confer Level 1 handling qualities when operating in degraded visual environments (DVE). Military operations in poor visibility have always been hazardous, with a pilot's full attention required for stabilisation (staying upright) and guidance (avoiding collisions). Stabilisation cannot directly help a pilot avoid colliding with obstacles but, importantly, reducing pilot workload frees up capacity for situation awareness and flight guidance; navigation can also be a significant challenge for a pilot at low level of course. Initially, in an attempt to define the level of visual degradation, pilots were asked to quantify the value of the outside visual cues for flight control (OVCs, Fig. 26, Ref. 51). The conventional terms VMC and IMC (visual and instrument meteorological conditions) are used in the description of the levels of degradation. The distinction between the impact of the quality (i.e. the availability and richness) of the spatial attitude and velocity 'cues' is made.

While it is clear that pilots use a combination of visual information to guide and stabilise motion, their ability to articulate the details of how they do this requires introspection and cognitive extrapolation from

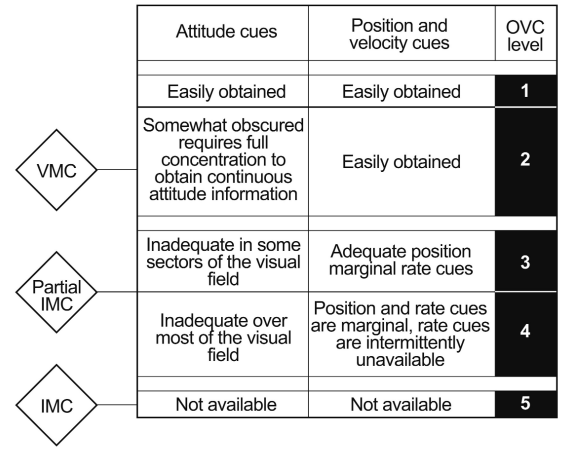
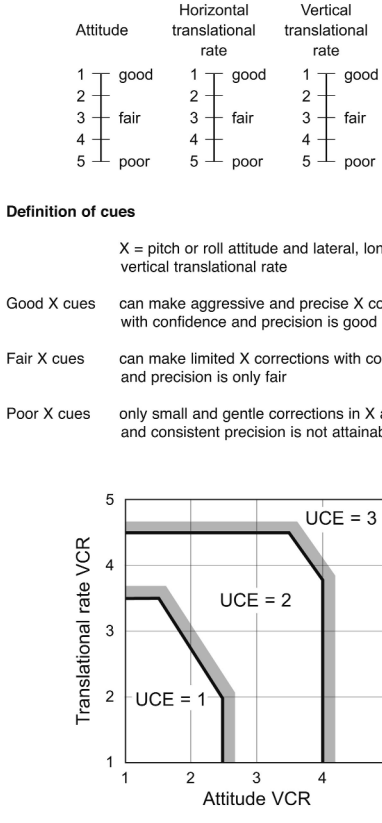


Figure 26. Outside visual cues rating scale[51].

subliminal actions. Such actions are not readily accessible to the higher brain functions and the assessment process evolved into one where pilots were required to rate what they knew about – their ability to fly with precision and aggressiveness. With the publication of ADS-33C all references to the word 'cues' were eliminated, although the descriptions in Fig. 26 are implied. The Usable Cue Environment chart and visual cue rating descriptors are shown in Fig. 27[52,53]; also shown are the response type required in the different UCE's to assure Level 1 handling qualities. The need for 'higher order' response types as the visual cues degrade was an important step in the development of handling qualities. As an example, for the pilot to experience level 1 handling in the degraded visual conditions of UCE3, the pilot should be able to command velocity directly – with the TRC (translational-rate-command) response type. The corollary is also likely to be the case. So a



UCE	Response types in hover/low speed flight
UCE 3	TRC + RCDH + RCHH + PH
UCE 2	ACAH + RCDH + RCHH + PH
UCE 1	RC

Response types

RC – rate command
TC – turn coordination (applies to yaw and pitch response)
ACAH – attitude command, attitude hold (roll and pitch)
RCDH – rate command, direction hold (yaw)
RCHH – rate command, height hold (heave)
PH – position hold (horizontal plane)
TRC – translational rate command

Figure 27. The usable cue environment chart; descriptors for the visual cue ratings and required response types to confer Level 1 handling qualities.

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pilot flying a rate-command helicopter, designed to have level 1 handling in good visual conditions, is likely to experience level 2 handling as the UCE degrades to 2 and level 3 handling in UCE3. As with all subjective ratings scales, it was recognised that guidance would be needed to ensure consistency of results. Such guidance first started to appear in Ref. 47, and a selection are paraphrased below,

(*i*) Assign ratings based only on the ability to be precise and aggressive,
  (a) Use precision hover and vertical landing tasks as a measure of precision
  (b) Use the ability to stabilise quickly at the end of the pirouette, sidestep and acceleration/deceleration manoeuvres as a measure of aggressiveness.

(*ii*) Do not try to make a distinction between the aircraft dynamics and the visual cueing environment that is being evaluated.

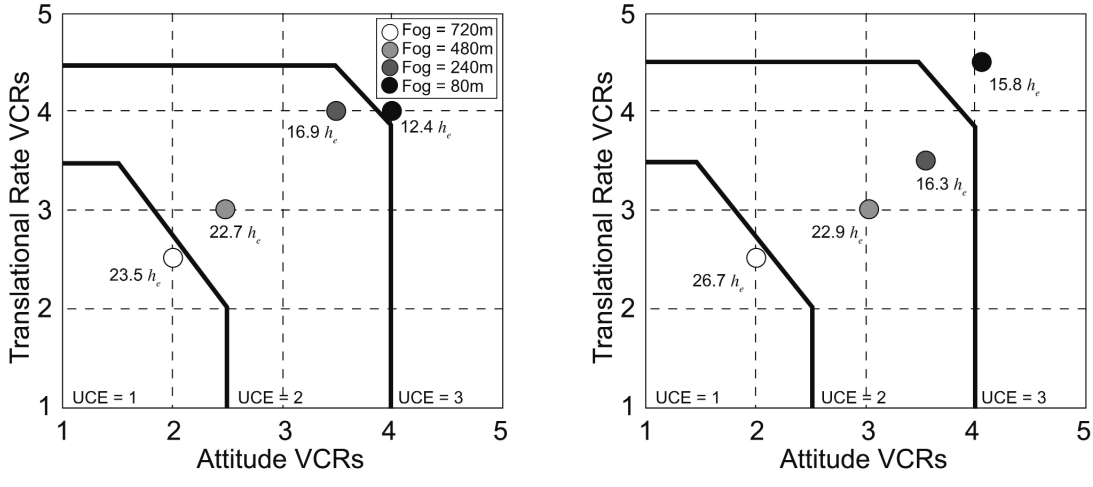
(*iii*) Try to meet the desired performance standards for most of the manoeuvre; an inability to aggressively correct back to the desired region without exciting undesirable aircraft excursions or oscillations should be cause to consider the fair-to-poor regions of the scale.

(*iv*) The inability to achieve good VCRs can usually be traced back to a lack of visible details and should not be related to the inability to see obstructions soon enough.

So the pilot's attention should be focussed on how precise and how aggressive he or she could be and the inability to see obstructions 'soon enough' because of cockpit restrictions should not influence the VCRs. None of the MTEs used for UCE capture involved obstacle avoidance so the issue of whether the pilot could or could not see obstructions in the flight path would never be an issue. What the translational rate VCRs do relate to is the pilot's ability to use the visual information in the control of horizontal and vertical velocity. This author interprets the 'visible details' referred to in point (*iv*). above as the optical flow on the surfaces around the aircraft as it moves. The optical flow contains both spatial and temporal range and range rate information but the premise of the author's research is that τ and its derivatives provide the fundamental 'cues' and hence should have a relationship with VCRs and the UCE.

For safe flight in conditions where a pilot cannot see the surface or obstacles with their naked eyes, the design approach involves using a vision aid to provide information to a level of UCE 2 or, at worst, UCE 3, then to assure level 1 handling by tailoring the response characteristics appropriately. By the early 1990s this construct had become 'established' in a formal test procedure but had not been fully validated in application. In fact, the first formal assessments conducted in the US LHX competition were undertaken in ground-based piloted simulation and the facilities used were not considered of sufficiently high fidelity to provide a UCE 1 in good/day visual conditions. At the same time research was continuing into what cues the pilot used, essentially the functional content of the UCE, and how these might be re-created artificially in the development of vision systems that took advantage of emerging sensor and display technologies. Research on this theme was informed by the results from a NASA Human Factors workshop in 1989, where Gibson's optical flow featured in several contributions. Within the published output, NASA CP 3118[54], it was noted that one of the central debates of the workshop was '*whether human visual perception was anchored to retinal or optical arrays or frames of reference*'; no strong conclusions were drawn on these fundamental questions nor, indeed, on how useful visual information might be quantified. A Rotorcraft Flying Qualities/Human Factors Conference held in 1993 brought the engineering and human factors communities together to compare perspectives and address the growing need for an integrated approach to the design of piloting aids[55]. This was the third of four such conferences that were held over a 25 year period (1983-2008) to review progress on the rapidly developing discipline of rotorcraft handling qualities, reporting on the maturity of design methods and emerging technologies, but the first that purposefully brought the handling qualities and human factors communities together. In her paper[56] entitled '*Visual information for judging temporal range*' Mary Kaiser states '*we suggest that a temporal scaling of the external environment, i.e. gauging the time to reach a chosen waypoint at current vehicle speed, is a highly useful metric for the pilot. And, in fact, there is sufficient information in the optical flow to support such temporal metrics.*' Mary Kaiser noted that the first reference to time-to-contact (TTC) could be found in Fred Hoyle's novel '*The Black Cloud*' where the relationship between an approaching body's angular expansion and TTC was derived[57]. Reference 56 reported results on (passive) observers' judgements of time-to-pass for stars moving toward them on a vertical screen. The results supported the τ hypothesis but did not address control issues in gap-closing tasks. This was when author's attention was first drawn to optical flow and τ and again later when leading a team developing an evaluation methodology for technologies to support rotorcraft day-night all-weather operations[58]. Recurring questions were – what do pilots actually use for visual cues in the GVE, how might these be reconstructed artificially to support flight in the DVE, and how far ahead do sensors need to be able to 'see'? These fundamental questions needed fundamental research to answer, just as the UCE construct needed supporting research on the contributions to visual perception in flight. Reference 43 was the first open publication on results from this fundamental work, initiated by the author in 1998.

Having established a plausible model for flight control in the good visual environment (GVE), based on pilots following τ-guides,



(a) Climb Manoeuvre (b) Turn Manoeuvre

Figure 28. Usable cue environment results for climb and turn manoeuvres.

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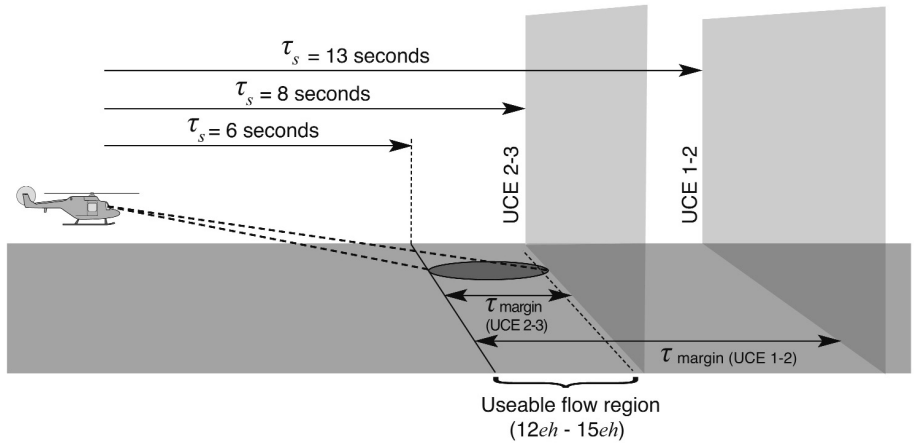


Figure 29. A suggested relationship between UCE and τ for safe margins of flight.

attention turned to how the guide-following might deteriorate as the visual conditions degraded. Gary Clark addressed this question in his PhD research, as described previously, but Gary also asked the question – can the UCE construct be re-cast in terms of τ? In particular, how far ahead of the aircraft does the pilot seek out information to ensure safe guidance? The results of his PhD study go some way to providing an answer and the title of our paper '*How long do pilots look forward...?*'[34] highlights that the focus of attention here was prospective control and τ, not distance. In his PhD thesis[35], Gary Clark presents a comprehensive set of VCR results for pilots flying the stopping, turning and climbing manoeuvres in a wide range of visual conditions, degraded by fog, as well as reductions in both surface micro-textures and macro-textures. The approach extended the UCE methodology in a similar way to the so-called SIMDUCE (SIMulated Day UCE) technique reported in Ref. 47. The aircraft used was the FLIGHTLAB Generic Rotorcraft (FGR; UH-60 like) with stability and control augmentation to confer Level 1 handling qualities in the GVE.

Figure 28 summarises the UCE results for the climb and turn manoeuvres, with fog obscuration increasing as visibility reduces to an extreme level of 80m. The pilot's ability to use both the translational rate and attitude visual information (to be precise and aggressive) degrades fairly uniformly as the fog increases in intensity. In the Figures, the eye-height distance to the fog is shown for each case and the results are similar for both manoeuvres. The reader should recall that the pilot was allowed to select the speed and height appropriate to each case. In the event, the pilot elected to fly at speeds between 2 and 2·5 eye-heights/sec in all cases, while the inertial velocity varied between 10 and 50ms^{-1} .

As expected, the UCE degraded as the obscuration increased, from 1 (720m fog line) to 2 (480m fog line) and 3 (80 < fog-line < 240m). In the worst conditions of UCE = 3, the pilot was still able to pick up information 12-15 eye-heights ahead or 5-6 seconds temporal range, but with a margin of less than 1 second. This suggests a UCE temporal metric related to the margin beyond the point where the pilot naturally picks up visual information. In Ref. 11, Perrone noted that in '*practical complex situations*', pilots might start to pick up velocity cues at a threshold of 40 minutes of arc/sec, so that '*...absolute velocity information is becoming sub-threshold at about 15 to 16 eye-height units away*'. The experiments conducted in the Bibby HELIFLIGHT simulator at Liverpool suggested a slightly reduced threshold of 12 to 15 eye-heights, but that could arguably be explained by the poorer surface textures in the simulator compare with the real world.

