

A Full Authority Helicopter Adaptive Neuro-Controller

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Abstract—This paper treats the development of a full authority, six degree of freedom controller for rotorcraft which provides autonomous, high performance, robust tracking of a specified trajectory. The nominal controller is a two time scale input-output-linearizing controller which exploits the well known nonlinearities in the equations of motion, but ignores the variations in the aerodynamically varying quantities. The nominal controller is enhanced with a simple two layer adaptive neural network which accommodates for the variations in the dynamics and guarantees ultimate boundedness of the tracking errors in closed loop. Simulation results are presented employing a high fidelity simulation for the Apache helicopter which has been validated at several flight conditions against flight test data.

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1. INTRODUCTION

The autonomous control of a helicopter to high accuracies is a very challenging problem due to the extensive nonlinearities in the helicopter dynamics, the changing dynamic properties with flight condition, and basically the inability to characterize the aerodynamics of the vehicle without high levels of fidelity incorporating empirically determined quantities. In particular, traditional proportional+integral+derivative (PID) and single-input-single-output (SISO) frequency domain approaches are very specific to the locally-determined model, while the modern linear approaches do not provide robustness to the swiftly varying nonlinear dynamics. In this paper we extend the work of [1] to include an outer loop feedback inversion and we apply the controller to a comprehensive rotorcraft simulation model which is characteristic of the actual vehicle dynamics and is validated against flight test data for several flight conditions.

2. THE FLIGHTLAB SIMULATION

An important step in the validation of a flight control system is its implementation in a nonlinear simulation. A sophisticated simulation model can be used to narrow the gap between controller synthesis and implementation on an actual vehicle. The FLIGHTLAB model of the Apache helicopter uses blade element theory to

calculate the forces on the rotor, look-up tables to provide aerodynamic coefficients, elastic modes for the blades and the fuselage, and second harmonic dynamic inflow just to name a few of the aspects related to the comprehensive nature of the simulation model. The system is solved in stages in order to maximize the efficiency and to allow for parallel computation. Because of the look-up tables and solution procedure, it is virtually impossible to obtain an explicit analytical model of the system. Clearly, this makes traditional, model-based, control design difficult and makes feedback linearization even more so. However, this also makes the controller synthesis procedure more realistic because an analytical model is even more difficult to obtain for an actual helicopter, in particular, due to the uncertainties in the aerodynamic model. The lack of an analytical model leads to the necessity of finding an approximate model of the system and fitting parameters to the model either by using input-output characteristics or by numerical techniques in the simulation.

3. MATHEMATICAL FORMULATION

In order to efficiently use the inherent controls of the helicopter, the nominal controller to be designed will be based on physical principles of the helicopter, i.e., decoupling of fast and slow dynamics and collective being primarily a force control and cyclic and pedals being primarily moment controls. There is in general a natural time scale separation between the rotational and translation dynamics of the vehicle. When developing a model for control purposes there may be inherent coupling between the inner and outer loop which masks the separation. Therefore, by making some decoupling approximations and by increasing the inner loop bandwidth using feedback, the time scale separation can be artificially forced. The method of forcing the time scale separation is a modification of the work done by Heiges [2] and Prasad and Lipp [3] and it is described in the control law development.

Approximate Equations of Motion

For the purpose of synthesizing a nominal controller, we use a simple linearized representation for the aerodynamics of the vehicle:

$$\dot{x} = Fx + G\eta + \Delta(x, \eta, t) \quad (1)$$

$$x = [u \ v \ w \ p \ q \ r \ X \ Y \ Z \ \phi \ \theta \ \psi]^T$$

$$\eta = [\delta_{lat} \ \delta_{lon} \ \delta_{col} \ \delta_{tr}]^T$$

The first six terms in the state vector, x , are the body rates, the next three are inertial positions and the last three are Euler angles. The coefficients of the matrices F and G are partial derivatives evaluated at a nominal hover trim condition and thus F and G represent constant Jacobian matrices. These matrices are obtained from the FLIGHTLAB simulation by trimming the vehicle at the desired flight condition, freezing the integration of the body states, perturbing each state and control by a small amount, and noting the resulting change in the accelerations. A central differencing scheme was used and the resulting accelerations were averaged over 36 rotor revolutions to eliminate the dependence of the approximate model on the rotor azimuth position (and thus the time) and to ensure that the rotor has been trimmed out (a quasi-steady approximation of rotor dynamics). Normalized states and controls were used in order to allow for uniform perturbation sizes, and x is the nondimensional perturbation state vector expressed in the body frame. Define S to be the scaling matrix and x_{BTRIM} to be the state vector in trim, such that

