Progress in the Development of a Robust Pilot Model for the Evaluation of Rotorcraft Performance, Control Strategy and Pilot Workload.[+]

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Nomenclature

k	Crossover gain.
$\bar{k}$	Operating point adjustment gain.
k_g	Guide coupling constant.
p,q,r	Body referenced angular velocity components.
u,v,w	Body referenced velocity components.
x_a, x_b, x_c, x_p	Lateral cyclic stick, longitudinal cyclic stick, collective lever, pedal.
x,u,y	State, control and output vectors of linear system.
$\bar{y}, \bar{y}_{ref}$	Output vector for linearising feedback, reference value.
A, B, C	State, control and output matrices of linear system.
$\bar{C}, \bar{D}$	Matrices of linearising feedback.
G,H	Matrices of linearising feedback for CTM.
T	Manoeuvre time.
U,V,W	Earth referenced velocity components.
X,Y,Z	Earth referenced position components.
ϕ, θ, ψ	Euler attitude angles.
$\theta_0, \theta_{1c}, \theta_{1s}, \theta_{0tr}$	Blade pitch angles: collective, lateral cyclic, longitudinal cyclic and tail rotor collective.
τ	Crossover delay.
$\tau, \tau_m, \tau_g,$	Closure time: general, manoeuvre and guide.
$\zeta,\ \omega$	Parameters of CTM

Abstract.

This paper describes the development of the SYCOS pilot model which has its origins in the need for an off-line (desk-top) simulation technique to evaluate rotorcraft performance and handling qualities in piloted flight through a set of standard manoeuvres such as the Mission Task Elements of ADS33. The aim of its development is to overcome some of the limitations of the precise, open loop, control of inverse simulation, by adopting a structure which includes a corrective component that adjusts the control strategy to counteract departures in the desired flight path. In its basic form the SYCOS model has two components. An error is detected between the required and desired performance which is then consolidated by a 'crossover' component and processed by a 'learned response' component which generates an appropriate corrective action to apply to the vehicle's controls. The model in its basic form may be implemented for a given application in a well defined and

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straightforward manner and has proved to be a reliable tool for piloting a state-of-the-art rotorcraft simulation. Its capability isl be demonstrated through a number of recent applications in performance, control strategy and pilot workload studies. Some of the applications benefit from enhancements to the basic structure and these are described in context.

Introduction

The SYCOS pilot model came into being in 1996 as a dynamic controller for helicopter simulations which could pilot a helicopter through prescribed manoeuvres in a manner similar to a human pilot. At the time there was considerable experience of inverse simulation [1] of helicopter flight and its ability to produce control actions which could guide a helicopter simulation through manoeuvres in a precise and efficient manner but there were certain features of a human pilot that the 'ideal' represented by inverse control could not address in a realistic manner. An important aspect was the reaction to external disturbances such as atmospheric turbulence. Inverse simulation in its pure form calculates control activity that will precisely nullify the effects of turbulence and, as a result, generates control activity with an unrepresentative proportion of high frequency activity. The human pilot normally largely ignores disturbances of such high frequency – reacting only to those frequencies which cause a lasting departure from the intended flight path. A further requirement was an ability to respond in a realistic manner to system constraints such as control limits which naturally cause failure of the inverse method. Modifications to the inverse algorithm can be made to carry it through regions where the basic algorithm is challenged but the aim in the SYCOS work was to respond to disturbances and constraints in a 'human' manner. Another motivating factor was the recognition that pure inverse simulation did not capture the compromises and trade-offs which a human pilot makes when the task demands are escalated. Originally, it was believed that a new design for a pilot model would be best carried through by a synthesis of control components based on the physio-neurological behaviour of human pilots and their behaviour when faced with the constraints of flight-path and helicopter systems. Hence the acronym SYCOS (Synthesis through COnstrained Simulation) was coined but in the event development took a different direction and a pilot model which was phenomenological, based on the work of McRuer and Krendel [2], resulted. In the sections which follow the basic model is developed, analysed and demonstrated in a range of applications. Extensions of the method which have been made in order to cater for different operational situations and to enhance the realism of the control activity are also described. The accumulation of experience with the SYCOS pilot leads one to the belief that it is a significant advance on inverse simulation as a predictor of human control activity during helicopter manoeuvring flight.

The basic SYCOS pilot model

The principal difference between the SYCOS model and inverse simulation lies in its configuration as a corrective system. That is, instead of the open loop structure where a set of control actions are generated from a reference output value, they are instead calculated from the difference between the reference output values and the outputs' current actual values. This structure is shown in Fig. 1.

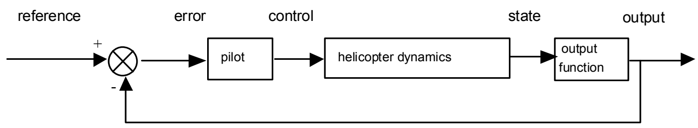


Figure. 1 The Corrective Pilot Model

The contribution of McRuer and Krendel [2] in their definitive study of human pilot behaviour is to provide evidence that in such a structure the human pilot adapts to the system being controlled in a particular way. A conclusion of their study is that pilots (human controllers) adapt their behaviour so that the transfer function between error and output is:

$$\frac{ke^{-\tau s}}{s}$$

where k is the loop gain and τ is a delay with typical values of 2 and 0.2 respectively. This adaptation is valuable because it enables a design for a pilot model to be based on the net result or outcome of the pilot's strategy rather than the detailed internal dynamic functioning. The result is that the model contains only two parameters, k and τ, and these are easily comprehended. In this form, the model is called the crossover model because at low frequency the output tracks the reference whereas high frequency changes in reference are reflected in the system output in only an attenuated form. For a zero value of τ we can write:

$$\frac{k}{s}(y_{ref} - y) = y$$

or

$$\frac{y}{y_{ref}} = \frac{k}{s+k} \qquad (1)$$

a transfer function with a break or crossover frequency equal to the gain *k*. This is the behaviour that is assigned to the adapted control of a human pilot. The principal focus of the original work was single input/single output systems so that for helicopter applications it is necessary to consider 4 axes of control with reference and control *vectors*, but the principle, that of an assumed adaptation to the system being controlled, is taken as the basis of the SYCOS model. It is therefore relatively sparse in tuneable parameters and contains only overall gain and delay parameters.