The results are summarised in a suggested relationship between UCE and τ illustrated in Fig. 29; here τ_s is the instantaneous time to pass over the surface ahead of the aircraft. Note that this only applies to the picking up of information related to translational rate motions, and the pilot's ability to correct such, with precision and aggression. The nominal (subjective) velocity is 2 eye-heights/sec. The results suggest that pilots need a τ_s margin for safety and will fly at a height and speed to give this. When this margin reduces to 6 seconds, the pilot no longer considers it safe. The margin to the UCE 2-3 boundary is then a further 2 seconds (τ_s = 8 seconds) and, to the UCE 1-2 boundary, a further 5 seconds (τ_s = 13 seconds) as shown in the figure. We hypothesise that the usable range of optical flow, where the pilot picks up the optical flow and τ_s information is between 12-15 eye-heights temporal range, giving the pilot 6 to 7·5 seconds temporal range with gaze depression angles of 4·9 to 3·8°.

The usable cue environment construct was developed to aid in the design of integrated control and vision guidance and several publications provide data to support its veracity[59-62]. The human element, the pilot, while amazingly adaptable, is also particularly vulnerable in a degraded visual environment as accident statistics suggest. Modelling pilot behaviour is a continuing area of study and the place of τ in this development is the next topic.

4.2 τ in pilot-vehicle 'system' modelling

As engineers we are drawn to creating simulation models to help us to analyse, describe and hence understand the behaviour of systems, in response to control inputs, to internal malfunctions and external disturbances. We build models to support decision making in design, to trouble-shoot in development and to provide insight into the causes and effects of accidents and incidents. These models are always approximations of reality with some limited range of application, linked to underlying assumptions, even when the governing laws of physics are well understood, as with aircraft dynamics. One might expect models of the aircraft and pilot combination to be more complex but amazing successes have been achieved with relatively simple models that take advantage of the pilot's actions that effectively suppress natural aircraft dynamics. Such models have become critical to the design and development of pilot-vehicle interface technologies and other aspects of handling qualities engineering. There is a substantial history to the development and successful application of integrated pilot-vehicle models. The place of optical τ in this story is not yet established but here are reported some limited success at new interpretations of established ideas and applications.

The origins of an organised hierarchical approach to flight control, within which a model of the pilot might be created, can be found in the early work of McRuer and colleagues, and it is helpful to the introduction of τ into pilot modelling to build from here. In a paper published in 1960[6], the Successive Organisation of Perception (SOP) framework was introduced and opened a new perspective on flight control. To quote, '*It is the thesis of this paper that eye-hand coordination skill development may be idealised as a progression from a compensatory display organisation through a pursuit type organisation culminating in an open-loop response, as the result of a stimulus organisation internal to the operator.*' The authors continue,

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... '*The culminating stage in this progression occurs when the operator is able to detect and take advantage of all of the internal coherence and predictability of his input signal (the error). In this case, depending on the extent of the input signal's internal coherence, the operator can accomplish total prediction for varying intervals of time.* ***The central nervous system may be thought of as generating this predicted signal to command the neuromuscular system.***' The author has emboldened the last sentence to draw attention to the early awareness of the idea of the pilot self-generating signals. The paper continues,.. *'Thus the operator demonstrates his capacity, based on a priori knowledge, effectively to enrich his stimulus input and to diminish his requirements for the display of the complete stimulus. As the predicted motion drifts off or the input signal is changed, the operator retraces his steps through at least the pursuit mode, and 'corrects' his 'predictor' to get back into the precognitive mode.'*

'*Something akin to the precognitive mode for perfectly predictable stimuli appears in other situations where the operator has thoroughly 'learned' his inputs and, by experience, seems to provide exactly the required output. Examples of this 'total prediction' are a helmsman's ability in 'meeting' a turning ship... Other skilled activities, like catching a ball and tagging a base runner in one continuous motion, counter-punching, serving a tennis ball, etc., are similar examples.*' Reference 6 concludes,... '*The SOP model, properly elaborated, provides a basis for specifying both the process by which a human operator develops a motor skill as well as the ultimate level of proficiency which can be attained.*'

SOP was proposed as a learning theory with a pilot applying compensatory (closed-loop) stabilisation to counter unpredictable disturbances, pursuit guidance (mix of open- and closed-loop) to follow defined motions and pre-learned, open-loop commands to change state. The intellectual novelty in this approach is striking and, understandably, the SOP approach has had a profound influence on the development of pilot-vehicle modelling[5,63]. It also forms a suitable framework in which to place the τ of flight control. The premise of this paper is that the skill involved in following τ guides is fundamentally a previously learned response to closing gaps. The guide following may appear as open-loop responses, but τ-theory posits that the pilot is continually closing the loop by sensing the τ of the gap and cancelling the error between τ_x and $k\tau_g$. But there is also an interpretation of guide following as a classical proportional-derivative feedback control model of pilot action, which is now examined.

Pilots develop skills by practising, by building the mental models of motion patterns and associated guides and, as such, any training practices (*ab-initio*, recurrent or conversion) must be sufficiently realistic that these skills can be readily transferred to operations. One of the applications of pilot-vehicle modelling, championed by, amongst others, Robert Heffley, is in support of the qualification and validation of training simulators. In a series of papers some 30 years ago, Heffley and co-authors reported the results of a study into the effectiveness of flight simulators for training pilots to land commercial transport aircraft[41]. Results from this work have already been presented earlier (Figs 13 and 14), but Heffley was also able to quantify the changes to pilot control strategy in the simulator compared with flight, by creating a model of the pilot-vehicle system, matching with the test data, and noting the differences in key parameters such as closed-loop bandwidth and phase margin[40,64]. The study recognised that the phase plane portraits for the final approach and flare had the curious appearance of the open-loop response of a second order dynamic system. The combined pilot-vehicle behaviour then took the form of an initial value problem, with h the height gap and $\dot{h}$ the sink rate (subscript *FL* refers to the flare.),

$$\ddot{h} + 2\zeta_{FL}\omega_{FL}\dot{h} + \omega_{FL}^2 h = 0 \qquad \ldots (18)$$

where ζ_{FL} and ω_{FL} are the closed-loop damping ratio and natural frequency. Combining this model with an approximate model of the dynamic response of the aircraft to elevator commands leads to an approximation of pilot strategy as a feedback controller of height and height rate, with gains k_h and $k_{\dot{h}}$, assumed constant during the flare.

$$\theta = -k_h h - k_{\dot{h}}\dot{h}$$

$$k_h = \frac{\omega_{FL}^2 - \omega_p^2}{U} T_{\theta_2} \quad k_{\dot{h}} = \frac{2\zeta_{FL}\omega_{FL}T_{\theta_2} - \frac{T_{\theta_2}}{T_{\theta_1}} - 1}{U} \qquad \ldots (19)$$

The expressions for the pilot gains include the aircraft dynamic parameters (T_{θ_1}, T_{θ_2} – time lags in flight path and speed response to aircraft pitch changes, U – the flight speed, ω_p– the frequency of the phugoid mode), in addition to the closed-loop system characteristics. The parameter identification process adopted in Ref. 40 involved finding a best fit of the measured time histories with the model Equation (18), and deriving the pilot gains from Equation (19). In Ref. 40, Heffley postulates several mechanisms for the pilot picking up the cues to be able to adopt the proportional-derivative (PD) control strategy in Equation (19), e.g. the perception of the instantaneous flight path angle detected from the 'focus of expansion of streamers', combined with 'the pilot-centred generation of height time derivative, i.e. a first order lead compensation'. In matching the closed-loop model to the flight data it was noted that the shape of the flare trajectory was mainly a function of natural frequency ω_{FL}, while the proportion of sink rate reduction was mainly a function of the relative damping ζ_{FL}. Reference 41 includes a comprehensive analysis of flare manoeuvres in the various groupings described earlier (Fig. 14 e.g. check flights by pilots trained in flight or trained in the simulator). In his thesis, Mike Jump presents a τ analysis of the flare data showing, amongst other things, the absence of the 'τ pausing' (or what Heffley calls the 'duck-under' technique), just before touchdown by the simulator trained, Type 2, pilots and the consequent hard landings[36]. Reference 41 concludes that flight-trained pilots tend to be more aggressive and decisive in the flare (larger ω_{FL}) while simulator trained pilots experience greater loss of speed margin and higher sink rates. The lower relative damping estimated for the simulator-trained pilots resulted from lower sink rate gains ($k_{\dot{h}}$) and an overall longer pilot lag in response to flare cues. Reference 41 concluded that, 'The simulator does not appear to be supporting the generation of effective lead compensation'. Poor surface visual resolution and system delays were suggested as contributory factors, noting that this research was undertaken more than 30 years ago.

In Ref. 64 Heffley extended this work to examine integrated pilot-vehicle models for helicopter manoeuvres, including the quick-stop. During an aggressive quick-stop, pilot gains of 0·2deg/kt and 1deg/ft (pitch attitude to range rate and range), were estimated from flight test data for a model of pilot range control, corresponding to a closed-loop relative damping and natural frequency of 0·7/sec and 0·8rad/sec respectively. Heffley noted that this corresponds to an 'extraordinary high bandwidth for an *x*-axis task', and suggests an open-loop pitch attitude bandwidth requirement of about 2·5 rad/sec. The minimum bandwidth requirement for tracking tasks in ADS-33 would later be set at 2rad/sec[43]. In the same paper, Heffley drew attention to comparative results from a training simulator where the pilot control strategy was modelled with significantly reduced range (practically 0deg/ft) and range rate (0·2deg/kt) gains. Visual system deficiencies were again included in the potential causes of the significantly reduced aggressiveness recorded in simulation.

These results formed the starting point for an investigation by the present author into what we describe as the adaptive pilot model (APM), for complete manoeuvres. In Heffley's work, with perhaps one exception (where the pilot gain was a function of perceived range), the pilot model gains were fixed and while this may be a reasonable assumption for manoeuvres that last only a few seconds, complete acceleration-deceleration manoeuvres are likely to feature large variations in closed-loop frequency and damping, in part due to the pilot adapting to the changing 'cues', the evolving task requirements and varying vehicle dynamics. The author introduced the APM in Ref. 65 and Robert Armstrong, in his PhD study, later extended the work by transforming the APM structure into the τ domain[66,67].

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The general hypothesis behind the APM is that the pilot acts to transform the complex coupled aircraft-pilot system to a much simpler relationship between command and output. In the acceleration-deceleration manoeuvre, for example, the pilot initiates the manoeuvre from a hover in response to the range command R_c and finishes in a new hover when the error (R_c-R) is reduced to zero (Fig. 30). The distance to stop is defined as $-x$.

In Fig. 31, portraying the closed-loop control scheme, θ_c is the commanded pitch attitude and θ is the current pitch attitude.

A transfer function representation is used for convenience at this stage, recognising that the nonlinear, time-dependent nature of the APM, and its τ manifestation, precludes this approach. In a similar way to Heffley's flare model, the pilot guidance transfer function Y_{PR} is assumed to take the form of proportional and rate feedback (K_R and $K_{\dot{R}}$), but in this case on range error,

$$Y_{PR} = -K_R - K_{\dot{R}}s \qquad \ldots (20)$$

The transfer function $Y_{P\theta}$ represents the stabilisation function of the pilot-aircraft system, the short-term pitch dynamics, and is assumed to take the form of a first order lag with time constant τ_θ,

$$Y_{P\theta} = \frac{1}{1+\tau_\theta s} \qquad \ldots (21)$$

The aircraft transfer function between range and pitch attitude is approximated in first order form, including the drag derivative X_u,

$$Y_{A\theta} = \frac{-g}{s(s-X_u)} \qquad \ldots (22)$$

Bringing these together, the open-loop transfer function between range error and range is then given by,

$$Y = Y_{PR}\, Y_{P\theta}\, Y_{A\theta} = -\frac{g}{s(s-X_u)}\frac{1}{(1+\tau_\theta s)}\left(K_R + K_{\dot{R}}s\right) \qquad \ldots (23)$$

The dynamics of the free response of the system to a displaced initial range are defined by the solutions to the equation $1 + Y = 0$,

$$\frac{s^3}{\omega_\theta} + \left(1 - \frac{X_u}{\omega_\theta}\right)s^2 + \left(gK_{\dot{R}} - X_u\right)s + gK_R = 0 \qquad \ldots (24)$$

Applying the further approximation that the closed-loop attitude dynamics are much faster than the translational dynamics (i.e. stabilisation much faster than guidance), and that $\omega_\theta >> -X_u$, so that a constant pitch attitude gives a constant acceleration or deceleration, the system reduces to 2nd order form,

$$s^2 + 2\zeta_R\omega_R\, s + \omega_R{}^2 = 0 \qquad \ldots (25)$$

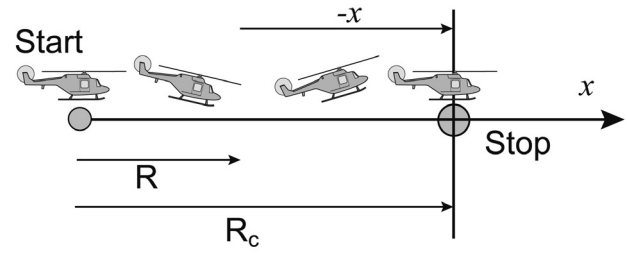


Figure 30. Kinematics of the acceleration-deceleration manoeuvre.