$$x_B = Sx + x_{BTRIM}$$

$$\dot{x}_B = S\dot{x} + \dot{x}_{BTRIM}$$

where x_B is the total, dimensional state vector with the first six terms expressed in the body frame and the last six terms are the inertial positions and the Euler angles, respectively. The vector \dot{x}_{BTRIM} is not necessarily zero because \dot{X} may be nonzero in trim. The

system is now defined in the body frame. But desired commands, in general, are in terms of inertial quantities so it is convenient to express the system in a combined inertial/Euler angle frame (herein denoted *inertial frame* for simplicity) as follows: Define the body to inertial transformation for the system, $\mathcal{L}_{IB}(x)$, so that $x_I = \mathcal{L}_{IB}(x)x_B$.

Thus, the approximate model from the FLIGHTLAB simulation is

$$\begin{aligned}\dot{x}_I &= \mathcal{L}_{IB}(x)\dot{x}_B + \dot{\mathcal{L}}_{IB}(x)x_B \\ &= [\dot{\mathcal{L}}_{IB}(x)S + \mathcal{L}_{IB}(x)SF]x + \dot{\mathcal{L}}_{IB}(x)x_{B_{TRIM}} + \mathcal{L}_{IB}(x)SG\eta\end{aligned}\quad (2)$$

where x_I is the inertial state vector and

$$x_I = [\dot{X} \ \dot{Y} \ \dot{Z} \ \dot{\phi} \ \dot{\theta} \ \dot{\psi} \ X \ Y \ Z \ \phi \ \theta \ \psi]^T$$

The body to inertial transformation depends upon the Euler angles and can be expressed as

$$\mathcal{L}_{IB} = \begin{pmatrix} L_{IB} & 0_{3 \times 3} & 0_{6 \times 6} \\ 0_{3 \times 3} & L_{IBAR} & \\ & 0_{6 \times 6} & I_{6 \times 6} \end{pmatrix} \quad (3)$$

where from Ref. [4]

$$L_{IB} = \begin{bmatrix} c\theta c\psi & c\theta s\psi & -s\theta \\ s\phi s\theta c\psi - c\phi s\psi & s\phi s\theta s\psi + c\phi c\psi & s\phi c\theta \\ c\phi s\theta c\psi + s\phi s\psi & c\phi s\theta s\psi - s\phi c\psi & c\phi c\theta \end{bmatrix}$$

where c denotes the cosine operation and s denotes the sine operation. and [4]

$$L_{IBAR} = \begin{bmatrix} 1 & s\phi t\phi & c\phi t\theta \\ 0 & c\phi & -s\phi \\ 0 & s\phi se\phi & c\phi se\theta \end{bmatrix}$$

where t denotes the tangent operation and se denotes the secant operation.

Controller Synthesis

The outer loop inversion provides the collective pitch control and the pitch and roll pseudocommands based on the X , Y , and Z direction pseudocontrols. Thus, the small forces

produced by the moment controls, i.e., lateral cyclic, longitudinal cyclic, and tail rotor collective are ignored in the outer loop. Additionally, to ensure that the outer loop inversion is truly on a slow time scale, the attitudes are assumed to have steadied out at the pseudocommand values and thus any appearances of ϕ and θ in the equations of motion are replaced with $\bar{\phi}$ and $\bar{\theta}$ in the outer loop control laws.

