Simplified approach for modelling pilot pursuit control behaviour in multi-loop flight control tasks

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Abstract: A control-theoretic procedure for modelling human pilot pursuit control behaviour is presented. The procedure allows for the development of human pilot behavioural models in multi-loop flight control tasks in a simplified framework emphasizing frequency-domain techniques. Beginning with the primary control loops, each control loop is closed using a combination of output-rate feedback and output-error feedback. It is demonstrated that this approach can accommodate any vehicle dynamics that can be stabilized by a human pilot. In addition, the modelling approach identifies vehicle dynamics that approach the limits of human pilot controllability. The well-documented increase in pilot effective time delays that have been shown to accompany vehicle dynamics requiring lead compensation is also replicated by this modelling approach. A method for predicting handling-qualitiy levels that would be assigned to a particular vehicle and task is presented. A visual cue model is included, which can approximate the effects of degraded visual cues. It is shown that this model can be used to reproduce the three most important measurable effects of visual cue quality upon human operator dynamics, namely, an increase in 'effective' pilot time delay, a decrease in crossover frequency, and an increase in error-injected remnant. The ability of the modelling procedure to accommodate different levels of pilot aggressiveness in completing manoeuvres is demonstrated. Finally, an application to a multi-axis rotorcraft flight control problem is presented.

Keywords: pilot models, handling qualities, manual control

1 INTRODUCTION

Modelling human pilot control behaviour is an important aspect of any pilot/vehicle analysis technique. Models of the human pilot that have been developed can be categorized as isomorphic, algorithmic, or behavioral-based [1]. Each of the models that have been developed in these areas has proven useful in a variety of applications. For example, the structural model of the human pilot has been employed in several pilot/vehicle analyses [2–4]. As useful as these modelling approaches are, their inclusion in computer simulations of realistic piloting tasks can be quite complex and requires some 'art' in their successful application. The purpose of the research to be described is to create a unified, albeit simplified, pilot modelling approach that requires a minimum set of application rules and that is applicable to the study of realistic piloting tasks. The proposed model is a simplification of the structural pilot model and builds upon research published nearly 30 years ago [5]. The model will be applicable only to the so-called pursuit tracking tasks in which the pilot can observe system output and command variables, i.e. purely compensatory tasks in which error information, alone, is available will not be treated.

2 MODELLING APPROACH FOR SINGLE AXIS TASKS

2.1 Introduction

Figure 1 represents a model of a human pilot in a simple, single-axis tracking task that will serve as a

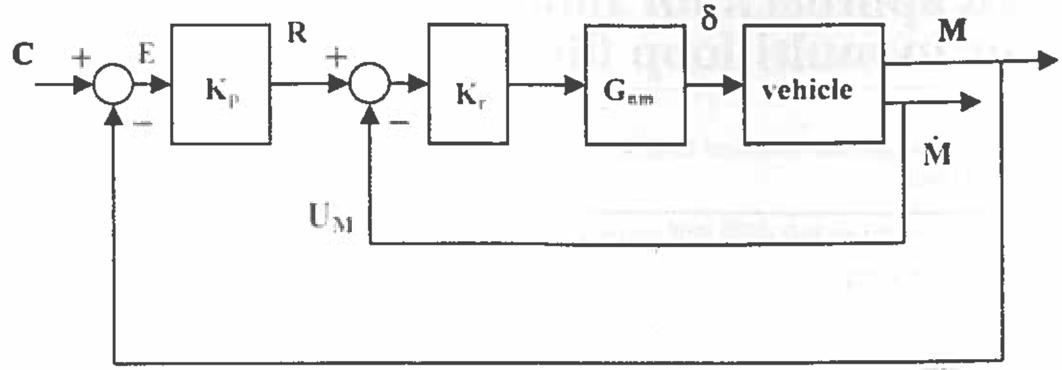

Fig. 1 A model of human pilot control behaviour

point of departure for this study. In Fig. 1, M and $\dot{M}$ represent the vehicle output and output rate for the response variable being controlled and C represents the input or desired value of M. G_{nm} represents a highly simplified model of the pilot's neuromotor dynamics in the limb (arm or leg) that create the control inputs. This model will be given by [2]