The pilot gains are related to the natural frequency ω_R and damping ratio ζ_R by the expressions,

$$K_{\dot{R}} \approx \frac{2\zeta_R\omega_R}{g} \qquad K_R \approx \frac{\omega_R^2}{g} \qquad \ldots (26)$$

Expressed as an initial value problem in terms of the distance to go, the APM takes the form;

$$\frac{d^2x}{dt^2} + 2\zeta_x\omega_x\frac{dx}{dt} + \omega_x{}^2\, x = 0, \qquad x(0) = -R_c \qquad \ldots (27)$$

The procedure for estimating the pilot gains and closed-loop system parameters can then follow Heffley's method; this is returned to later. At this point we have restricted the analysis to motions where the system natural frequency ω_x and relative damping ζ_R are constant. In general there is no reason why they should be of course and the pilot's adaptation can be captured by variations in these system parameters. The model can also be expressed in terms of the time to stop in the manoeuvre, $\tau_x(t)$ where as usual,

$$\tau_x(t) = \frac{x}{\dot{x}} \qquad \dot{\tau}_x = 1 - \frac{x\ddot{x}}{\dot{x}^2} \qquad \ldots (28)$$

Multiplying Equation (27) by $x/\dot{x}^2$ and combining with Equation (28), the APM can be written in the form,

$$\frac{x\ddot{x}}{\dot{x}^2} = 1 - \dot{\tau} = -2\zeta_x(\omega_x\tau) - (\omega_x\tau)^2 \qquad \ldots (29)$$

or,

$$\dot{\tau} - 1 = 2\zeta_x(\omega_x\tau) + (\omega_x\tau)^2 \qquad \ldots (30)$$

The quadratic relationship in this first order non-linear differential equation in τ holds for the whole manoeuvre. Treated as an algebraic equation, the general solution is given by,

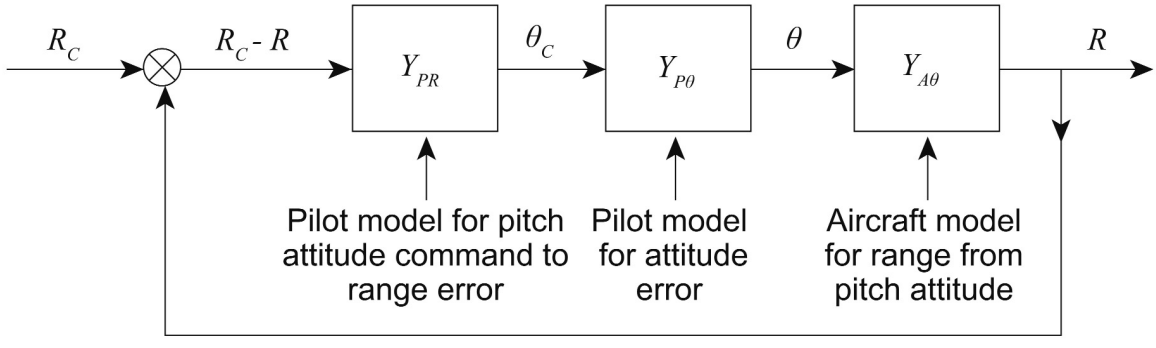


Figure 31. Closed-loop control of aircraft range.

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$$\omega_x \tau = -\zeta_x \pm \sqrt{\zeta_x^2 + (\dot{\tau} - 1)} \qquad \ldots (31)$$

These relationships are independent of the nature of the τ-guide following and apply to any longitudinal manoeuvre where pitch attitude changes are more rapid than speed and range changes. In the special case of a deceleration with constant $\dot{\tau}$ and constant relative damping, the closed-loop bandwidth increases inversely proportional to τ, as the stopping point is approached, eventually requiring infinite pilot gain. The solution to Equation (31) is shown in Fig. 32, for various values of damping ratio ζ_x.

It is worth pausing at this point to examine some features of these variations and their physical implications.

a) When $(\dot{\tau} - 1) > 0$, the aircraft is in the acceleration phase; when $(\dot{\tau} - 1) < 0$, the aircraft is decelerating towards the stop

b) If the damping ratio is constant, the manoeuvre will follow one of the trajectories shown and the pilot gains are only a function of the natural frequency ω_x.

c) When $\dot{\tau} = 1$, $\tau = -\frac{2\zeta_x}{\omega_x}$, occurring at the transition between the acceleration and deceleration

d) $\dot{\tau}$ reaches a minimum value during the deceleration ($\dot{\tau} = 1 - \zeta_x^2$) when $\omega_x \tau = -\zeta_x$ increasing to 1 again at the stop point.

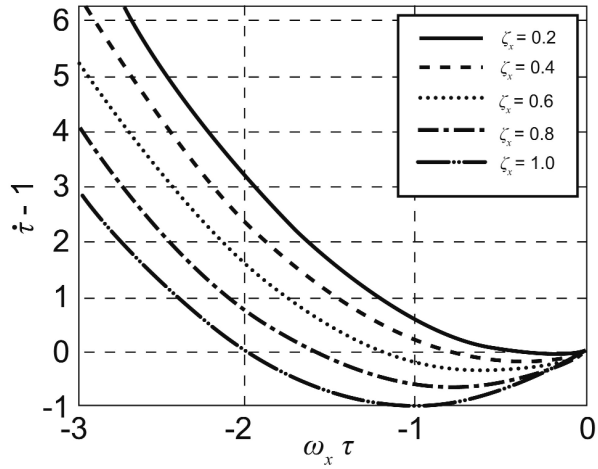


Figure 32. Motion profiles for the accel-decel manoeuvre in the τ-domain.

Earlier in the paper it was shown that pilots can fly an acceleration-deceleration manoeuvre by following a constant acceleration τ guide given by,

$$\tau_g = \frac{1}{2}\left(t - \frac{T^2}{t}\right) \quad \text{and} \quad \dot{\tau}_g = \frac{1}{2}\left(1 + \left(\frac{T}{t}\right)^2\right) \qquad \ldots (32)$$

such that,

$$\tau_x = k\tau_g \qquad \ldots (33)$$

Combining these relationships with the dynamic model of the pilot-vehicle system enables us to examine the nature of the variations in system frequency and damping, and corresponding pilot gains, during the manoeuvre for control strategies that follow τ_g. In the very initial stages of the manoeuvre, when $t << T$, an approximation for the natural frequency can be written as,

$$\omega_x \approx -\frac{\sqrt{\dot{\tau}}}{\tau} \approx \frac{1}{T}\sqrt{\frac{2}{k}} \qquad \ldots (34)$$

indicating that the initial closed-loop natural frequency is inversely proportional to the manoeuvre time. One might intuitively expect something like this, as the effective spring need not be strong if T is large; the commanded pitch angle would then need to be unrealistically large. If the τ-coupling is weak (k small, stronger K_x), then the pilot has elected to accelerate more rapidly initially, reaching the maximum velocity early in the manoeuvre, hence the inverse scaling with the coupling coefficient k. If we assume $T = 20$ seconds and $k = 0{\cdot}3$ (values typical of an accel-decel), then $\omega_x(0) = 0{\cdot}13$rad/sec. The results suggest that the pilot may adopt a strategy that keeps the positional gain constant (frequency remains constant) during the acceleration phase and then stiffens to a maximum as the hover is approached. At the singular point when the acceleration ends and the deceleration begins we can derive the relationship between frequency and damping,

$$\omega_x \tau = -2\zeta_x = -\frac{K_{\dot{x}}}{K_x}\omega_x \qquad \ldots (35)$$

At the reversal, the accelerative and braking components are equal and opposite, and the time that this occurs can be derived as a function of k,

$$\dot{\tau}_x = \frac{k}{2}\left(1 + \left(\frac{T}{t_r}\right)^2\right) = 1 \qquad \text{or} \qquad t_r = \sqrt{\frac{k}{2-k}}\,T \qquad \ldots (36)$$

Thus when $k = 0{\cdot}2$, $t_r = 0{\cdot}333T$, when $k = 0{\cdot}4$, $t_r = 0{\cdot}5T$ and when $k = 0{\cdot}6$, $t_r = 0{\cdot}67T$, etc.

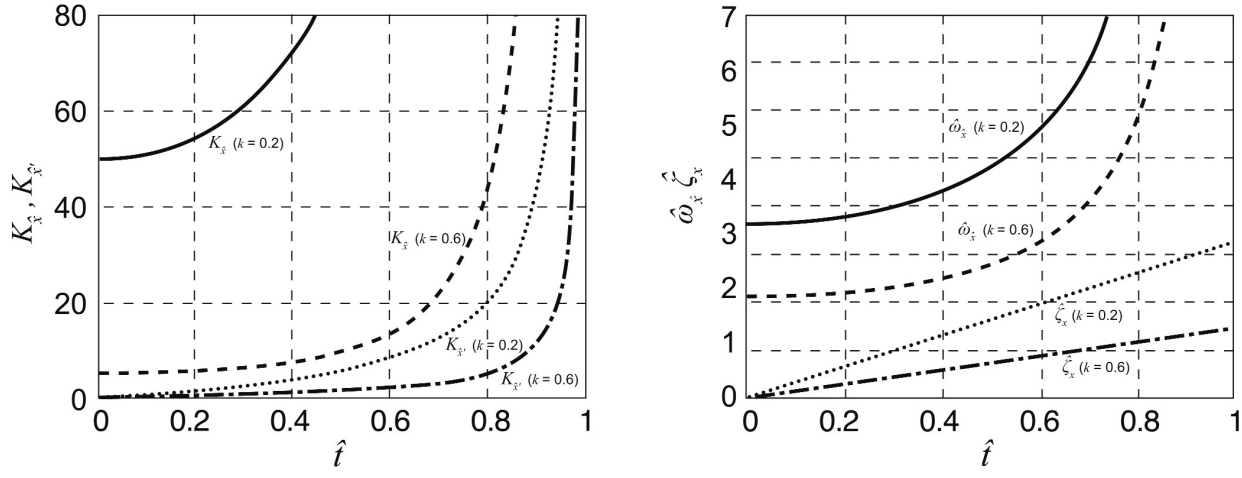


Figure 33. Variation of pilot gains with normalised manoeuvre time.

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The variation of ω and ζ for motion following the constant acceleration τ_g can be derived from the motion profiles in Table 1. The acceleration/deceleration is given in normalised form by,

$$\hat{x}''=-\frac{2}{k}\left[(\frac{2}{k}-1)\hat{t}^2-1\right](1-\hat{t}^2)^{(\frac{1}{k}-2)} \quad \ldots (37)$$

Following Heffley's approach, assuming a proportional-derivative feedback,

$$\hat{x}''=K_{\hat{x}}\,\hat{x}+K_{\hat{x}'}\,\hat{x}' \quad \ldots (38)$$

$$K_{\hat{x}}=T^2K_x \qquad K_{\hat{x}'}=T\,K_{\dot{x}}$$

The gains can be written as a function of k and normalised manoeuvre time $\hat{t}$.

$$K_{\hat{x}}=-\frac{2}{k(1-\hat{t}^2)^2} \quad \ldots (39)$$

$$K_{\hat{x}'}=-(\frac{2}{k}-1)\frac{\hat{t}}{(1-\hat{t}^2)} \quad \ldots (40)$$

Time and distance have been normalised, in the usual way, by the manoeuvre duration and distance respectively. It follows that,

$$\hat{\omega}_{\hat{x}}=T\,\omega_x=\sqrt{\frac{2}{k}}\,\frac{1}{(1-\hat{t}^2)} \quad \ldots (41)$$

$$\hat{\zeta}_{\hat{x}}=\zeta_x=\sqrt{\frac{k}{2}}\,(\frac{2}{k}-1)\hat{t} \quad \ldots (42)$$

Figure 33 shows the variations in the pilot gains, frequency and damping ratio as a function of normalised manoeuvre time for different τ – coupling k.

Both pilot gains increase gradually during the acceleration and rise to infinity at the stop. The system natural frequency mirrors this variation while the relative damping is predicted to increase linearly throughout the manoeuvre. Referring back to Heffley's results in Ref. 64, for a 20 second accel-decel, the quoted value of ω_x of 0·8 rad/sec corresponds to $\hat{\omega}_{\dot{x}}$ = 16 , consistent with the values shown in Fig. 33 in the closing stages of the manoeuvre.

Robert Armstrong applied this modelling analysis to flight and simulation test results for a Bo105 helicopter (Fig. 34). The simulation tests were conducted in the Bibby HELIFLIGHT simulator at Liverpool (Fig. 3). Typical results for the pitch attitude variation during the acceleration-deceleration manoeuvre are shown in Fig. 35. The ADS-33 accel-decel mission task element is designed to assess handling qualities during '...aggressive maneuvering near the rotorcraft limits of performance', with maximum power achieved within 1·5 seconds of the launch and 30deg nose up attitude achieved during the deceleration. Pilots tended to be more aggressive in flight, using far larger pitch angles, as shown in Fig. 35. In HELIFLIGHT, pilots were only prepared to use a maximum/minimum pitch angle of +/–20°; beyond this they lost important information in the vertical field of view.

As part of his research into simulation fidelity, Robert Armstrong evaluated the impact of visual cues (micro and macro-textures) on the pilot performance and workload and on the degree of τ-coupling during the manoeuvre. Figure 36 presents a summary of some of the results from Ref. 67. As the visual information degraded (UCE from 1 to 2 to 3), the coupling k increased from 0·29 to 0·36, indicating the pilot electing to delay the transition to deceleration until later in the manoeuvre (k = 0·4 corresponds to reversal at the half way point). This delay is assumed to stem from the loss of visual information leading the pilot to slow down as UCE degraded, but initiating the deceleration at a similar value of τ (8-9 seconds). The flight test data show a much higher coupling, with k = 0·63, associated with the higher level of aggressiveness adopted on the controls. In all cases the correlation coefficient was high enough to distil confidence that the τ_g following was a good model of the strategy. The hypothesis



Figure 34. The DLR experimental Bo105, S-123.

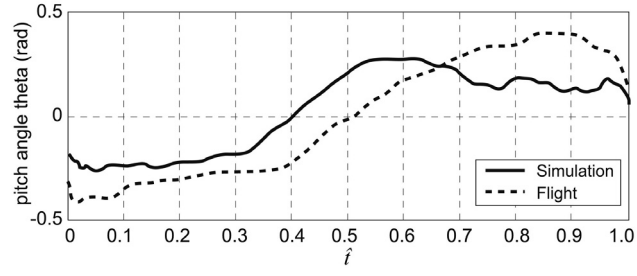


Figure 35. Comparison of pitch angle variations in simulator and flight test for the Bo105 during the acceleration-deceleration manoeuvre[66].