The next step is to determine an implementation which gives the required overall transfer function. One solution is the simple structure consisting of a crossover component and an inverse shown in Fig. 2.

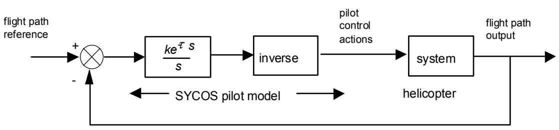


Figure 2. The basic SYCOS structure.

The inverse component combines with the system to form an identity so that overall the behaviour is described by the tracking model above (Eqn. 1). Here, of course, there are four gains to assign and four delays – assuming that the matrix *k* has a diagonal structure. In fact, the formal inversion of dynamical systems does not always result in an exact inverse, as will be discussed below, and, in any case, the inversion of a complex model is not a trivial exercise computationally and may be intractable analytically. Nevertheless the form above has been successfully used with the VSH (very simple helicopter) model where an analytical inverse can be found [3]. In a wide range of applications the need for an exact inverse has been found unnecessary and moreover since the inverse, from a design point of view, represents the learning or adaptation of the pilot to the response of the system output to control inputs, it is not expected that exact adaptation takes place. Therefore for two reasons (i) computational simplicity and (ii) pilot modelling, an approximate inverse is an acceptable substitute which has proved successful in many applications. The nature of the most suitable approximation has not yet been fully explored and there are options for retaining some of the non-linearity but for the applications discussed here a linear inverse has been employed: specifically, the inverse of a 6 DOF linearisation of the helicopter being piloted.

The derivation is straightforward. From a linearisation of the helicopter in the usual form:

$$\dot{x} = Ax + Bu$$

with state and control vectors $x = (u, v, w, p, q, r, \phi, \theta, \psi)$ and $u = (\theta_0, \theta_{1c}, \theta_{1s}, \theta_{0tr})$ respectively and output equation

$$y = Cx\ .$$

The inverse is obtained by linearising feedback. (Alternatively, the control vector may be expressed in inceptor positions: $u = (x_a, x_b, x_c, x_p)$). Some important issues can be explained by describing a specific case so consider the common situation where a manoeuvre is defined by prescribing the three earth referenced components of velocity and the heading angle. The output vector is then

$$y = (U, V, W, \psi)'$$

and the development of the feedback to invert the original system with respect to the output y begins by differentiating the output equation to get

$$\dot{y} = C\dot{x} = CAx + CBu$$

In this case CB is singular. The last row of CB is identically zero reflecting the fact that the rate of change of heading is not directly influenced by the controls. The product CB is rank 3 because the controls, however, do directly influence the body referenced accelerations. Differentiating again gives

$$\ddot{y} = CA^2 x + CABu + CB\dot{u}$$

and the last equation, which is for the heading acceleration, $\ddot{\psi}$, does not involve $\dot{u}$ since it is known that the last row of CB is zero. It is therefore possible to write

$$\overline{y} = \overline{C}x + \overline{D}u$$

where:

$$\overline{y} = (\dot{U}, \dot{V}, \dot{W}, \ddot{\psi})'$$

and

$$\overline{C} = \begin{bmatrix} CA(1:3,:) \\ CA^2(4,:) \end{bmatrix}, \overline{D} = \begin{bmatrix} CB(1:3,:) \\ CAB(4,:) \end{bmatrix}$$

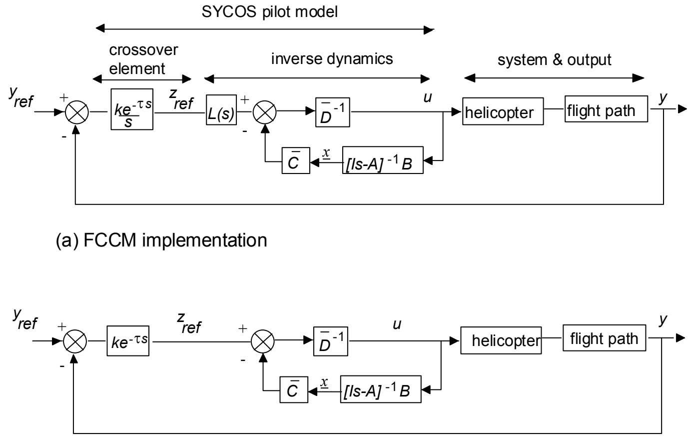
The matrix $\overline{D}$ is non singular so that when u is found from

$$u = \overline{D}^{-1}(\overline{y}_{ref} - \overline{C}x)$$

it is this feedback which guarantees that the output $\overline{y}$ is equal to its reference values.

The use of side-slip angle rather than the heading angle presents an interesting special case for the linearising feedback approach. It is discussed in the Appendix and, once established, is only a slight complication of the basic method.

In the SYCOS structure this inversion must be applied to the output from the crossover element rather than the vector of references. The resulting structure is shown in Fig 3a where the diagonal component $L(s)$ contains the differentiations to generate $\overline{y}$ from y. Combining $L(s)$ with the integration from the crossover component simplifies Fig 3a to the structure in Fig 3b where only the heading component needs to be differentiated. In fact, if the output is cast in terms of the rate of change of heading from the outset – possible since it can be expressed solely in terms of the state vector (that is, not involving the control vector) then no differentiations are required at all. The structure in Fig. 3 is termed the FCCM version of SYCOS – the Fully Compensating Crossover Model and it is driven by references consisting of velocities and rate of heading angle.