The pseudocontrol vector defines the desired dynamic behavior, where the *com* subscript denotes the commanded value:

$$v = \dot{x}_{I_{com}} + A(x_{I_{com}} - x_I) \quad (4)$$

The pitch and roll pseudocommands are computed by considering the commanded tilt on the vehicle:

$$\bar{\phi} = \arctan\left\{\frac{v_1 \sin \psi_{com} - v_2 \cos \psi_{com}}{v_3 - g}\right\} + \phi_{trim} \quad (5)$$

$$\bar{\theta} = \arctan\left\{\frac{v_1 \cos \psi_{com} + v_2 \sin \psi_{com}}{v_3 - g}\right\} + \theta_{trim} \quad (6)$$

For convenience, define the *inertial frame dynamics field*, $f(\bar{x})$, as

$$f(\bar{x}) = [\dot{\mathcal{L}}_{IB}(\bar{x})S + \mathcal{L}_{IB}(\bar{x})SF]x + \dot{\mathcal{L}}_{IB}(\bar{x})x_{B_{TRIM}} \quad (7)$$

and the *inertial frame control matrix*,

$$g(\bar{x}) = \mathcal{L}_{IB}(\bar{x})SG \quad (8)$$

where \bar{x} is simply x with the elements ϕ and θ replaced by $\bar{\phi}$ and $\bar{\theta}$.

Let f_i denote element i of the field $f(x)$ and let g_{ij} denote the element at row i , column j of the matrix $g(x)$. The collective is assumed only to produce a vertical force and is thus computed from the equation

$$\Delta\delta_{col} = \frac{\{v_3 - f_3(\bar{x})\}}{g_{33}(\bar{x})} \quad (9)$$

where the total collective control is computed by adding $\Delta\delta_{col}$ to the trim value of collective

from the hover flight condition. The (3,3) element of g is the control sensitivity of \ddot{Z} with respect to main rotor collective pitch, and v_3 is the third, or Z -element of v .

The quantities $\bar{\phi}$, $\bar{\theta}$, and ψ_{com} are passed through second order filters, of which the output signals, rates, and accelerations are used as tracking commands for the inner loop. The effect of $\Delta\delta_{col}$ is included in the synthesis of the inner loop control law.

The inner loop inversion control law provides the moment controls; lateral and longitudinal cyclic, and tail rotor collective pitch in terms of the moment pseudocontrols, v_4 , v_5 , and v_6 . Define the inner loop dynamic field, $f_I(x)$, as

$$f_I(x) = \begin{bmatrix} f_4(x) + g_{43}(x)\Delta\delta_{col} \\ f_5(x) + g_{53}(x)\Delta\delta_{col} \\ f_6(x) + g_{63}(x)\Delta\delta_{col} \end{bmatrix} \quad (10)$$

and the inner loop control matrix

$$g_I(x) = \begin{bmatrix} g_{44}(x) & g_{45}(x) & g_{46}(x) \\ g_{54}(x) & g_{55}(x) & g_{56}(x) \\ g_{64}(x) & g_{65}(x) & g_{66}(x) \end{bmatrix} \quad (11)$$

where g_I represents the sensitivity of $\ddot{\phi}$, $\ddot{\theta}$, and $\ddot{\psi}$ to changes in lateral cyclic, longitudinal cyclic, and tail rotor collective pitch. Also define the inner loop pseudocontrol vector

$$v_I = \begin{bmatrix} v_4(x) \\ v_5(x) \\ v_6(x) \end{bmatrix} \quad (12)$$

and the inner loop control vector

$$u_I = \begin{bmatrix} \Delta\delta_{lat} \\ \Delta\delta_{lon} \\ \Delta\delta_{ped} \end{bmatrix} \quad (13)$$

The control law is

$$u_I = g_I^{-1}\{v_I - f_I(x)\} + u_{ITRIM} \quad (14)$$

where u_{ITRIM} is a vector of trim values for lateral cyclic, longitudinal cyclic, and tail rotor collective from the hover flight condition.

All commands and pseudocommands are filtered in order to provide rate and acceleration commands. Both the inner and outer loop inversions leave residual dynamics after the inversion. However, if the time scales between the inner and outer loop are sufficiently separated and the dynamics are sufficiently decoupled, then the two time scale inversion process can be considered to be a full state feedback linearization of two independent systems and thus zero dynamics conditions do not become an issue.

Adaptive Control Using Online Neural Networks

To this point the synthesis technique has been presented for the nominal controller for the helicopter dynamics. Nothing has been shown yet to guarantee any robustness or stability of the controller in the presence of the inversion error. In this section, the theory approach presented in [1] is applied for the design of a stable adaptation algorithm to be used in conjunction with the nominal controller described in the previous section. This approach provides an ultimate boundedness guarantee in the face of bounded uncertainties, which is presented in [1]. In this paper we also apply the neuro-controller to the inner loop, but we extend the results by applying an outer loop inversion controller for full authority control and we apply the controller to a comprehensive, validated simulation model which is characteristic of an actual helicopter. The most significant errors and variations are assumed to occur within the inner loop, so the outer loop controller remains fixed. In the following sections we will consider the application of the neural network to the inner loop equations of motion.