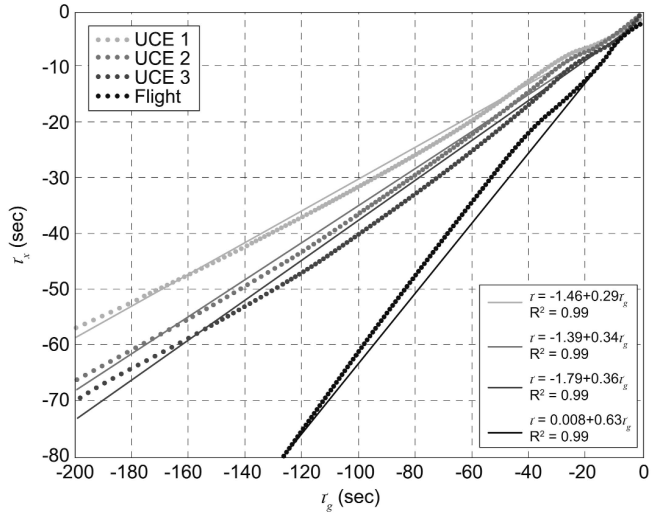


Figure 36. Variations of τ_x with constant acceleration τ_g for the Bo105 in an accel-decel manoeuvre showing the effect of UCE on the strength of the coupling in simulation and flight test[67].

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Figure 37. The Canadian Flight Research Laboratory ASRA Bell412 in-flight simulator in the closing moments of the acceleration-deceleration manoeuvre.

prior to the tests was that the trend of decreasing coupling with improving visual flow information would be reflected in flight so the distinctly opposite trend was a surprise. The value of τ at the reversal was much lower in flight (≈5 seconds) than simulation and it appears that the increased aggressiveness in flight was accompanied by increased confidence that the deceleration could be delayed, and a higher pitch angle used in the deceleration. Robert Armstrong concluded that the resulting δk between flight and simulation (≈0·3) indicated poor fidelity of HELIFLIGHT for the ADS-33 accel-decel manoeuvre where pitch angles > 20° are required.

The accel-decel manoeuvres reported by Robert Armstrong in his thesis and in Ref. 66, have since been repeated using the HELIFLIGHT-R simulator at Liverpool (Fig. 3), a facility with significantly increased field of view, both horizontally and vertically, and motion base travel[14]. The tests were conducted as part of a collaboration on flight control and simulation fidelity between the Flight Research Laboratory of the NRC Canada and the University of Liverpool's Flight Science Group using the Advanced Systems Research Aircraft (ASRA) Bell-412 (Fig. 37) and the FLIGHTLAB F-B412 simulation model[68]. Some of the results of this collaboration have already been reported in Refs 69 and 70. Here are presented some of the comparative findings from the application of the APM to the accel-decel manoeuvre; the results were computed by researcher Philip Perfect as part of Liverpool's 'Lifting Standards' research project.

Figure 38 shows a typical comparison for the aircraft's longitudinal velocity and pitch angle as a function of normalised time. Both flight and simulator are flown by the same test pilot and the comparison shows that the pilot is essentially using the same strategy – a nose down pitch attitude of 10°, giving a fairly constant acceleration for the first 40% of the manoeuvre to a velocity of about 35kt, followed by a rapid pitch reversal and gradual deceleration with peak pitch attitude of about 20°, prior to stopping. The guidance profile is augmented by a higher frequency, stabilisation, component visible in the pitch attitude.

A similar τ-analysis was applied by Philip Perfect at Liverpool to the B-412 data as previously shown for the Bo105 and the temporal APM results are shown in Fig. 39. The coupling constants from flight and simulation are practically identical and slightly lower than the flight results obtained with the Bo105 (0·63). The closed-loop APM natural frequency (shown in physical units) increases to 1·0rad/sec and higher in the last 10% of the manoeuvre with the damping rising beyond critical to about 1·4/sec. The pilot is 'braking' hard as the aircraft pitch stays high until the very last moment. With the close agreement between flight and simulation, the results confirm the higher fidelity of the HELIFLIGHT-R simulator.

The adaptive pilot model in its 3rd order form (Equation (23)) has the potential to be able to model both guidance and stabilisation components during a manoeuvre like the accel-decel. This is the topic of ongoing research that holds a promise of fully integrating τ control into the 'successive organisation of perception' framework. To accomplish this we need to reconcile the guide-following feedback control hypothesised in τ-theory with the error absorbing integrator transfer function $G(s)$ in the established cross-over model of the combined pilot-vehicle, featuring a pilot gain K and time delay τ_d[5].

$$G(s)=\frac{K e^{-\tau_d s}}{s} \qquad \ldots (43)$$

As a first comparison of the cross-over model with the τ-model behaviour, it is useful to make the assumption that $\tau_d T << 1$ and examine the closed-loop transfer function in the form,

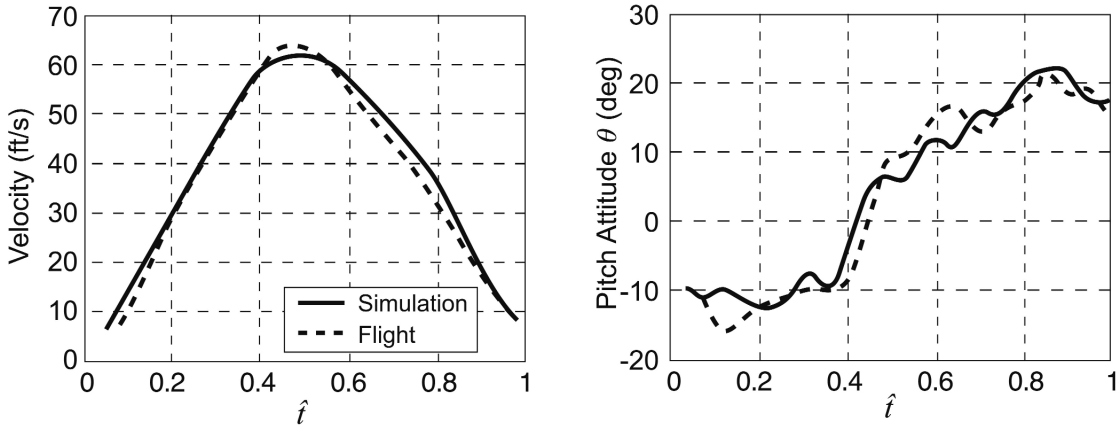


Figure 38. Velocity and pitch attitude profiles during an accel-decel manoeuvre for a Bell 412 in simulation and flight test.

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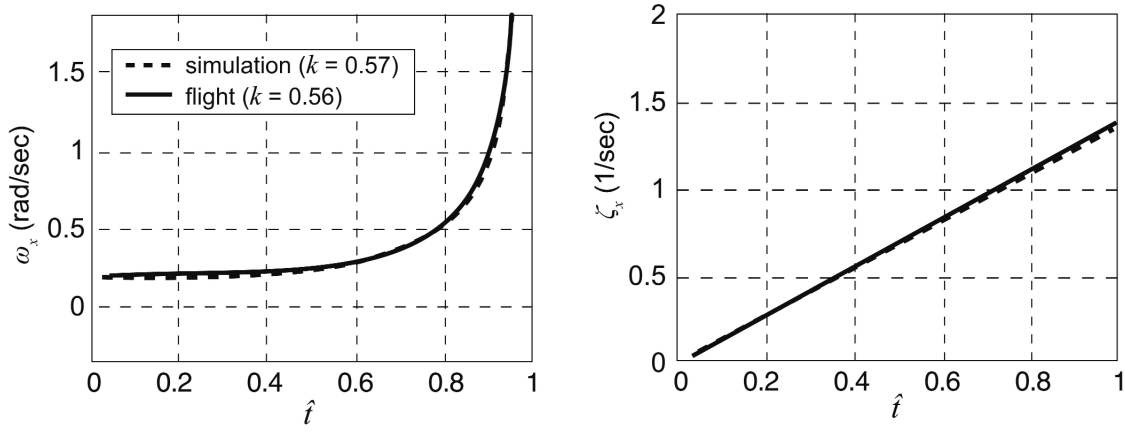


Figure 39. Flight and simulator comparative results for APM closed-loop natural frequency and relative damping; constant coupling parameter (flight k = 0·56, simulator k = 0·57).

$$G_{CL} \approx \frac{K}{s+K} \qquad \ldots (44)$$

and as the initial value problem,

$$\dot{x} - Kx = 0, \qquad x(0) = x_0 \qquad \ldots (45)$$

In the cross-over model the response subsides in exponential form, with gain $K = -1/\tau$. Constant τ implies the commanded value is never reached of course.

$$x(t) = x_0 e^{-Kt} \qquad \ldots (46)$$

In the τ model, the response subsides following the constant deceleration guide in the form,

$$x(t) = x(0)(1-\hat{t})^{2/k} \qquad \ldots (47)$$

When k = 1, the pilot gain initialises with the same value as that predicted by the cross-over model, but increases to infinity as $\hat{t} \to 1$.

$$K = \frac{2}{kT}(1-\hat{t})^{-1} \qquad \ldots (48)$$

Another of the author's PhD students at Liverpool, Helen Baker, investigated the application of the cross-over model to helicopter tracking tasks in hover and estimated values of K as high as 6 rad/sec, along with time delays of 300ms[71]. The tasks investigated by Helen included pitch tracking (stabilisation) imposed on longitudinal transitions (guidance). The pilot 'remnants' were sometimes more than 30% of the pilot's control activity but the analysis did not show this to be related to the guidance component. It is clear that a pilot needs to predict the future state of the aircraft for both guidance and stabilisation and continued research efforts to find a pilot-vehicle model that captures both will doubtless reap reward. This is particularly true for situations where the pilot gain and corresponding τ coupling increases to the point where closed-loop stability is threatened; initial results from a study into the modelling of pilot-induced-oscillations has been particularly fruitful and is described next.

4.3 τ in aircraft-pilot-couplings

The author began his research career with an investigation into the stability of aircraft under constraint as an undergraduate project under the supervision of Ronald Milne. Ronald had developed an elegant theory for the analysis of 'weakly coupled dynamical systems'[72], based on the partitioning of a system into a set of inter-connected sub-systems. The conditions for weak-coupling between the sub-systems related to the degree of separation of the natural modes on the one hand and the level of interaction or coupling between the sub-systems, on the other. We published the work in Ref. 3, illustrating how strong control by a pilot could lead to a separation of the constrained and unconstrained motions effectively into fast and slow modes and, in many cases, lead to the loss of stability in the slow mode. We showed how the theory was able to explain the build-up to limiting cases such as the loss of speed stability during an approach when the pilot applied high gain closing the flight path to elevator loop, and the nose-slice departure that can occur when pilots constrain bank angle with aileron during tracking tasks. These classic adverse aircraft-pilot couplings (APCs) had already been identified some years earlier by Neumark[73] and Pinsker[74] respectively at the Royal Aircraft Establishment, and approximation theory developed for, effectively, infinite gain situations. Reference 3 provided a general framework for explaining a class of aircraft-pilot couplings that could also be used to support the design of stability augmentation systems, where high gain can be troublesome in reducing stability margins of unconstrained modes. The destabilisation of the regressing lag mode as a result of high gains in the stability augmentation of rotorcraft is a topical example[75-78]. Reference 3, titled '*The Strongly Controlled Aircraft*' was published 40 years ago and the concept has been used extensively by the author in his applied research. During her PhD study, Beth Davidson[79] put the theory to the test in a series of pilot simulations to investigate a range of aircraft-pilot couplings including the two classic cases described above. At this time, Duane McRuer had completed a study for the US National Research Council and defined APCs in three categories[80]; weakly coupled system theory applied to Category I APCs, where the problem was essentially a linear one. Beth was also able to test a related hypothesis and theory which proposed that, in aggressive manoeuvring there might be a critical ratio between the pilot-aircraft 'bandwidth' and the task 'bandwidth' beyond which APCs might occur[1]. In a similar way to that expressed in Ref. 1, the pilot is unable to focus attention on one or two flight variables at the expense of others. Figure 40, from Ref. 79, summarises some of Beth's results for the F-UH60 flown in a slalom manoeuvre. The pilot awarded handling qualities ratings (HQRs) are plotted against the frequency ratio parameter (ω_ϕ / ω_t) where the aircraft frequency is given by,

$$\omega_\phi^{\,2} = 1/\tau_\beta \tau_p \qquad \ldots (49)$$

τ_β is the rotor flap time constant and τ_p is the roll time constant, and the task frequency for a single slalom is $\omega_t = 2\pi/T$. T is the task time. The trend lines have been drawn to pass through the HQ Level 2/3 boundary when $\omega_\phi/\omega_t = 6$, or $2n_v$ where n_v is the number of flight path commands required in a manoeuvre; in the case of the slalom $n_v = 3$.

Beth Davidson's research brought together several strands from the story of CAT I APCs but the underlying linear theory could not explain some of the more complex and nonlinear CAT II and CAT III APCs classified by McRuer. These are potentially more serious both in consequence and in the fact that they could remain hidden throughout design

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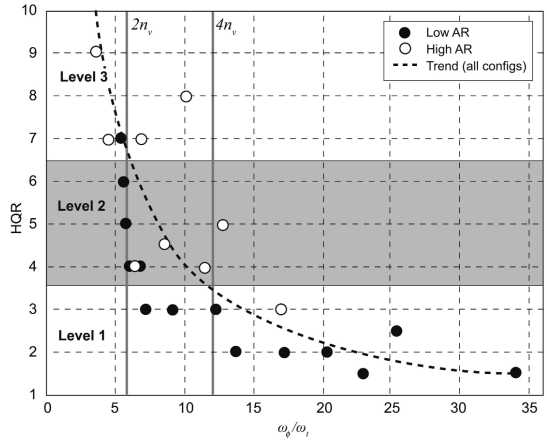


Figure 40. Variation in assigned handling qualities ratings (HQRs) for a F-UH60 flying a slalom manoeuvre as a function of aircraft/task frequency ratio[79].

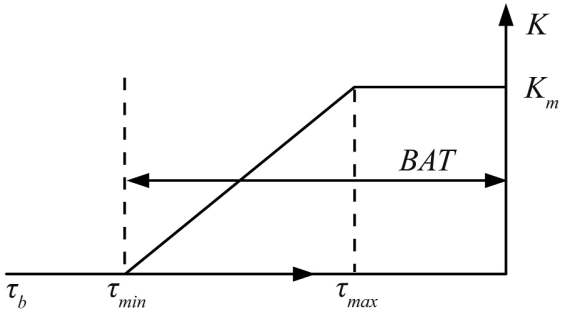


Figure 41. Variation of pilot gain K with time to contact the boundary τ_b during boundary avoidance tracking[81].