(a) FCCM implementation

(b) FCCM simplified implementation

Figure 3. (a) The SYCOS Fully Compensating Crossover Model, (b) Simplified implementation.

Accel-Decel manoeuvre.

To demonstrate the effectiveness of the SYCOS model we consider an accel-decel manoeuvre flown by a Lynx helicopter simulated in the ART Flightlab environment. The manoeuvre is carried out over 545 ft and takes 28 seconds with a maximum velocity of 40 ft/sec second. The velocity references V, W and the heading ψ are set to zero and the longitudinal motion is defined by a profile for the velocity U which increases smoothly from hover through an interval of constant acceleration and then decreases through a similar interval of deceleration and return to hover.

The resulting response is shown in Fig. 4 with the crossover parameters k =2 and τ=0.2. The x-axis velocity and displacement are seen to track the reference values in the expected manner with a delay of 0.5 seconds, while the remaining references (not shown) hold the zero values reasonably well. The control activity relative to trim is shown in Fig 5 and the coordinated actions necessary to fly the manoeuvre are clear. The main activity is in the longitudinal cyclic but the collective is dropped in the middle of the manoeuvre separating the accelerating and decelerating phases.

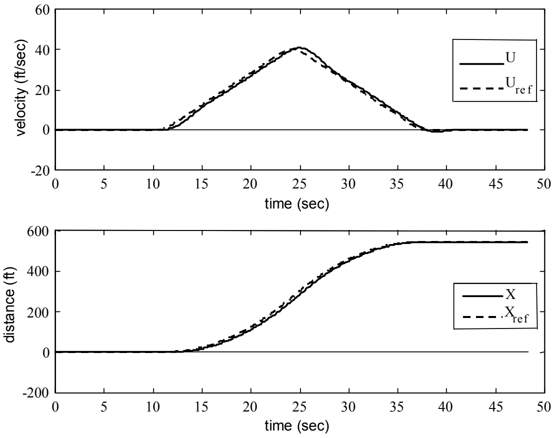


Figure 4 Output response of FCCM during accel-decel manoeuvre.

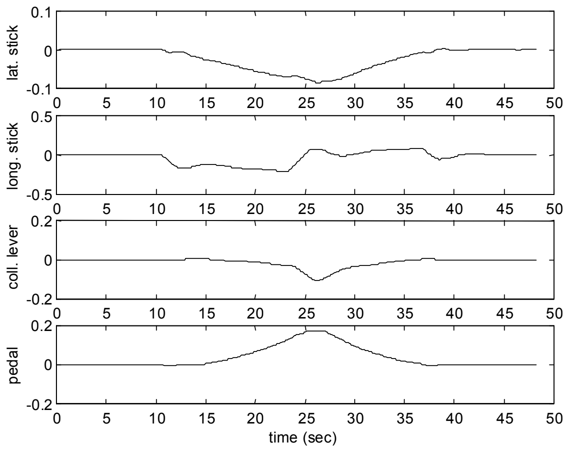


Figure 5 Control activity produced by FCCM during accel/decel manoeuvre

Hovering in turbulence

The second example is of a helicopter configured in the Flightlab environment to resemble a helicopter of the S76 type. Turbulence from wind tunnel measurements of flow around an offshore platform is scaled and applied to the simulation. The pilot model is therefore required to hold station and correct departures from the zero velocity reference datum. Fig. 6 shows the collective lever responses of both the SYCOS pilot and a corresponding piloted simulation (Pilot B) for 25 seconds of hovering flight 10 m above the centre of the helideck in a wind of 35 knots from the direction of the exhaust stacks.

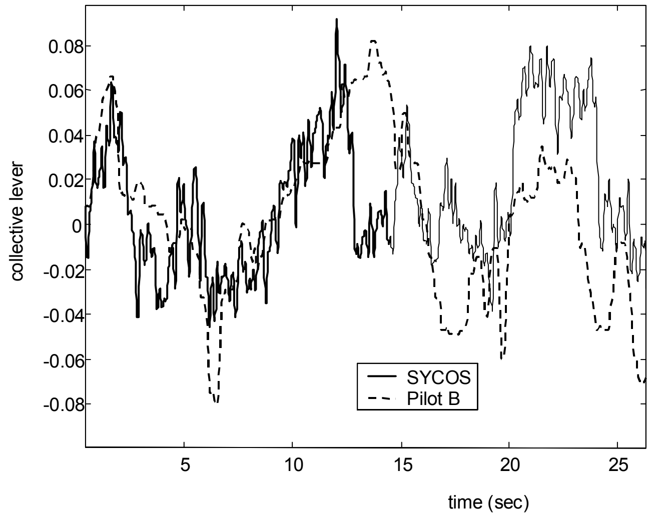


Figure 6. Collective lever activity hovering in turbulence (S76 type).

Simulations were carried out for wind speeds in the range 15-60 knots for wind directions that were both unobstructed and from the direction of obstructions such as derricks, exhaust stacks, and cranes. In a comprehensive study [4], it was demonstrated that the workload predicted by the SYCOS pilot was in the range of values typical of human pilots.

XV15 Tilt rotor accel-decel

The development above for a conventional helicopter is easily extended to the tilt rotor configuration where in helicopter mode there are five controls:

1. Combined collective pitch,
2. Combined longitudinal cyclic pitch,
3. Combined lateral cyclic pitch,
4. Differential collective pitch,
5. Differential longitudinal cyclic pitch.