Development of the network equations—In order to consider the network applied to the inner loop equations, it is convenient to focus only on the dynamics of the Euler angles for analysis. Defining the vector of Euler angles, $y = \{\phi, \theta, \psi\}$, the closed loop moment equa-

tions can be written as

$$\ddot{y} = U - \chi \quad (15)$$

where χ denotes the *inversion error* and U represents the moment portion of the pseudocontrol vector. If the inversion error can be eliminated in the presence of model uncertainties, then the controller provides robust performance and stability. The network is thus introduced for the sole purpose of cancelling the inversion error. The network outputs are adaptive signals which enter the equations for the components of U , i.e., U_ϕ , U_θ , and U_ψ in an additive fashion, generating equations of the following form:

$$U_\phi = K_{p\phi}(\phi_c - \phi) + K_{d\phi}(\dot{\phi}_c - \dot{\phi}) + \ddot{\phi}_c - U_{ad\phi} \quad (16)$$

$$U_\theta = K_{p\theta}(\theta_c - \theta) + K_{d\theta}(\dot{\theta}_c - \dot{\theta}) + \ddot{\theta}_c - U_{ad\theta} \quad (17)$$

$$U_\psi = K_{p\psi}(\psi_c - \psi) + K_{d\psi}(\dot{\psi}_c - \dot{\psi}) + \ddot{\psi}_c - U_{ad\psi} \quad (18)$$

This modifies the closed loop system dynamics to equations of the form:

$$\ddot{y}_i + K_{d_i}\dot{y}_i + K_{p_i}y_i = \ddot{y}_{i_c} + K_{d_i}\dot{y}_{i_c} + K_{p_i}y_{i_c} + \chi_i - U_{ad_i} \quad (19)$$

which can be rewritten in terms of the tracking errors ($\tilde{y} = y_c - y$):

$$\ddot{\tilde{y}}_i + K_{d_i}\dot{\tilde{y}}_i + K_{p_i}\tilde{y}_i = U_{ad_i} - \chi_i \quad (20)$$

so that the inversion is perfect when the network exactly reconstructs the inversion error. The interface of the network within the inner loop controller structure is illustrated in Figure 1. The quantity $U_{ad_i} - \chi_i$ is an ideal measure for how the network is performing and it will be termed the *adjusted inversion error*.

It is helpful to rewrite Equation 20 in state space form. For each channel the error dynamics are a second order system of the form (dropping the i subscripts for convenience)

$$\dot{e} = Ae + b(U_{ad} - \chi) \quad (21)$$

where $e = [\tilde{y} \ \dot{\tilde{y}}]^T$, $b = [0 \ 1]^T$, and

$$A = \begin{bmatrix} 0 & 1 \\ -K_p & -K_d \end{bmatrix} \quad (22)$$

The task now is to perform the reconstruction based on available measurements in the system. Thus, the adaptive control law in each channel is defined as

$$U_{ad_i} = w^T g \quad (23)$$

$$\dot{w} = -ks g \quad (24)$$

where the vector g is a set of basis functions used to approximate the uncertainty and the vector w is the set of coefficients of each basis function. The update law is designed based on Lyapunov stability of the error signals in the system and is the result of the work of Kim and Calise in [5] and is updated in [6]. The s term is an error metric dependent upon the tracking errors in the system, defined as follows:

$$s = \frac{1}{2K_p}\tilde{y} + \frac{1}{2\lambda K_p}\dot{\tilde{y}} \quad (25)$$

where e is the tracking error and λ is defined in terms of the Lyapunov equation used to prove stability in Reference [7].

Now define the optimal vector of weights [7] for each channel as w^* and let $\tilde{w} = w - w^*$. This enables Equation 21 to be rewritten as

$$\dot{e} = Ae + b\tilde{w}^T g + b(w^{*T} g - \chi) \quad (26)$$

Let

$$\epsilon \equiv \sup_z |w^{*T} g(z) - \chi(z)| \quad (27)$$

which represents the residual inversion error that is unmodeled by the neural network. The vector z consists of all known independent variables of the inversion error. Equation 27 essentially defines ϵ as the worst case difference between the inversion error and the best approximation for the inversion error for the given set of network inputs.