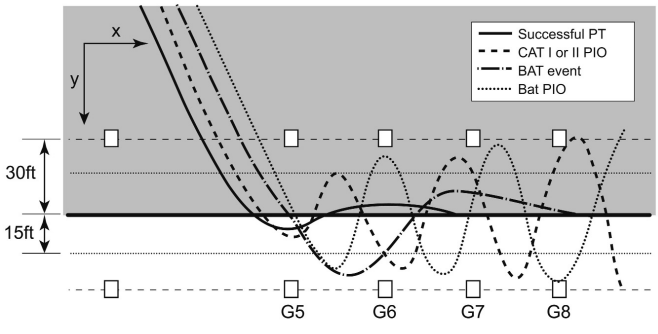


Figure 42. Possible tracking scenarios in the roll-step MTE[82].

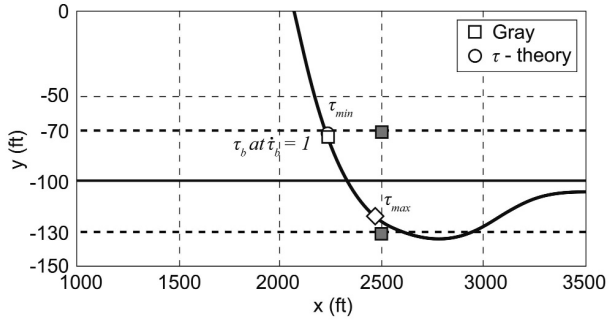


Figure 43. Plan view of the flight path showing location of τ values[82].

and development and perhaps not emerge until an operational pilot inadvertently found himself in that corner of the flight envelope. One such APC featured in the research undertaken by Bill Gray at the US Air Force Test Pilot School and reported in Ref. 81. From discussions with test pilots, Gray hypothesised that some APCs resulted from pilots attempting to avoid two opposing boundaries either side of the primary tracking task. In special circumstances pilots can find themselves 'locked' between two limits, e.g. departure and ground collision, when they exhibit behaviour manifested in large and rapid control reversals that are triggered by proximity to the boundaries. Curiously, the proximity did not appear to be critical and the rapidly developing boundary-avoidance-tracking (BAT) pilot-induced-oscillation, could not be explained by theories associated with CAT I or CAT II APCs. In Ref. 81, Gray noted that, '*...a boundary-avoidance PIO could quickly arise from a disturbance large enough to assault one of the boundaries, provided the boundaries were sufficiently tight and/or the increase in gain brought by boundary-avoidance tracking was sufficiently greater than the gain for the point-tracking task*'. Gray developed a control model that described this extreme pilot behaviour with a ramp bang-bang strategy by the pilot with the critical variable as the time to contact the boundary, τ_b.

$$K = \frac{\tau_b - \tau_{\min}}{\tau_{\max} - \tau_{\min}} K_m \qquad \ldots (50)$$

K is the pilot gain, with K_m as the maximum value, often defined by the control stops; τ_{min} and τ_{max} are values of τ_b that define the initiation and end of the control application and are the times that Gray and his colleagues have developed methods to estimate. τ was seen as the trigger to the BAT strategy and τ_{min} occurring as the pilot applied a maximum acceleration to the control. The control 'law' in Equation (50) is illustrated in Fig. 41.

In Ref. 82, the present author, together with co-authors Linghai Lu and Mike Jump, reported a study which placed the BAT PIO and associated phenomena within the framework of τ-theory. The research identified τ_{min} as the point when $\dot{\tau}_b = 1$ and also showed how BAT events and PIOs might be predicted through incipient variations in $\dot{\tau}$ when the pilot is trying to hold this at a constant value as the goal is approached. The BAT problem was examined in a series of rotorcraft manoeuvres including the lateral transition or roll-step mission task element[83]. During the roll-step MTE the pilot flies from one side of a runway to the other, lining up with the runway edge through narrow gates at zero roll angle and heading error; the tolerances for desired performance are ±5° and for adequate performance are ±10°. Corresponding lateral track errors are ±15ft and ±30ft. This manoeuvre does not have 'hard' boundaries envisaged by Gray in BAT PIOs but, nonetheless, does serve to illustrate the τ mechanics involved. At some time (or some τ_e to the runway edge) during the runway crossing, the pilot decides to reverse the roll and initiate the runway edge capture. Several scenarios are then possible as illustrated in Fig. 42, from Ref. 82. In Scenario 1, the pilot successfully flies through the gate and tracks the edge well within the desired performance boundaries. In Scenario 2, a CAT I or II PIO occurs, resulting perhaps from the roll attitude bandwidth being too low, or the aircraft/task bandwidth ratio being < 2 n_v, referring back to the discussion in the previous section. A CAT II PIO could arise from actuation rate limiting for example. The roll and lateral displacements continue to grow as the pilot control inputs drive the oscillatory motion, the only remedy being to release the controls. In Scenario 3, the pilot has left the reversal late, perhaps misjudging τ_e, and overshoots the runway edge. In the process the τ to the adequate performance boundary, τ_b becomes the focus of attention. The pilot has switched his goal from edge tracking to avoiding the boundary and, in this case, manages to accomplish this, although crossing the desired boundary, and eventually tracks the boundary. Gray describes this scenario as a BAT event. Scenario 4 is similar but the pilot becomes alternately fixated on the outer boundaries and applies large and rapid control reversals to recover the situation, resulting in a BAT PIO.

The roll step manoeuvres flown in the Liverpool simulator were carried out as part of a collaborative programme with the Flight

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Table 2
Conditions for BAT event and PIOs at the runway edge crossing[82]

$\dot{\tau}_b$	$\ddot{\tau}_b$	Result	Cases
$\dot{\tau}_b < 0{\cdot}5$	$\ddot{\tau}_b > 0$	BAT event or BAT PIO possible	S(8)
	$\ddot{\tau}_b < 0$	BAT event possible/BAT PIO unlikely	S(14), F(4)
$0{\cdot}5 < \dot{\tau}_b < 1$	$\ddot{\tau}_b > 0$	BAT PIO or C-PIO likely	S(1)
	$\ddot{\tau}_b < 0$	BAT event/BAT PIO likely	S(1)
$\dot{\tau}_b > 1$	$\ddot{\tau}_b > 0$	BAT or C-PIO very likely	0
	$\ddot{\tau}_b < 0$	BAT or C-PIO likely	0

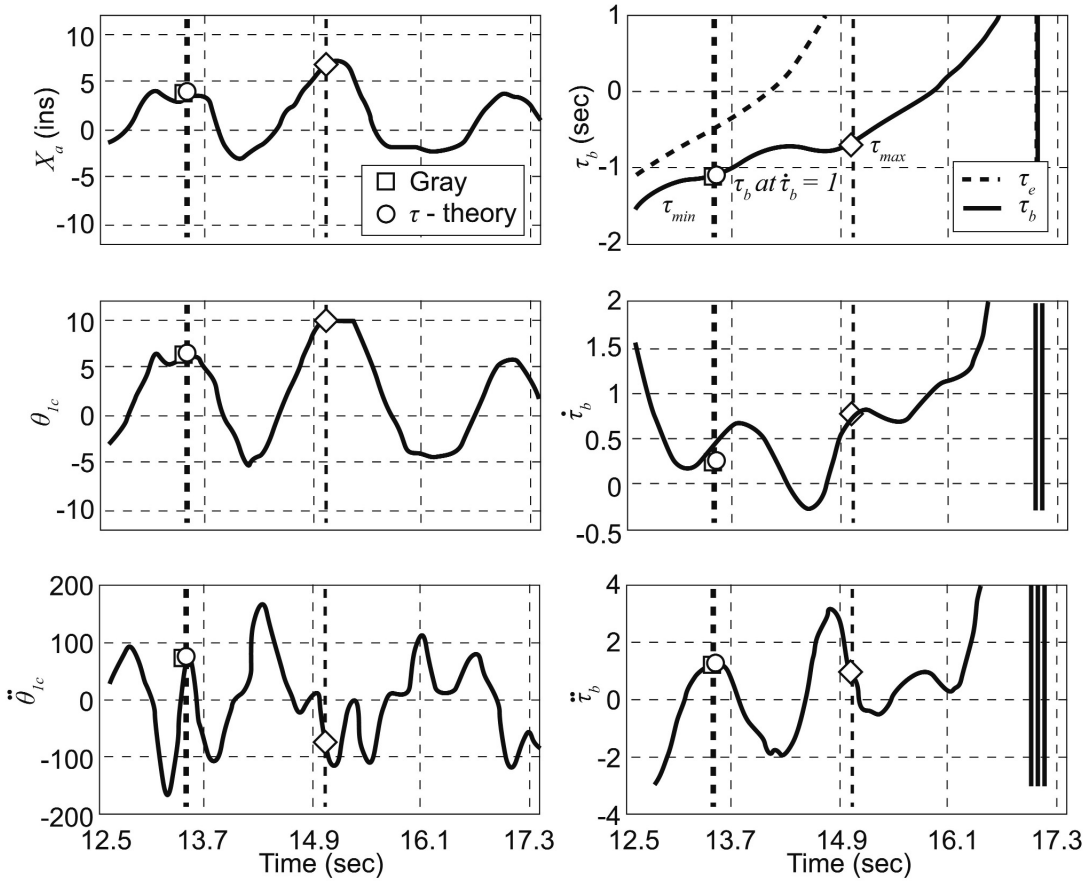


Figure 44. Selection of BAT parameters from τ-theory and Gray's method (flight SA9)[81].

Research Laboratory (Ottawa), using the ASRA research aircraft and the F-B412 simulation. In all cases flown in both aircraft and simulator, at different speeds and heights and aircraft configurations, the value of τ_e, when the pilot initiated the lateral deceleration, was close to 2 seconds. If $\dot{\tau}_e$ then drops to less than 0·5, the pilot is likely to track the runway edge successfully. If $\dot{\tau}_e > 0{\cdot}5$, the aircraft is likely to overshoot the edge, and the pilot's attention is drawn to the performance boundary. If τ_b is less than some critical value then a BAT event or BAT PIO 'may' occur, depending on the value of $\dot{\tau}_b$ at the runway edge crossing. The crossing is likely to have been preceded by the pilot applying corrective control (at Gray's τ_{min}) and $\dot{\tau}_b$ passing through unity. The hypothesised conditions are summarised in Table 2, where C-PIO refers to a classical PIO in the sense of the CAT I/II/III framework[80]. For the roll-step MTE the adequate performance boundary was displaced 30ft from the runway edge and no BAT PIOs were experienced; however, several BAT events did occur.

If $\dot{\tau}_b < 0{\cdot}5$, a BAT event is possible but a BAT PIO is only possible if $\dot{\tau}_b$ continues to increase; in the simulation trials (S), 8 cases fitted the $\ddot{\tau}_b > 0$ condition and 14 fitted the $\ddot{\tau}_b < 0$ condition, along with 4 flight cases (*F*). If $0{\cdot}5 > \dot{\tau}_b > 1$, a PIO is likely and the one case where $\ddot{\tau}_b < 0$ is examined in more detail below, when the pilot managed to avoid a PIO but at the expense of task failure, as the adequate performance boundary was exceeded. If $\dot{\tau}_b > 1$, the pilot is accelerating towards the boundary and has little hope of avoiding a BAT PIO; no such cases were encountered in flight or simulator for the roll-step MTE.

Figures 43 and 44 show results for the $\ddot{\tau}_b < 0$ case in the middle category above, in more detail. Fig. 43 shows that τ_{min} and $\dot{\tau}_b = 1$ occur at essentially the same location, $\tau_b = 1{\cdot}1$ and $1{\cdot}2$ seconds respectively, and

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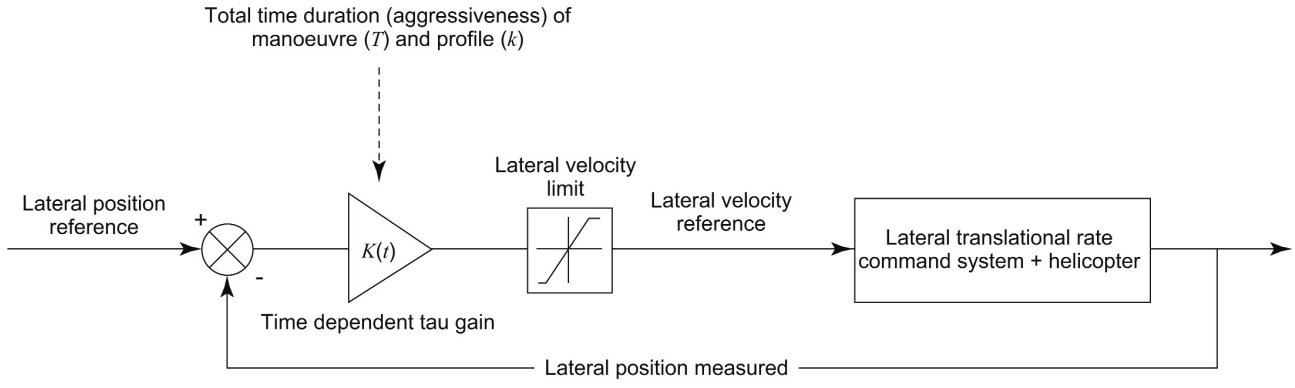


Figure 45. Control law concept for a τ_g following feedback controller[85].

as the inner adequate boundary is crossed. Figure 44 shows that $\dot{\tau}_b$ and $\ddot{\tau}_b$ are at the edge of the critical conditions as the runway edge is crossed. $\dot{\tau}_b > 0{\cdot}5$ and the mean $\ddot{\tau}_b$ transitioning from negative to positive. Rapid pilot control action activated the actuator rate limiter, shown as the 'sawtooth' pattern of the lateral cyclic pitch (θ_{lc}), followed by a maximum control input, held for about 0·5 seconds; in this time the stability augmentation system continues to apply rapid oscillatory inputs as seen in the trace of the rotor lateral cyclic (θ_{lc}) acceleration. A Cat II PIO was then a real possibility but the pilot quickly and safely brought the helicopter back within the outer adequate boundary. This situation is described as a severe BAT event. The peak of $\ddot{\tau}_b$, at $t = 13{\cdot}5$ seconds, determines τ_{min}, as shown in Fig. 44.