It is possible with this combination to satisfy five reference outputs and one of interest additional to those discussed earlier is the maintaining of a specified bank angle, φ. The development follows similar lines to that of the heading angle so that the rate of change of φ is ultimately specified. If the output vector is established as

$$y = (U, V, W, \psi, \varphi)'$$

then the same procedure leads to the linearising feedback

$$u = \overline{D}^{-1}(\overline{y}_{ref} - \overline{C}x)$$

where

$$\overline{C} = \begin{bmatrix} CA(1{:}3,:) \\ CA^2(4{:}5,:) \end{bmatrix}, \overline{D} = \begin{bmatrix} CB(1{:}3,:) \\ CAB(4{:}5,:) \end{bmatrix}$$

The adaptation to the new configuration is quite straightforward and Fig. 7 shows the control activity and vehicle attitude during a speed burst manoeuvre – an accel-decel from a 15 m/s trim - of low aggression for a fully non-linear, individual blade model of an XV15 tilt rotor [5] in helicopter mode. In this case a FORTRAN model is imported into a Matlab® environment where the linearisation and model reduction for the SYCOS formulation together with the final simulation take place.

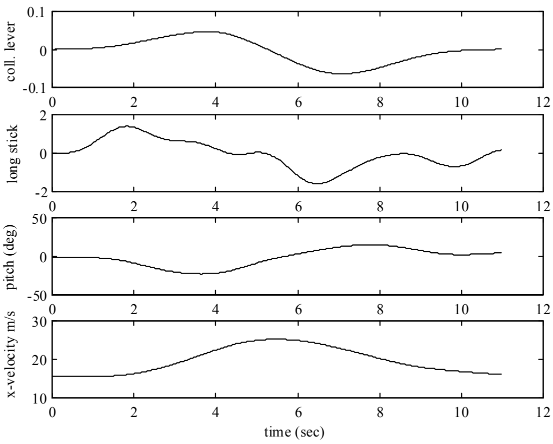


Figure 7. Response of a XV15 tilt rotor simulation during a speed-burst manoeuvre from 25 m/s to 25 m/s.

Model following Controller (PAFCA)

The Partial Authority Flight Control Augmentation [6] makes use of the series actuator to implement a model following controller via the AFCS limited authority series actuator. A simplified form of the PAFCA structure is shown in Fig. 8. The model is designed to implement a decoupled rate control system so that fore-aft and collective inceptor movements alone are required for an accel-decel manoeuvre. The compensating inputs are applied through the series actuator as shown.

The derivation of the SYCOS model is straightforward even in this tightly controlled architecture with the design model, controller dynamics, and helicopter model all included in the model reduction procedure. Figs 9 and 10 show results for an accel-decel manoeuvre for a hover to hover time of ten seconds and a peak velocity of 10 m/s. In Fig. 9 the series actuator limits are set to 50% and there is no saturation during the manoeuvre. The SYCOS control displacements are completely decoupled with no pedal or right/left inceptor activity required. The compensating inputs of the series actuator are also shown in Fig 10. In Figs. 11 and 12 the series actuator limits are set to 20% and the extra coordinated inputs of the SYCOS pilot are evident as the series actuator saturates.

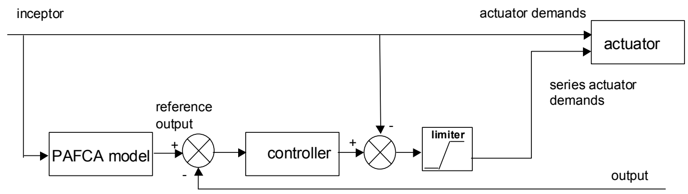


Figure 8 Structure of the PAFCA system

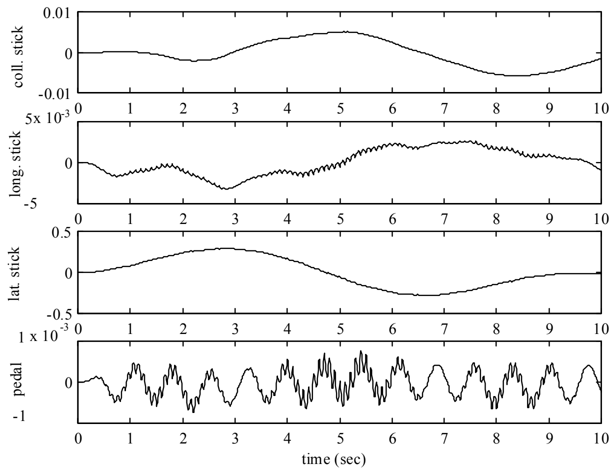


Figure 9 Inceptor inputs to the PAFCA system in side step (50% authority)

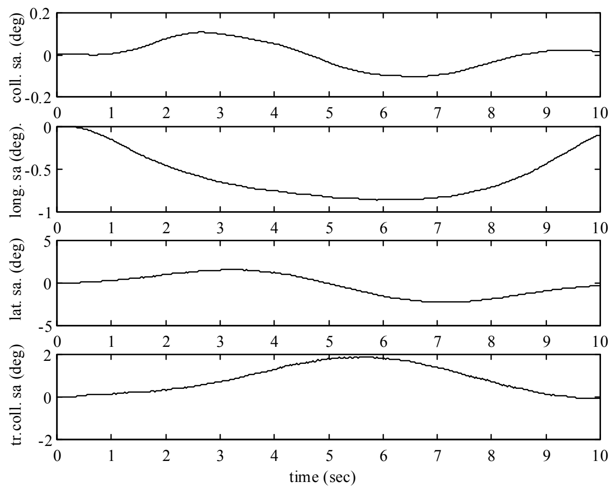


Figure 10 Series actuator inputs to the PAFCA system in side step (50% authority)