$$G_{nm} = \frac{10^2}{s^2 + 2(0.707)10s + 10^2} \tag{1}$$

The normalization procedure that is part of the pilot modelling procedure obviates the necessity of providing units in equation (1). K_p and K_r represent gains on the output error and the difference $R - U_M$, respectively. K_r is chosen as the gain value that results in a minimum damping ratio of $\zeta_{min} = 0.15$ for any oscillatory mode in the inner, closed-loop transfer function $\dot{M}/R$ in Fig. 1. Typically, the oscillatory mode will emanate from the neuromotor roots. Alternately, K_r can be chosen on the basis of a Bode plot of the $\dot{M}/R$ transfer function. Here, K_r is the value that will yield a 10 dB magnitude difference between the 'neuromuscular mode' peak and the mid-frequency magnitude of the transfer function. This is exemplified by Fig. 2. This alternate procedure is often easier when more complicated vehicle dynamics are in evidence, as will be the case in a later section.

The gain K_p is chosen to provide a desired, open-loop crossover frequency for the entire pilot model. The nominal value of this crossover frequency will be 2.0 rad/s. This value is not arbitrary and represents a reasonable approximation of moderately high-gain pilot control. See references [6, 7] for crossover frequency values that have been measured in flight test. The reader will note that no time delay or inceptor force/feel dynamics are included in the model. This simplification allows a single crossover frequency of 2.0 rad/s for the M/E transfer function to be used for both handling qualities and performance analysis.

In the model of Fig. 1, a pursuit 'display' is assumed. Here 'display' is used in a general sense to mean a set of command/response variables that can be observed by the pilot. 'Pursuit' assumes the pilot can observe system output (and infer or sense output-rate), system command, and from output and command, system error. Figure 3(a) represents a pursuit display in a single-axis laboratory human-in-the-loop tracking experiment. If only system error is presented to the human, as shown in Fig. 3(b), a 'compensatory' display results. The model of Fig. 1 will not be applicable to the study of systems in which only compensatory behaviour is possible, e.g. when a pilot is attempting to null errors in a flight director display where only error information is displayed.

The model of Fig. 1 will now be implemented with the following stereotypical controlled element (vehicle) dynamics

$$Y_c = \frac{1}{s(s+10)};\ \frac{1}{(s^2+2(0.707)5s+25)};\ \frac{1}{s(s+4)};\ \frac{1}{s(s+2)};\ \frac{1}{s^2};\ \frac{0.696(s+0.14)}{s^3+0.424s^2+0.0353s+0.397} \tag{2}$$

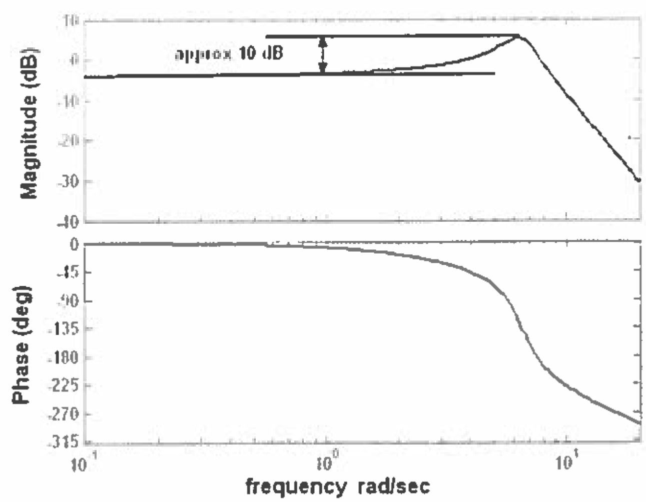

Fig. 2 Choosing K_r from the Bode diagram of $\dot{M}/R$ (Fig. 1)