To recap, a pilot approaching a tracking task can inadvertently overshoot and become engaged in avoiding a boundary. Gray has developed a control theory with a trigger at τ_{min} estimated by a large change in the acceleration of the pilot's control movement. A BAT event occurs when the pilot has transitioned to boundary tracking but successfully recovers to task tracking; a BAT PIO occurs when the pilot continues to apply alternate control inputs as the aircraft oscillates from one boundary to the other. τ-theory has been used to describe this particular behaviour and suggest alternative mechanisms, based on τ derivatives, for predicting the incipience of a BAT event/PIO. This research application is still in its infancy but could well form the basis for pilot warning systems or even direct intervention control systems as an element of PIO-prevention technology. Such a system would need to solve the problem of how to measure τ and its derivatives directly, recalling that Gibson's theory of direct perception builds on the premise that the perception system picks up the optical flow variables directly, with no mental processing required. In the meantime, τ can be computed from inertial measurements of position and velocity to form the basis of conventional feedback control, the topic of the next section.

4.4 τ in control augmentation

Based on the research described in previous sections, guidance systems that mimic τ_g -following behaviour have considerable attractions; they are based on a product of evolution, are efficient, robust and simple. However, to engineer such a system will require new sensing and processing technologies. Towards this goal, Mike Jump designed preliminary display concepts as part of his PhD research[36,39] and examined a variety of applications, including conventional director-type symbology, driven by τ guides, to assist fixed-wing commercial transport pilots landing and taking off in low visibility, lead aircraft programmed to fly the intended manoeuvre in a τ_g manner and τ_g – formed sky tunnels – all overlaid on the outside world scene. The parameters used to provide τ information for these novel displays were those that already feature in the sensor suites of jet transport, e.g. radar altitude, localiser and glide slope; so τ and its derivatives were not sensed but rather derived from conventional sensors, albeit ones that use time as a fundamental measurement, e.g. radar altimeter. Overall, pilots performed at least as well with the τ – guide displays as with state of the art, head-up, displays that were entering service at that time. However, it was recognised that significant improvements could be made. As with all symbolic displays, pilot workload can be very high during precision flight path tasks and handling qualities are very sensitive to display and aircraft flight dynamics. While closing gaps between symbols on a display, pilots may well utilise the same τ-based strategies, but the visual information is sparse compared with the 3D world of surfaces and objects.

Encouraging a more prospective control strategy using τ – guide displays is a step on the road towards fully automating manoeuvres and there have been two applications of this kind at Liverpool over the last few years. The first was undertaken by Mark Voskuijl as part of his PhD study[84], including an examination of helicopter automatic deck landings and hover-to-hover re-position tasks. The research is reported in Refs 84 and 85 and the design concepts and results of the automatic sidestep manoeuvre are summarised here. The basic idea was that, if the functional form of the τ strategy required to close a gap is known, this could be used as the command trajectory in a conventional feedback system. The error between the actual flight path and the commanded flight path would then form the input to the controller that would automatically fly a manoeuvre, even in the presence of disturbances. To minimise the deviations from the commanded flight path due to, for example, atmospheric disturbances, an inner-loop stabilisation system was designed to provide Level 1 handling qualities for general manoeuvring – attitude command, attitude hold in pitch and roll with rate command in yaw and heave. On top of this stabilisation system, an outer loop guidance system was designed that featured translational rate command for horizontal manoeuvring, coupled with height and heading hold. All of these functions are now state of the art in helicopter flight control technology, thanks to several decades of focussed research. In other words, there is no fundamental reason why a new or upgraded helicopter should not enter service with Level 1 handling qualities for flight in both GVE and DVE. The guidance system then provides the entry point for the manoeuvre error functions, as shown in Fig. 45.

The lateral position reference (the commanded, constant acceleration τ_g – following trajectory) is compared with the actual lateral position (initially zero) to form the error function. The manoeuvre duration (T) and acceleration profile (k) are the familiar parameters in the τ guide that define the non-linear controller gain $K(t)$. The limited input is then applied to the command system and through to the helicopter model; the system parameters were refined using a high-order linear version of the FGR and verified using the nonlinear FLIGHTLAB model, initially off-line followed by piloted simulation. Typical results from an automated lateral re-position (sidestep) manoeuvre are shown in Figs 46 and 47. The manoeuvre time T was set at 17 seconds (note the ADS-33 value for the manoeuvre is 18 seconds) and $k = 0{\cdot}5$, the maximum velocity occurring about 60% into the manoeuvre. It is common for pilots to

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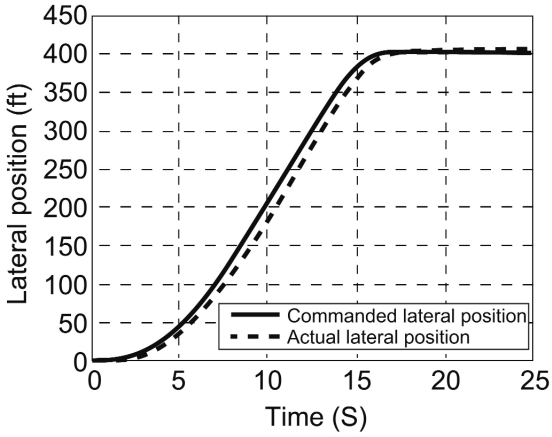


Figure 46. Lateral flight path trajectory during an automated lateral re-position manoeuvre[85].

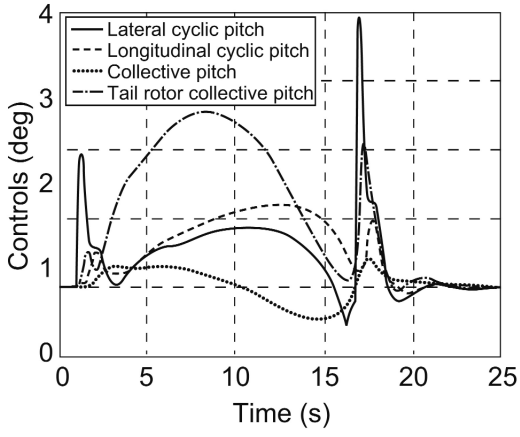


Figure 47. Control activity during an automated lateral re-position manoeuvre[85].

delay the deceleration to the 3rd quarter of the manoeuvre and to decelerate more aggressively than the acceleration, which may be limited by power. Figure 46 shows that the commanded trajectory is followed closely with about 0·5 seconds delay, a feature stemming from the lags introduced by the controller and vehicle dynamics. The rotor control movements used by the system to fly the manoeuvre automatically are shown in Fig. 47. The initial lateral cyclic pulse stems from the step command in lateral position, a feature that would not be so abrupt in a 'natural', more prospective, controller. As the manoeuvre progresses, all controls vary smoothly, all contributing to the smooth lateral transition in addition to cancelling heading, height and fore-aft displacements from zero.

Automatic manoeuvring is not new in concept or application of course; auto-landings are conducted regularly and drones can be programmed to fly complex manoeuvres. However, none of the controller designs in these applications feature τ as a parameter, either as itself or as a part of an algorithm that generates a manoeuvre trajectory.

Finally in this section on the use of τ in automation, the research of another PhD student at Liverpool, Simon Childs, who designed a flight envelope protection system for tilt rotor aircraft, is drawn from Refs 86 and 87. In his thesis, Simon Childs examined the problems of exceeding the envelope during manoeuvres in the conversion corridor, where the nacelles can vary between 90° (helicopter mode) and zero (aircraft mode) and the pilot can manoeuvre with nacelles fixed at different angles, e.g. 60°[83]. With nacelles fixed at 60° the pilot typically has an airspeed range $80 < V < 140$kt, the upper boundary set by control limits and/or rotor loads, the lower limit by wing stall. The boundaries of the

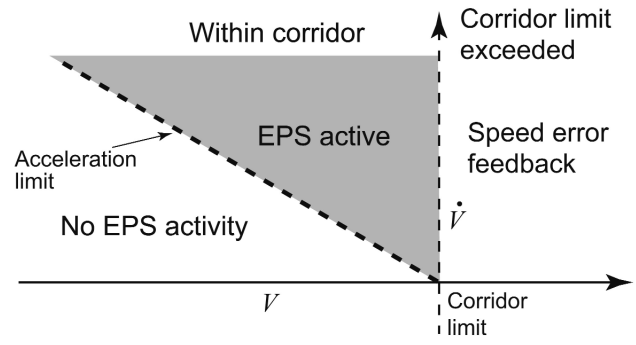


Figure 48. Envelope protection system concept for manoeuvring in the conversion corridor[86].

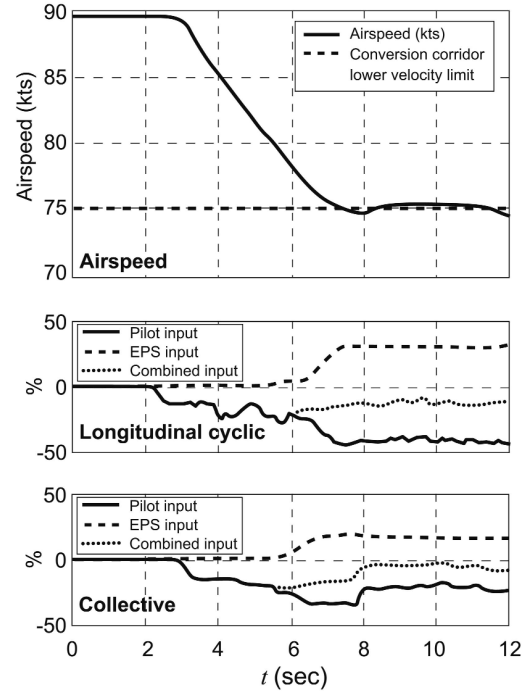


Figure 49. Airspeed and variation and control activity during an aggressive approach to the edge of the conversion corridor[86].

conversion corridor can be hard, in that exceedance can lead to loss of control. The concept developed by Simon Childs, shown schematically in Fig. 48, was an automatic envelope protection system (EPS) based indirectly on τ. The EPS only becomes active when the ratio of airspeed (V) to acceleration ($\dot{V}$), or $\tau_{\dot{v}}$, reduces below a defined value. The higher the airspeed, the larger the acceleration that triggered the EPS. Conversely, the lower the acceleration, the smaller the airspeed that triggered the EPS.

The system was evaluated in piloted simulation and a typical result is shown in Fig. 49. The aircraft is the European Civil Tilt Rotor concept, ERICA[88], developed jointly by AgustaWestland/Eurocopter, in its FLIGHTLAB manifestation developed by Agusta/Liverpool/NLR. From an initial trim speed of 90kt the pilot has pitched the aircraft up by about 15°, decelerating at about 4kt/sec towards the lower corridor boundary at 75kt. The EPS activates about four seconds into the manoeuvre, reducing the deceleration to zero within two seconds through the combined application of cyclic (30%) and collective (20%) control. The aircraft is then held on the envelope boundary despite the continuing pitch up command by the pilot. Although not investigated as

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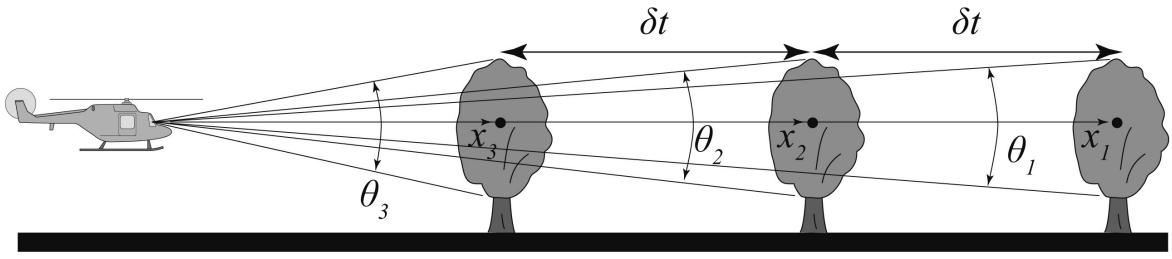


Figure 50. Deriving τ_x from looming.

part of this τ inspired controller, a tactile cue applied through the pilot's controls would have been an additional benefit to pilot awareness[(7) p 502].

One of the concerns of this kind of controller, and specifically raised by Mark Voskiujl in his thesis, is the question of stability for a nonlinear, time varying τ controller. A general stability theory for such systems does not exist and verification requirements of certification will mean that this has to be addressed before widespread use of τ-based controllers is acceptable. This will be eased by the very simplistic nature of the algorithms involved. Ironically, if the hypothesis that τ and its derivatives are the fundamental measurements for control in nature, then τ-based controllers are already ubiquitous, and the answers to questions of stability, robustness and reliability may also lie, once again, in a better understanding of how τ guidance has become so effective in the natural world.

5.0 THE WAY FORWARD AND FUTURE RESEARCH IN τ-THEORY AND APPLICATIONS

τ-theory posits that all purposeful action – catching a ball, playing a musical instrument, fell running or flying a helicopter – is conducted by following guides that are played back from memory instinctively or automatically, as required. The author has presented results that support this behavioural theory, without attempting to explain the physiological of psychological basis, which are outside the author's domain of expertise. Reference 89 provided an excellent source for the author to position τ-theory within these disciplines. The works of James Gibson, the father of optical flow, also provide underpinning material for this multi-disciplinary topic. In one his earliest publications[(90)], Gibson refers to the 'field of safe travel' in automobile driving ('*the field of possible paths which the car make take unimpeded*'); Gibson describes this as a spatial field but, in reading Ref. 90, one expects Gibson to make the leap to a temporal description and τ; however, he does not. Nor does he in a later work[(91)] on visually controlled locomotion in general, where he discusses looming during an approach; to quote.. '*This accelerated expansion in the field of view specifies imminent collision, and is unquestionably an effective stimulus for behaviour in animals with well developed visual systems..... At lesser intensities this 'looming motion', as it may be called, presumably yields lesser degrees of aversion, or a slowing down of approach. The fact is that animals need to make contact without collision with many solid objects of their environment: food objects, sex objects, and the landing surfaces on which insects and birds alight (not to mention helicopter pilots)*'. Gibson did not mention τ but he did make the link with helicopter flying. The description of purposeful action as a response to optical flow became the fertile ground for the development of a mathematical basis of optical flow and τ-theory, developed by David Lee following his collaboration with James Gibson at Cornell in the later 1960s. One of David Lee's early papers[(21)] is a mathematical companion to Gibson's descriptions in Ref. 91.