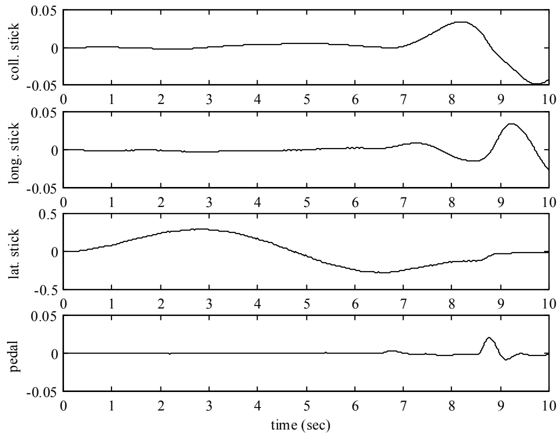


Figure 10 Inceptor inputs to the PAFCA system in side step (25% authority)

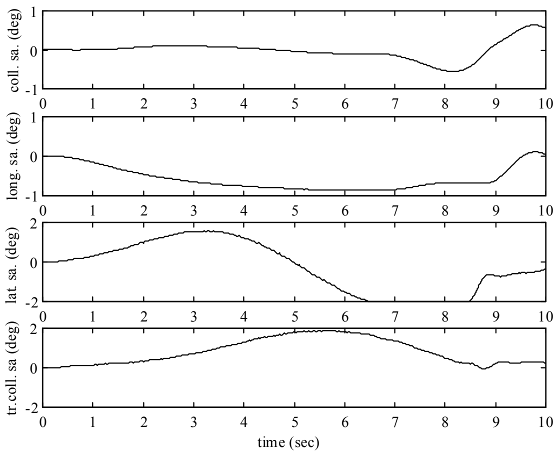


Figure 11 Series actuator inputs to the PAFCA system in side step (25% authority)

The SYCOS approach successfully produces a pilot model with which to assess the performance of the controller in defined tasks.

Optical τ control.

In a significant contribution to understanding how human pilots use visual cues to perform the principal tasks of manoeuvring flight, Padfield et al [7] espoused the pioneering work of Lee [8] to investigate the role of the time to closure variable, optical τ.

For example, when a helicopter is travelling at speed *v* towards a stopping point a distance *d* away then the time to close is given by

$$\tau = d / v$$

it is found that pilots control their deceleration by maintaining a constant value of rate of change of τ typically in the range -0.4 to -0.5. The value –0.5 results in a steady deceleration to stop while values either side result in a hard (<-0.5) or soft stop (>-0.5). These concepts have been applied to various manoeuvres including accel-decels, side steps, and pull ups. Alongside the investigations involving piloted simulation, work has been carried out to incorporate this human-like control strategy into the SYCOS framework. Given a τ-based strategy – that is, knowing τ as a function of time – the closure relationship can be recast as:

$$v = d / \tau$$

and the evaluated *v* employed as reference values for the FCCM in the normal way.

Fig 13 shows typical responses from a 1100 ft accel-decel manoeuvre flown by a SYCOS piloted UH60 Flightlab simulation based solely on this strategy with the time to closure τ_m of the manoeuvre determined from pilot's internally generated guide τ_g by

$$\tau_m = k_g \, \tau_g$$

where τ_g is hypothesised to be:

$$\tau_g = \left(\frac{T^2 - t^2}{2t} \right). \qquad (2)$$

where *T* is the total manoeuvre time, in this case 29 sec. This approach is potentially important because it encapsulates in a single parameter k_g a whole manoeuvre strategy and a detailed specification of a velocity profile is not required.

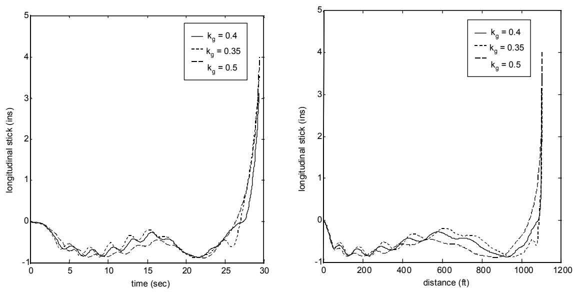


Figure 12 SYCOS responses from a tau-guided accel –decel k_g=0.35-0.5

Some appropriate trends in the control strategy can be identified, for example the sharp pull up at the end of the manoeuvre, but again it may be noted that the detail of the control activity is not what would be expected from a human pilot. An example of the stick activity of a human pilot flying a similar accel-decel manoeuvre in the HEMP trial on the flight simulation facility at the University of Liverpool is shown in Fig. 14. Over the greater part of the manoeuvre the coupling corresponds to value of $k_g \approx 0.5$ obtained by fitting an appropriate segment of the simulation data to the profile above (Eqn. 2). The general trends of the control activity are well captured by the SYCOS simulation but the start and finish behaviour is not. This discrepancy is to be expected at the start of the manoeuvre where the human pilot has to first pitch the helicopter into the acceleration demanded by the guide profile but at the very finish of the manoeuvre it appears that the pilot eases off to achieve a soft stop.

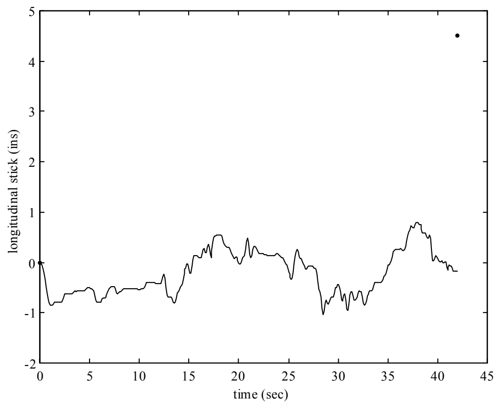


Figure 14 Human control activity for accel –decel

Positional References

While velocities are acceptable variables in which to define many manoeuvres, in some applications it is necessary to use actual displacements as references. This can be achieved in several ways. One that has been used in a number of studies replaces the output vector above with

$$y = (X, Y, Z, \psi)'.$$

For this output vector, it is appropriate to use a linear model of order twelve:

$$\dot{x} = Ax + Bu$$

where the state vector is $x = (X, Y, Z, u, v, w, p, q, r, \phi, \theta, \psi)$. The output equation is again

$$y = Cx$$

where C has a simple form since its elements are zero or one for the specified output.