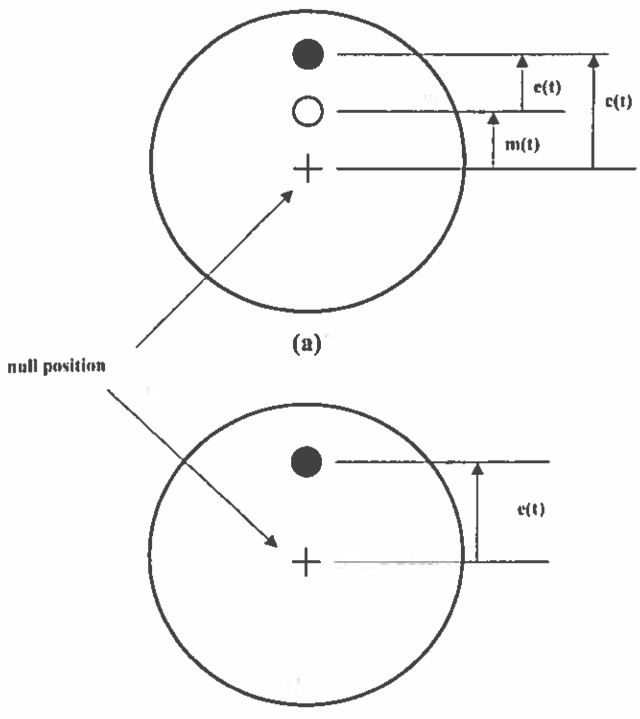

Fig. 3 Pursuit (a) and compensatory (b) displays in a laboratory tracking task

The last transfer function represents the pitch-attitude dynamics of an unaugmented, hovering V/STOL aircraft taken from reference [8]. Figure 4 shows the Bode diagrams of the resulting open-loop pilot/vehicle transfer functions (M/E in Fig. 1) for the six controlled elements given in equation (2) and an additional controlled element to be introduced.

As Fig. 4 indicates, the dictates of the 'crossover model' of the human pilot [9] are met in each case, i.e. around the open-loop crossover frequency

$$\frac{M}{E}(s) \approx \frac{\omega_c}{s} e^{-\tau_e s} \tag{3}$$

where ω_c represents the crossover frequency and τ_e represents an 'effective' time delay. 'Effective delay' in the right-hand side of equation (3) means that any phase lags in the Bode plot of the transfer function on the right-hand side of equation (3) beyond the -90° lag from the ω_c/s term are subsumed into a delay term. These phase lags would accrue from actual time delays in human input/output characteristics, from neuromuscular and force/feel system dynamics, and from higher-order dynamics in the controlled element, itself. The value of τ_e that one would choose in fitting the crossover model would be a function of the particular controlled element.

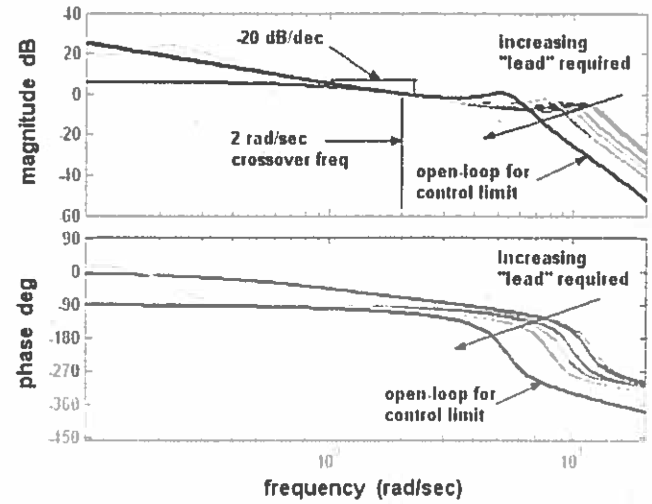

Fig. 4 Bode diagrams of open-loop pilot/vehicle transfer functions for the controlled elements of equation (2) and an element representing limits of manual control

In particular, τ_e would increase as the necessity of required lead in an equivalent, single-loop, serial model of the human pilot increases (increase in the lead time constant). The dependence of τ_e on required lead is an important characteristic of measured pilot/vehicle transfer functions [9]. Values of K_p and K_r that resulted from the application of the pilot model 'adjustment rules' stated below equation (1) are given in Table 1. The last controlled element in the table will be described in a section to follow. The order in which the controlled elements are listed in the first column of Table 1 corresponds to the requirement of lead generation in terms of an equivalent, single-loop, serial model of the human pilot, i.e. as one moves down the column, more lead generation would be required of such a model. In terms of the pilot model discussed here, however, rate feedback is always needed.

Table 1 Pilot model gain values

Controlled element	K_r	K_p
$\frac{1}{s(s+10)}$	20.5	2.91
$\frac{1}{(s^2+2(0.707)5s+25)}$	13.5	3.62
$\frac{1}{s(s+4)}$	11.5	2.56
$\frac{1}{s(s+2)}$	9.19	2.35
$\frac{1}{s^2}$	7.58	1.91
$\frac{0.696(s+0.14)}{s^3+0.424s^2+0.0353s+0.397}$	11.3	1.96
$\frac{1}{s^2(s+11)}$	58	1.76