Clearly, more needs to be done to validate and ground the theory and support application in the field of flight control. Firstly, underpinning engineering research is needed in the sensing of τ. Active sensors in current use, including radar and sonar, are actually based on measurements of the time for signals to be reflected by objects, so the core temporal information is available. Most of nature's visual motion sensors are passive†, however, and rely on the 'interpretation' of dynamic images on, for example, retinal surfaces to perceive τ and its derivatives. τ-theory purports that motion control is achieved by maintaining invariants in the optical flow; for example $\dot{\tau}$, or the difference between the τ of a motion gap and a scaled guide, $k\tau_g$. But even without purposeful control, our sensors pick up information necessary for us to initiate action, as when flying with constant velocity over terrain and initiating a manoeuvre to avoid an obstacle. Given sufficient visual information, and Fig. 29 suggests that flow from 6-8 seconds ahead is sufficient for helicopter pilots, we are able to establish our presence in a world moving around us and with remarkable accuracy, at least in terms of when to initiate a manoeuvre to close a gap. In principle, with enough resolution, a camera can capture, frame by frame, the optical flow on surfaces, and consequently the looming and hence τ's to contact or pass these surfaces. Here it is assumed that the ratio of an object's growth to its rate of change of growth can be derived from a series of frames at constant frame rate δt (Fig. 50). As the helicopter approaches the tree in Fig. 50, at constant velocity, the times to contact are given by,

$$\tau_{x1} = \frac{\theta_1}{\dot{\theta}}, \qquad \tau_{x2} = \frac{\theta_2}{\dot{\theta}}, \ldots\ldots \qquad \ldots (51)$$

Noting that, for small θ, $\tau_x \cong \tau_\theta$. If $\dot{\theta}$ is constant, which it approximately is for small angles, then an approximation to τ can we written in the form,

$$\tau_{xi} = \frac{\theta_i}{\theta_i - \theta_{i-1}} \delta t \qquad \ldots (52)$$

The ratio $\theta/\delta\theta$ is a continually varying quantity although, for constant velocity approaches, δθ is approximately constant for a range of x. Knowing δt and δθ, the computation of τ appears to be very straightforward. In the natural world we can imagine that the relationship between δt and δθ needs to be regularly updated, and it is interesting to speculate whether small, timed, movements of the sensors (for example, by head movements) can provide this updating; such system calibration motions may be critical to securing reliable visual information. This approach to τ measurement is practically feasible.

In fact, sensors that measure τ directly have already been 'invented'[(92,93)] and recently tested in laboratory conditions[(94)] for application to autonomous air vehicles. Such experimental systems are the first generation of what are likely to become components of practical τ-based control systems, integrating the functions of navigation, guidance and stabilisation, but there is some way to go for such to be fully realised.

A second area where underpinning research is needed concerns τ-coupling during the simultaneous closing of multiple gaps. Humans are adept at performing multiple synchronised motions, for example guitar playing, where more than ten synchronised movements per second are

† In the sense that no signal is emitted from the sensor prior to reception.

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not unusual. A conventional helicopter has four controls – two through the cyclic stick, one through the collective lever and one through the pedals – and a pilot is often required to apply multiple control inputs at the same time; learning to fly a helicopter is difficult and requires the pilot to first find the appropriate spatial gaps and then learn to close them using τ. Figure 51 shows an example of pilot control activity during the acceleration-deceleration manoeuvre; the case is the same one discussed earlier for the NRC ASRA 412 flown on the ADS-33 track at Ottawa[39]. These results were from flight tests with the bare-airframe configuration, for which the pilot awarded Level 2 handling qualities ratings. The pilot is continuously working hard on all controls, attempting to close gaps in horizontal position, heading and height. During the final five seconds of the manoeuvre, the pilot is attempting to hold a hover and is only just able to maintain the aircraft within the adequate performance standards. The various gaps are unlikely to have entirely synchronised dynamics so a pilot has to divide attention in closing them. Observing a pilot struggling to maintain a hover in gusty conditions, this divided attention is seen as the pilot moving head and eyes to pick up the relevant visual motion information. There is often a pattern to this scan, most obvious when the pilot is flying on instruments and is only able to give each gap limited attention during the scan pattern. Only when the gaps are truly synchronised can the pilot couple them together with the same control strategy, with $\tau_x = k\tau_y$. Otherwise we can imagine that closing the multiple gaps involves finely tuned prospective control activity, the pilot relying on memory of the guide following as he/she divides attention between the gaps. Alternatively, is it possible that the perceptual system can close unsynchronised gaps in parallel? A hovering kestrel demonstrates that, with a much larger number of control effectors and integrated visual, vestibular and other sources of motion 'cues', hovering flight with quite incredible precision is possible. We also see this in the most complex of gymnastic manoeuvres, as discussed in Ref. 27. Research undertaken to explore multiple gap closing would be valuable to flight control developments for fully autonomous vehicles that attempt to mimic nature.

In Fig. 51, the two characteristic components of control, guidance and stabilisation, can be seen, particularly in the collective and pedal activity. The bare-airframe is so unstable that the primary axis of control, longitudinal cyclic is dominated by stabilisation. The low task guidance frequency (0·3 rad/sec) is modulated by higher stabilisation frequencies (> 3 rad/sec). Flight in turbulence and/or with aircraft that have low attitude damping or are unstable, often results in flight path or attitude deviations oscillating about a mean value, which the pilot is trying to track. Gaps open and are closed, only to appear as a new gap increasing in the opposite direction. Recently the author was on a helicopter flight and, while hovering, he noticed the pilot moving the cyclic with a continuous, low amplitude motion, with frequency about 1Hz; the pilot appeared to be casually gazing into the distance as he communicated with tower control. The author asked the pilot if the aircraft had a stability augmentation system installed. The pilot tapped his head, indicating where the stability augmentation came from, quickly moving his hand back to the controls. He was acknowledging the automation within his system.

The topic of tracking was discussed in an earlier section, where it was shown how pilots can be triggered to adopt goal or boundary tracking depending on τ to the goal or the boundary. Developing τ-theory to integrate guidance and stabilisation control is the third area where the author considers more basic research is required. On this theme, some initial work has been undertaken at Liverpool where subjects are required to 'manoeuvre' a ball across a screen using a joystick, in this case the cyclic control in the HELIFLIGHT simulator, Fig. 52.

The dynamics of the ball were modelled as a second order system with natural frequency ω_n and relative damping ζ,

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = \omega_n^2 K y \qquad \ldots (53)$$

where x is the ball displacement and y is the controller input; K is the gain between input and output. The response x to a step input in y varies significantly with variations in ω_n and ζ of course. The 'short period'

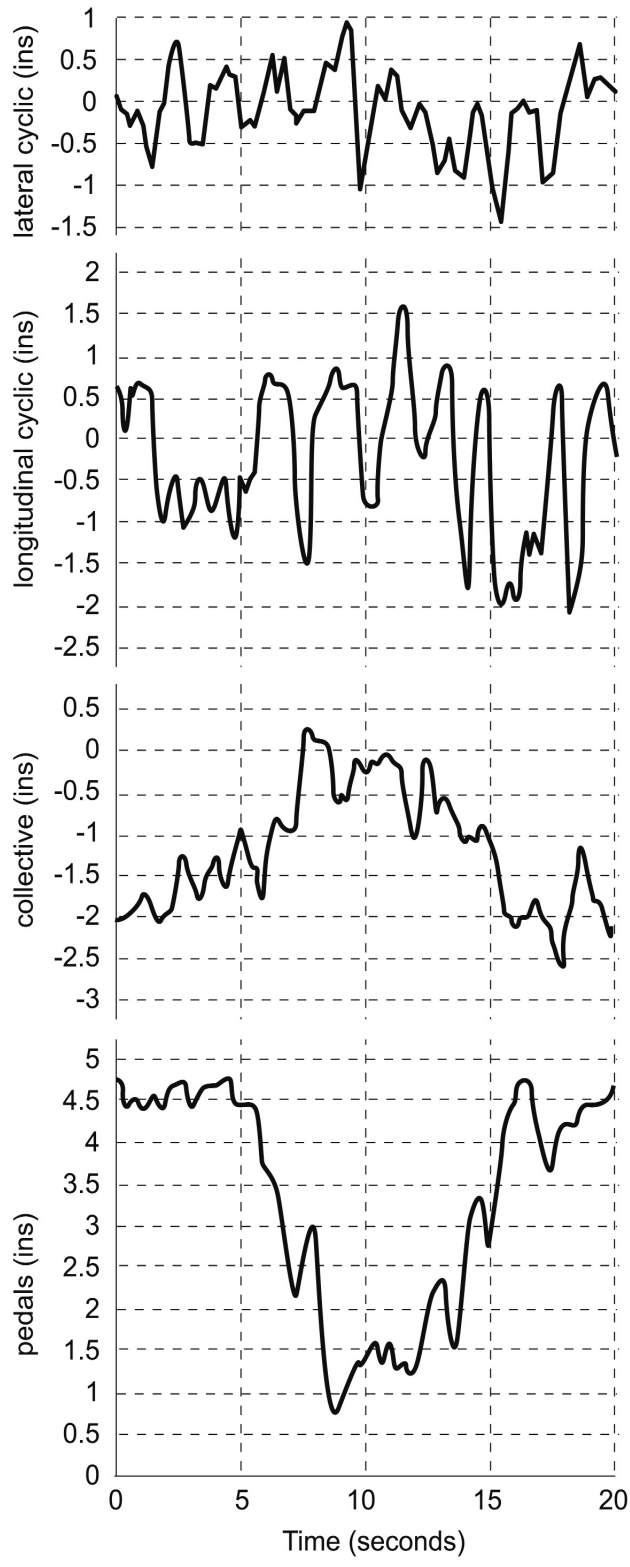


Figure 51. Control activity during the accel-decel manoeuvre; ASRA flight test.

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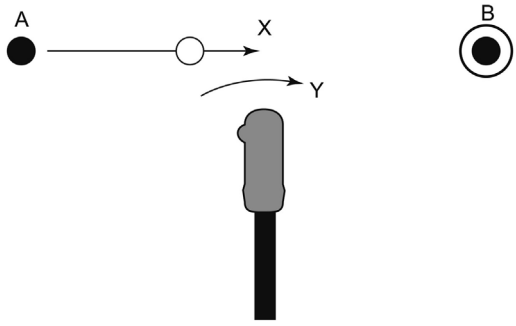


Figure 52. Manoeuvring a ball from A to B.

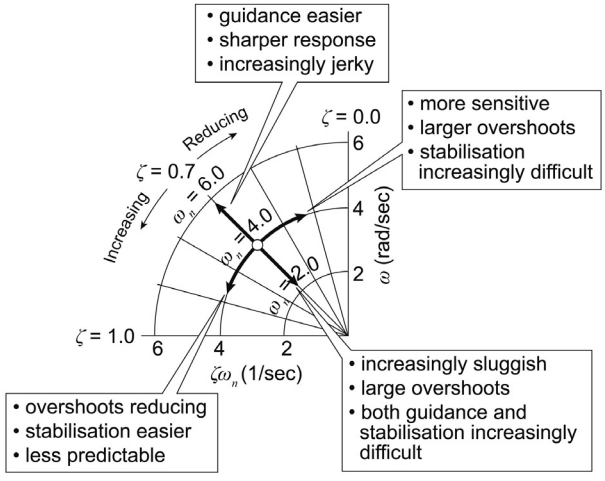


Figure 53. Chart showing how variations in ω_n and ζ impacted subject impressions.

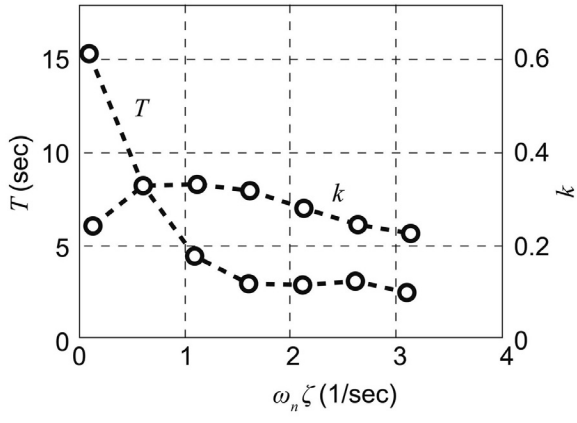


Figure 54. Estimated variations in manoeuvre time T and coupling parameter k with system damping.

response of the rate of change of flight path angle to elevator takes the form of Equation (53) and it is known that pilots have preferences for particular dynamics for flight path tracking manoeuvres[95]. The preliminary results shown below are derived from tests conducted by the author with 24 different configurations on the ω_n, ζ chart (Fig. 53). The circular arcs are lines of constant ω_n while the radial lines are constant ζ. From a nominal configuration (ω_n = 4, ζ = 0·7) variations in both frequency and damping led to a degradation in performance and increases in 'workload' in the manner indicated on the diagram. Guidance refers to the control actions to transition the ball from A to B and stabilisation refers largely to the task of arresting the motion of the ball without overshoot beyond half a ball diameter.

Subjects were asked to conduct the task promptly but taking sufficient time to achieve the task performance of arresting the ball within the outer ring in Fig. 52. As the response became more 'sluggish', larger control inputs were required but these had to be carefully reduced and reversed as the target approached to avoid overshoot. A control strategy that follows a constant acceleration guide ($\tau_x = k\tau_g$) would result in exactly the same response for all combinations of ω_n and ζ. In fact, as the normalised response solutions in Table 1 show, the shapes are also independent of the manoeuvre time T, they simply shrink or stretch accordingly. The control requirements are quite different of course, but a common feature is that the natural dynamics are suppressed by τ_g – following control strategies. This aspect will be discussed further in a future paper but, for now, the results shown in Fig. 54 are worth highlighting. The figure shows how the estimated manoeuvre time T and coupling constant k (averaged over six runs per configuration) varied with the system damping $\omega_n\zeta$, inversely proportional to the system time constant. The author is the subject 'pilot'. As the time constant is increased above one second ($\omega_n\zeta$ reducing), T increases sharply. The ratio of the manoeuvre time to system time constant when $\omega_n\zeta$ = 0·5 is about 12, which accords with the bandwidth ratio concept discussed in Ref. 1 and in the previous discussion in this paper on 'τ *in aircraft-pilot-couplings*'. The trend in k is noted, although all values lie below k = 0·4, indicating that the deceleration was always initiated before the half way point. This research is continuing and includes assessment of subject compensation, as a measure as the difference between the actual control used and that predicted by the τ_g following strategy, which always achieves the same, in some sense optimum, response. These results will be reported in a future publication.