In fact the product CB is zero in the differentiated equation

$$\dot{y} = CAx + CBu$$

so that

$$\dot{y} = CAx$$

and

$$\ddot{y} = CA^2 x + CABu$$

Following the earlier practice we write

$$\overline{C} = CA^2, \overline{D} = CAB$$

and put

$$Hy_{ref} = \ddot{y} + G\dot{y} + Hy$$

where $H=diag(\omega^2)$ and $G=diag(2\omega\zeta)$ so that the reference vector is tracked by the output in the manner of a damped second order system with natural frequency ω and damping factor ζ. The feedback for inversion and tracking is simply obtained from

$$Hy_{ref} = \overline{C}x + \overline{D}u + GCAx + HCx$$

as

$$u = \overline{D}^{-1}(Hy_{ref} - (\overline{C} + GCA + HC)x)$$

The structure of the SYCOS model with this formulation is shown in Fig 15 and is called the CTM (Compensating Tracking Model). It has been used successfully to investigate the simulation of deck traverses in the presence of airwake and turbulence in a study of the Heli/Ship dynamic interface [9]. There are additional parameters in the CTM model, the damping ζ and the frequency ω, for which values of 0.4 and 5 respectively have been used in various studies. This component of the structure and the values chosen for its parameters have not yet been validated against human pilot control activity but without position auto-guidance, the pilot is faced with holding a position reference essentially by controlling acceleration so *some* strategy must be adopted. It should also be noted that each reference channel can be tuned separately by selecting different values for ζ and ω.

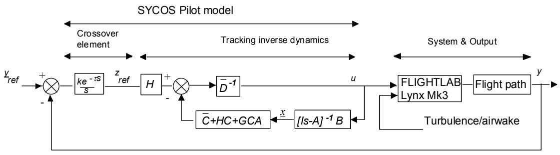


Fig 15 The structure of the CTM (Compensating tracking model)

The CTM structure modifies the basic stability properties of the SYCOS model. The tracking dynamics leading to Eqn. 1 are replaced by:

$$k\omega \;+ s(\omega^2 + 2\omega\varsigma s + s^2) = 0.$$

The criterion for stability of these dynamics is determined from Routh-Hurwitz theory to be

$$k < 2\varsigma\omega\,.$$

In the case of a simulation involving a non-linear helicopter model and atmospheric turbulence this stability boundary is a useful, but not definitive guide.

External biases.

Long–lasting gusts, or entry into a different wind condition, are ameliorated but not eliminated by the SYCOS pilot. The effect is reduced in proportion to the loop gain *k* but the human pilot would act to offset the changing trim position even to the extent of re-trimming the aircraft. It has been possible to emulate this behaviour to a certain extent by introducing a feedback loop which senses persistent changes in the operating conditions of the aircraft. The combination of aircraft/inverse should result in an identity relationship and departure from this can be sensed and corrective actions introduced. This is illustrated in Fig. 16 where $\bar{k}$ is the gain associated with this loop. It has successfully provided control offsets to back off the effects of changing wind conditions and as a result of the optimism introduced by being able to deal with such situations it was dubbed the SYCOS super-pilot.

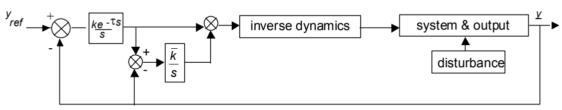


Figure16. The SYCOS super-pilot structure.

This backing off is illustrated in Fig. 17 where a Lynx helicopter, hovering in still air, is subjected after 2 seconds, to a 10 knot wind from the lateral (green 90) direction. The adaptation of the control positions to these new flight conditions can be seen. The value of $\bar{k}$ needs to reflect both the pilot's perception of a persistent change and the time scale of the adjustment to correct for it. In this example a time scale of 10 seconds ($\bar{k}$ = 0.1) has been employed. Similar results for a 10 knot wind from ahead are shown in Fig. 18.

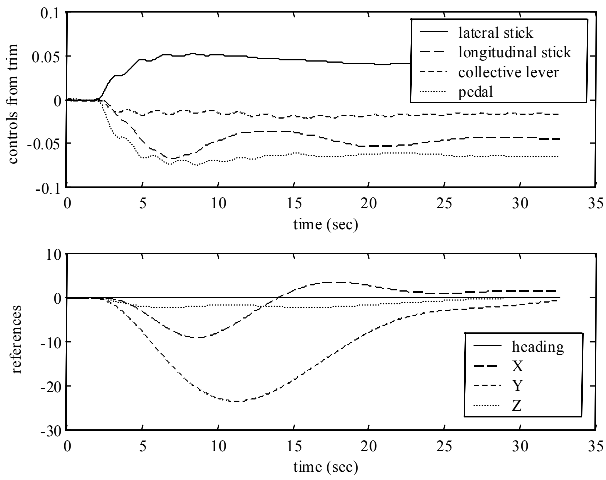


Figure 17. Super-pilot responses to green 90 instantaneous 10 knot wind references and controls.

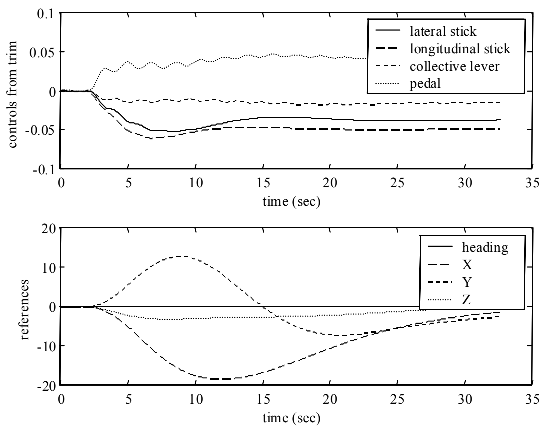


Figure 178. Super-pilot responses to instantaneous 10 knot wind from ahead: references and controls.

Non-linear Elements

Limitations in the authenticity of the predicted control activity led to the inclusion of additional components in the

SYCOS structure which attempted to capture specific human pilot characteristics. The basic structure was enhanced by (i) a dead zone to emulate uncertainly in detecting the error between outputs and reference values and (ii) hysteresis to capture hesitation in moving the controls. The latter effect could be observed on traces of collective lever and pedal control activity in piloted simulation. The enhanced structure is depicted in Fig. 19.

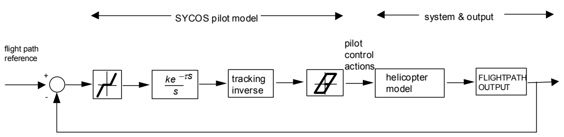


Figure 19 The SYCOS pilot with non-linear elements

Fig. 19 shows sample results from the use of this enhanced structure for a traverse of a Westland Lynx across a deck in the presence of turbulence and airwake [9]. It can be seen that the collective responses, and to a lesser extent, the pedal activity give a realistic comparison with the control activity of a human pilot in the AFS (Advanced Flight Simulator) facility at QinetiQ Bedford. The cyclic stick activity is not so good: it does not capture the higher level of activity of the human pilot who appears to have components of almost spontaneous activity.

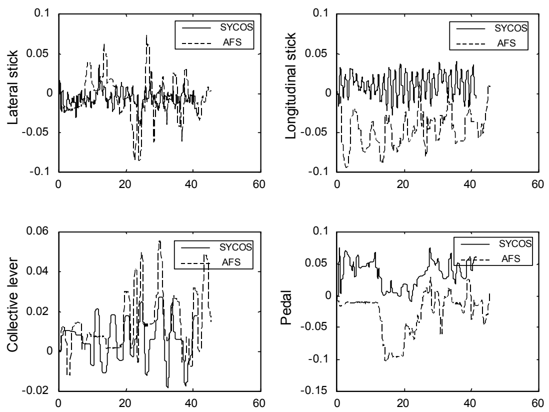


Figure 19. Predicted and human pilot control activity for a traverse in turbulence and airwake

The absence of the full range of detail of pilot activity makes the predicted responses deficient in the components which would allow the successful application of wavelet–based workload metrics [9].

PIO reduction.

The Appendix contains an analysis of the inverse component of the SYCOS model. It derives eigenvalues associated with the zero dynamics. They correspond to lightly damped oscillations in both lateral and longitudinal axes. This behaviour is typical of all types of conventional helicopter investigated so far (The tilt rotor directly controls the roll angle in helicopter mode so only the longitudinal oscillations are present). There may be more or less damping – or even encroach into unstable positive values – but the oscillatory behaviour appears to be generic. Earlier work [10] has associated this behaviour with tightly controlled piloting strategy which, as the workload increases, gives rise to a PIO. While there may be some debate about this being the source of PIO, the SYCOS model does include an inverse components which can introduce an oscillatory element into the predicted control actions. These are engendered by external disturbances or lack of smoothness in the supplied references and it is recognised that in situations of low workload they can be unrepresentative of what the human pilot would do. It is believed that the human pilot would not allow such behaviour to develop unless his attention was directed to more important activities. He would, it is believed, relax the performance requirements of the manoeuvre in order to subdue the unpleasant oscillations. Two ways of addressing this behaviour in the context of the SYCOS model have been considered. The first is to use pole placement techniques to calculate an appropriate feedback for the inverse model. The second is to amend the references by including an element of the associated attitude angle. The latter method is detailed in the Appendix. This has the effect of introducing a damping of the oscillations in a way that has a physical interpretation. The pole placement method essentially carries out a similar type of feedback but from a control design standpoint. To date, it is accepted that these devices, are not validated and are simply a fix to attempt to include more authenticity into the responses from SYCOS . What it does do is illustrate that the pilot has a wider piloting task than simply following references and that the basic SYCOS model has limitations in that respect.

Conclusions and Future work

This paper has brought together, and illustrated, the SYCOS pilot model and some recent developments. Its achievements may be listed as:

(i) It is effective at piloting rotorcraft through prescribed manoeuvres.

(ii) As required, it corrects for atmospheric turbulence and similar disturbances.

(iii) It can compensate for changes in wind speed and direction.

(iv) It is flexible in that the procedure can be applied to a variety of rotorcraft configurations even with FCS included.

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(v) It can replicate some of the features of human pilot control activity.

On the other hand there are certain limitations that are clear and should be targeted for immediate future work; here we identify three.

The first limitation is in the authenticity of the control activity. Human pilots are not comparable in the detail of their piloting technique so precise replication of time responses are inappropriate. Rather, the aim is to be able to produce control responses that give statistics for workload metrics that are indistinguishable from a human pilot. The human pilot trades off guidance and stabilisation tasks during a manoeuvre – this trade off may need to be explicitly included in the SYCOS model.

The second limitation is the nature of the approximate inverse in the SYCOS formulation. At present the pilot's *learning* is represented by an inverse of a 6 DOF linearisation of the helicopter dynamics about a reference flight condition. While this approach has been adequate for the applications so far considered, it is likely that the human pilot perceives a model of a simpler structure but one which adapts to a wider range of flight conditions.

Finally, the SYCOS model, being essentially corrective, does not anticipate future demands. For some external disturbances, for example due to turbulence, this is credible since they are random in nature. For tracking a flight path reference, however, it is unlikely to be valid since the pilot is fully aware of where he needs to be in the immediate future. There is scope therefore for including anticipation, in the form of a lead component, on the flight path references but not onto the vehicle outputs.