Simple experiments like the one described above might shed light on some of the fundamental aspects of the τ of flight control, that can remain hidden in the unaccountable 'remnant' in the pilot control activity when flying complex manoeuvres. One possibility being considered is that pilots may be able to adjust k during a manoeuvre and this might be able to explain higher frequency stabilisation inputs modulating the guidance. Pilots may also have to change T, or stretch or dilate $\hat{t}$ during a manoeuvre, as the ship begins to move away from the descending helicopter or the re-fuelling basket falls away as the aircraft being refuelled is hit by a gust. In the natural world $\hat{t}$ and T are not measured in seconds, but rather in units connected with the perception system; do variations in T indicate the level of gain a pilot is adopting and can these aspects be brought out during training for example? The author considers the 'successive organisation of perception' concept introduced in Ref. 6 as a starting point for the engineering approach to modelling pilot actions, and over time more and more complex models of behaviour have been developed by engineers. In Ref. 91, James Gibson discusses the dilemma – in which disciplines models of perception might be created – physiology or psychology? To quote, '*Depth of space perception has been taken to be an internal process involving the interpreting or organising of sensations. Theories of this process have never achieved either simplicity or plausibility and, if it is a process of association, the difficulty arises of why animals do not make more errors than they do in the acquisition of locomotor behavior. The writer has argued (1950,* this paper's *Ref. 24) that the only way out of this theoretical muddle is to discard the original assumption about sensory response to light on the one hand and perceptual response to objects on the other*'. In developing a new theory, 'The Senses considered as Perceptual Systems'[96], Gibson went on to lay down the foundation for an integrated approach, an ecological approach to motion perception, introducing the idea of active senses – '*We shall have to conceive the external sense in a new way, as active rather than passive, as systems rather than channels, and as interrelated rather than mutually exclusive. If they function to pick up information, not simply to arouse sensations, this function should be donated by a different term. They will here be called perceptual systems*'. David Lee built on Gibson's optical flow theory, developing a rigorous theoretical framework, and extending and deepening the significance. The range of

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applications explored by Lee and colleagues has been vast, enriching the scope for cross-disciplinary fertilisation and spurs to innovation. Lee selects samples from this wide range in Ref. 97 and just two are highlighted here. Musician's expression is through a flow of sound, sustained and crafted through continuous feedback from audio perception to expression, e.g. the singer's voice or the movement of fingers over the strings of an instrument and consequent sounds. This feedback has been shown to be τ-coupled. Analysis of song indicates that the coupling k is used to vary musical expression through the gaps in musical pitch or pitch-slides: Unstressed pitch-slides ended with a gentle deceleration (analogous to the helicopter soft stop), the stressed ones with a harsher deceleration (analogous to hard stop). Analysis of results from bass-playing suggests that the '*intensity-slides and the bow movements that produced them were tightly τ guided*'. High values of k correlated with sounds conveying a sad mood, low values with a happy mood, with the coupled sound and the bow movement. A second example is drawn from a study of Parkinsonian syndrome, where patients find it difficult to self generate movement (from intrinsic guides) while they are more able in movement that is aided by action gaps, e.g. catching a ball (using extrinsic τ-guides). The hypothesis that the failure of the central nervous system to generate the intrinsic τ guides leads to this form of dysfunction, is reinforced by the promising results of research into the development of τ-based sonic movement aids. The duration (T) and shape (k) of the associated pitch-glide '*can be regulated to match the duration and style of the action to be aided, e.g. walking steps. Typically, the patients listen to the sonic guide, remember it and later play it back in their heads when performing an act. Results so far indicate that walking can be improved.*'

To quote further from Lee's recent work[98], *'If there is a single take-home message from this article it must be that guiding movement purposively is the origin of being. All living creatures from the largest mammal to the tiniest microbe need to do this to live. Therefore to understand what it is to be alive we must understand how movement is guided. We need to grasp this at different levels – anatomical, physiological, neural, molecular, genetic – but first and foremost we need to understand it at the behavioural level. Only then can we ask informed biological questions at lower levels, and so avoid not seeing the wood for the trees.*'

The evolution of James Gibson's and later, David Lee's, ideas on perception and the control of motion have, in this author's opinion, great significance for flight control developments. However, τ-theory is still in its infancy regarding application to flight control and, to the author's knowledge, has not been applied in the 'real' world, outside simulation. The scope for its application is potentially very substantial – in the design of vision aids, control augmentation systems particularly for piloting uninhabited autonomous vehicles but also supporting manual flight 'recovery' strategies from complex disturbed conditions. In support of the investigation of handling qualities, theory has been shown to have a place in the prediction of aircraft-pilot-couplings and in understanding control strategies, hence in the development of qualification criteria for simulation fidelity. The last activity has a profound connection with pilot training, in itself an area where τ-theory will surely find a place. These are ongoing topics of research, some of which will be pursued at Liverpool, but there is a particular need for more inter-disciplinary activity, and a more common framework found for the engineering of natural behaviour.

This search for common ground echoes the author's intentions in using the title 'The Tau of Flight Control' for this paper and to suggest that a new 'tao' might be found within the theory and application. The analogy is perhaps more substantial than it seems since the eminent psychologist Jung[99] describes tao as '*a track which, though fixed in itself, leads from a beginning directly to the goal*'.

6.0 CONCLUDING REMARKS

In this paper, the author has presented a 'banquet' of results from research into the place of τ-theory in flight control at the behavioural level, undertaken at The University of Liverpool over the period 1999-2011. The essence of the theory is that purposeful motion control is carried out under the influence of τ and its derivatives, as a pilot tries to maintain invariants constant in the projected optical flow on the retina from the surfaces over and around which the aircraft is manoeuvred. Flight control is prospective in that pilots try to overlay their flight trajectory onto one laid out by mental schemata or intrinsic guides into the future, thus avoiding collision, most of the time. Thus physical gaps are closed with precision. τ provides information that is critical to prediction and the sequential process for closing a gap is straightforward – a motion gap is perceived along with associated τ and $\dot{\tau}$; τ variations are controlled by triggering and following an intrinsic guide, defined by manoeuvre parameters, the manoeuvre time T and the coupling constant k; provided no disturbance occurs, the gap is successfully closed with either a hard or soft stop; if the gap is perturbed during the closing, the pilot has the option of re-scaling T and/or adjusting the aggressiveness parameter k. Examples from flight test and simulation of rotary and fixed-wing aircraft manoeuvres have provided evidence to support the veracity of the theory advanced in this survey paper. Ideas for the future direction of further underpinning research are suggested.

ACKNOWLEDGMENTS

The author takes the opportunity to acknowledge many contributions here in some detail. The research reported is partially funded by the EPSRC-funded research project 'Lifting Standards' (2008-11, EP/G002932/1). The early application of tau to flight control was undertaken by the author as part of the UK MoD's rotorcraft Day/Night All Weather strategic research programme, initially during his time at DERA and later at the University of Liverpool. Contributions to this early work were made by Roy Bradley, Malcolm Charlton and Julia Tims; Julia conducted most of the early piloted simulations at Liverpool, investigating the impact of visual cues on τ strategies. Malcolm extended the work to civil helicopters in a study into helicopter accidents for the UK Civil Aviation Authority (CAA), with close support from the CAA's rotorcraft test pilot Nigel Talbot; the τ analysis of the trial data was undertaken by another of the author's post-graduate students/researchers, Ben Lawrence, now with NASA Ames. Roy Bradley incorporated τ-theory into his integrated pilot-vehicle system model, demonstrating for the first time how a pilot model based on tau could fly manoeuvres. This foundational work paved the way for the activities in a series of basic research projects at Liverpool funded by the UK EPSRC – 'Adaptive Pilot Model' (2001-3, GR/R02603/01), 'Prospective Skyguides' (2003-6, GR/R84795/01), 'Rotorcraft-Pilot-Couplings' (2006-9, EP/D003512/1) and 'Lifting Standards' (2008-11, EP/G002932/1). The research summarised in this paper draws extensively on the outputs of these activities.

The author owes a special and large debt of gratitude to David Lee, the founding father of optical τ, for being receptive when approached for more information on τ, and how it might relate to flight control. Later, as the application to flight control blossomed, Dave stayed 'on board' and continued to contribute directly to the research, kept the team briefed on non-aeronautical applications of τ and also participated in workshops, and involving the Liverpool team as members of the 'Perception in Action' Laboratory in Edinburgh. The numerous stimulating discussions on motion control have demonstrated to the author that cross disciplinary engagements can be powerful spurs to innovation.

Much of the research reviewed in this paper was also derived from the work of PhD students or post-doctoral researchers who the author had the pleasure and honour to supervise and work alongside. It is appropriate to summarise their contributions in this acknowledgement. Gary Clark focused on the general problem of helicopter flight in the DVE, examining τ in the context of low level terrain-following/avoidance manoeuvres. This research was conducted in collaboration with ONERA and Gary was based at Salon-de-Provence for much of his PhD, although all the experimental work he reports in his thesis was carried out at the Flight Simulation Laboratory in

https://doi.org/10.1017/S0001924000006187 Published online by Cambridge University Press

Liverpool. In addition to unifying τ-theory for horizontal and vertical manoeuvring, Gary was also able to make inroads into the description of the usable cue environment using τ-theory, a particularly important development as discussed in this paper. Gary now works for Airbus and, at the time of writing, is closely involved with the design of the A350 airliner. Mike Jump extended the application of τ-theory to fixed-wing aircraft flight control and developed a process for explaining the various approach and landing strategies adopted by pilots, including the so-called τ-pause, where pilots maintain τ-constant just before the final flare. Mike Jump's research formed part of the EPSRC funded 'Prospective Skyguides' project, in collaboration with BAE Systems, that focused on head-up displays as aids to flight in the degraded visual environment. This research resulted in the first τ-guidance algorithms that formed the basis of a pilot visual aid or might be used as a landing guide for an autonomous air system. Mike is now a Lecturer in Aerospace Engineering at the University of Liverpool and leading a number of research projects, including Liverpool's contributions to the new European FP7 projects ARISTOTEL and myCopter, both of which will feature applications of τ. The rotorcraft element of 'Prospective Skyguides' was undertaken by Heath Lockett. There was strong evidence from early NASA research that helicopter pilots preferred to follow τ-based guidance algorithms during 'directed' manual landings. Heath was able to repeat the NASA experiments and draw more general conclusions on the optimum deceleration and descent profiles. Heath also examined the presence of τ strategies during recoveries from upsets but, unfortunately, no firm conclusions could be drawn from the results; Heath recommended this as a potentially fruitful area of research in terms of the design of upset recovery visual aids. Heath Lockett now conducts market analysis in the 'connectivity' industry. Robert Armstrong utilised τ-theory in the development of simulator fidelity metrics, extending the adaptive pilot model into a temporal form. Rob was able to show correlations between τ patterns and simulator fidelity variations, and contributed to the derivation of the elegant τ-based model of a pilot-vehicle system, reducible to the classical crossover model when τ is constant. Robert now works with Thales and, at the time of writing, is on a team developing the Boeing 787 training simulator. Robert's research also helped to spur the new EPSRC project 'Lifting Standards' a joint project with Mark White, consolidating the τ-based fidelity metric work. Recent contributions by post-doctoral researcher, Philip Perfect, drawing on the Bell 412 test results from the collaboration with the Flight Research Laboratory in Ottawa, are also acknowledged. Beth Davidson's PhD research was on the theme of aircraft/rotorcraft pilot couplings, and identified configurations and manoeuvres that were prone to exciting pilot-induced oscillations, providing the first data that featured τ-like strategies for these difficult situations. Beth now works for BAE Systems at Warton in Lancashire. Helen Baker, in her PhD research also examined tracking manoeuvres and extended the application of the crossover model of pilot-aircraft behaviour to helicopter low speed flight, again providing data that featured τ characteristics; Helen now works in the wind energy industry. The application of τ-theory to boundary avoidance tracking (BAT) and PIO prediction has been taken forward by post-doctoral researcher Linghai Lu, initially as part of the EPSRC funded project 'Rotorcraft-Pilot Couplings' and more recently as part of the FP7 project, ARISTOTEL. With the author, Linghai was able to show how τ-theory explained the BAT phenomenon, first discovered by Gray at the USAF test pilot school. Linghai extended this work to the all important prediction of PIO imminence and understanding the variable which can be used to trigger pilot alert or intervention systems. If a single future PIO or BAT PIO, and they are very likely to occur, is prevented by the kind of research already conducted or continuing in ARISTOTEL, then the investment will be repaid several fold. Mark Voskuijl was the first researcher to apply τ-theory to the design of a conventional feedback system, deriving the error functions from the guide profiles. At the time of writing, the control laws developed for automatic deck landings and hover-to-hover repositioning manoeuvres have been successfully flown in simulation (as described in the paper) and are being prepared for flight evaluation on the Canadian NRC's ASRA in-flight simulator. Mark is now an Assistant Professor at the Technical University of Delft. Simon Childs undertook the flight envelope protection research as part of the European FP5 project, Active Control Technologies for Tilt Rotor Aircraft (ACT-TILT); Simon now works with Airbus in Toulouse.

Test pilots Andy Berryman and Steve Cheyne, both ex-Navy rotary-wing test pilots (and who worked with the author during his time at RAE/DERA), now commercial airliner pilots with British Airways, have contributed significantly with their skill and insight in all of the research projects. The flight simulation laboratory at The University of Liverpool is a unique and high quality research and teaching facility, underpinning a decade of leading edge research and teaching. The research reported in this paper and its references draws extensively on this facility and, frankly, could not have been accomplished without it. A motivated and well organised engineering manager, with a can-do attitude, is critical to the success of such a research and teaching laboratory. Mark White fulfils this role at Liverpool and has given the author, and other facility users, unstinting support over the last 12 years as well as leading his own research activities.

Acknowledging the sources of the flight test data, the Bo1o5 test results were provided by Wolfgang von Grunhagen (DLR) and the Bell 412 ASRA results by Bill Gubbels (NRC); these data have provided an essential source of validation for the simulation work at Liverpool.

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