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Appendix

In order to illustrate the stability properties of the SYCOS pilot a 6 DOF freedom linear model of a conventional helicopter is used. It has an articulated rotor and its weight is similar to a Westland Lynx. These features are not critical to the general results that are derived below. The eigenvalues of the system matrix of the example linear model

$$\dot{x} = Ax + Bu$$

are:

-4.3304
-1.5983
-0.2349 + 0.8195i
-0.2349 - 0.8195i
-0.1443 + 0.4947i
-0.1443 - 0.4947i
-0.4730
-0.1231
0.0000

which display a conventional form. For example, the fast decaying mode, λ= –4.3304, is the damping in roll. the slow mode, λ= –0.1231, is a stable spiral mode, while the zero eigenvalue is associated with the heading angle, which does not directly influence the dynamics. The output equation is:

$$y = Cx$$

for the output y given by:

$$y = (U, V, W, \psi)'$$

and differentiating gives

$$\dot{y} = C\dot{x} = CAx + CBu .$$

Ultimately, seeking a form that can be solved for the control *u* we obtain:

$$\overline{y} = \overline{C}x + \overline{D}u$$

where

$$\overline{y} = (\dot{U}, \dot{V}, \dot{W}, \ddot{\psi})'$$

and

$$\overline{C} = \begin{bmatrix} CA(1{:}3,:) \\ CA^2(4,:) \end{bmatrix}, \overline{D} = \begin{bmatrix} CB(1{:}3,:) \\ CAB(4,:) \end{bmatrix}$$

so that

$$u = \overline{D}^{-1}(\overline{y}_{ref} - \overline{C}x) .$$

Substituting this control into the linear system gives

$$\dot{x} = Ax + B(\overline{D}^{-1}(\overline{y}_{ref} - \overline{C}x)$$

or

$$\dot{x} = (A - B\overline{D}^{-1}\overline{C})x + B\overline{D}^{-1}\overline{y}_{ref}$$

where the modified (or constrained) system matrix now has eigenvalues

-0.3886 + 5.4897i
-0.3886 - 5.4897i
-0.1803 + 2.4075i
-0.1803 - 2.4075i
0.0000
0.0000
-0.0000 + 0.0000i
-0.0000 - 0.0000i
0.0000

There are now four additional zero eigenvalues corresponding to the four imposed constraints. The remaining modes correspond to oscillations about the centre of mass round the longitudinal and lateral axes. This oscillatory behaviour is typical of all conventional helicopters studied to date.

For the constrained side-slip condition, the output y is given by:

$$y = (v, U, V, W, v)'$$

but in the equation

$$\dot{y} = CAx + CBu .$$

while *CB* is singular, it no longer has its first row as zeros. As a consequence, direct differentiation will involve $\dot{u}$ in all four equations and there is no obvious way of solving for *u* in terms of *x* and *y*. This pathological case is dealt with by noting that since CB is of rank 3 there must be a vector λ such that:

$$\lambda' CB = 0$$

It follows that differentiation leads to:

$$\lambda' \ddot{y} = \lambda' CA^2 x + \lambda' CABu$$

which provides the fourth equation necessary to solve for u. That is:

$$u = \overline{D}^{-1}(\overline{y}_{ref} - \overline{C}x).$$

where

$$\overline{y} = (\dot{U}, \dot{V}, \dot{W}, \lambda' \dot{y})',$$

and

$$\overline{C} = \begin{bmatrix} CA(1{:}3,:) \\ \lambda' CA^2 \end{bmatrix}, \overline{D} = \begin{bmatrix} CB(1{:}3,:) \\ \lambda' CAB \end{bmatrix}.$$

The resulting side-slip constrained system matrix has eigenvalues

-0.4750 + 6.0862i
-0.4750 - 6.0862i
-0.1821 + 2.3856i
-0.1821 - 2.3856i
-0.0000
0.0000
0.0000
-0.0000
-0.0000

which are very similar to those of the constrained heading case.

Returning to the constrained heading formulation, when the inverse components are fitted into the SYCOS structure, the state matrix for the complete system is (setting the delay τ to zero):

$$\begin{bmatrix} A - B\overline{D}^{-1}\overline{C} & -BK\overline{D}^{-1}\hat{C} \\ -B\overline{D}^{-1}\overline{C} & A - BK\overline{D}^{-1}\hat{C} \end{bmatrix}$$

where

$$\hat{C} = \begin{bmatrix} C(1{:}3,:) \\ CA(4:) \end{bmatrix}$$

implements the rate of change of ψ. The eigenvalues of the whole SYCOS system for a gain k=2 are:

-0.3886 + 5.4897i
-0.3886 - 5.4897i
-4.3304
-0.1803 + 2.4075i
-0.1803 - 2.4075i
-1.5983
-0.2349 + 0.8195i
-0.2349 - 0.8195i
-0.1443 + 0.4947i
-0.1443 - 0.4947i
-0.4730
-0.1231
0.0006
0.0000
-2.0000
-2.0000
-2.0000
-2.0000

These eigenvalues replicate those of both the helicopter model and the inverse system except that the four zeros of the inversion now have a value of –2 corresponding to the gain k=2.
The modes of the inverse system (the zero dynamics) are usually close to marginal stability. It is possible to stabilise them by modifying the references. For example, if the reference V is changed to $V+\delta\phi$ where δ is a constant which scales the modification then, with δ=1 the eigenvalues of the inverse system become:

-0.8632 + 5.4395i
-0.8632 - 5.4395i
-0.1802 + 2.4072i
-0.1802 - 2.4072i
0.0000
-0.0000
-0.0000
0.0000
-0.0000

The pitch dynamics have been left virtually unchanged while the damping of the rolling mode has been significantly increased. The pitch dynamics can be similarly stabilised. The modelling view of this modification is that the pilot is sacrificing his attention to the flight path in order to stabilise the attitude of the aircraft.