4. RESULTS

In this paper we consider the autonomous tracking of an elliptical turn command. The essence of the command is the performance of three revolutions in yaw at one rad/sec, while maintaining a constant northbound inertial speed of 50 fps (15 m/s), all other directional speeds zero, and no change in altitude. The selected linear dynamics were taken from Kim [7] as $K_p = 0.188$ and $K_d = 0.613$ for the translational states and $K_p = 7.0$, $K_d = 10.6$ for the rotational states. These gains provide a closed loop system in which the rotational dynamics are significantly faster than the translational dynamics, and in which the slow dynamics are critically damped, while the fast dynamics are well overdamped. The reason for overdamping the outer loop dynamics is to mask the effects of the unmodeled rotor dynamics, which are unaccounted for in the theory. The adaptation rate was uniformly adjusted as described in Ref [6] and fixed at a value of 2800. This value corresponds the speed of update of the weighting coefficients and does not correspond to any physical quantity in an absolute sense. The selection is, in general, a tradeoff amongst achievable control bandwidth, allowable control activity, and tracking performance. Figures 2–4 are some of the outer loop tracking responses. Notably, all of the speed tracking errors remain within 3 fps (1 m/s), and the altitude error is less than one meter as well. A collection of the inner loop responses is shown in Figures 5–10. All of the tracking errors are minimal, and important to note is the consistent tracking performance between the outer loop speed commands, and the inner loop pseudo-commands (which are computed based upon outer loop commanded tilt). Figures 11 and 12 are the control motions for lateral cyclic and tail rotor collective pitch respectively. Both indicate that the controls remain within the actuation rate and position limits. A further point

to note is the appearance of multiple harmonics of the rotor frequency, 27 rad/sec. This is the transmission of the rotor vibrations into the vehicle dynamics, which is present because the rotor is never fully trimmed.

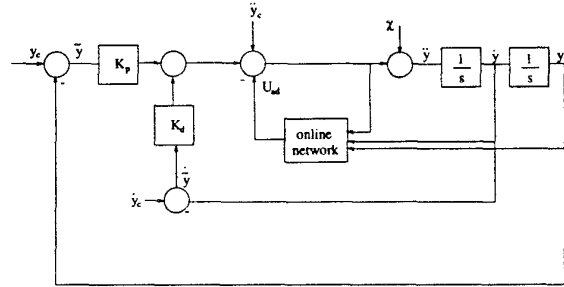


Figure 1: Interface of Neural Network within Inner Loop Controller Structure

5. CONCLUSIONS

In this paper, a controller design methodology was presented which is applicable to systems with uncertain and rapidly varying nonlinear dynamics. The synthesis exploits knowledge of the dynamics at a nominal flight condition for performing an approximate model inversion of the equations of motion. A simple, low order, neural network is used to accommodate the changing, uncertain dynamics, to provide guaranteed boundedness in the tracking errors. For demonstration, simulation results are presented in a validated, high fidelity simulation model of the Apache helicopter. The command performed is an aggressive, challenging maneuver called the elliptical turn, which brings the vehicle through the entire range of sideslip angles. Because the order of the simulation model is significantly higher than that used for controller design, a particularly high damping ra-

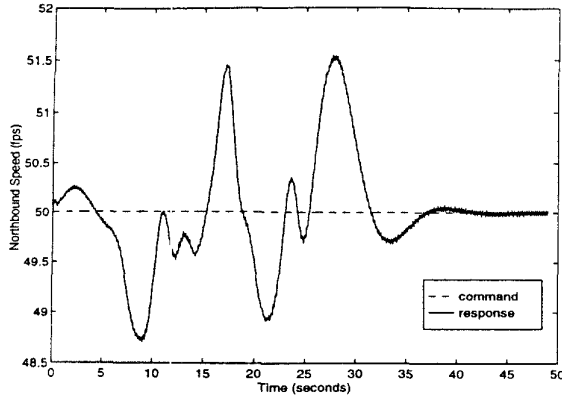


Figure 2: Northbound Speed History (Elliptical Turn, $k = 2800$)

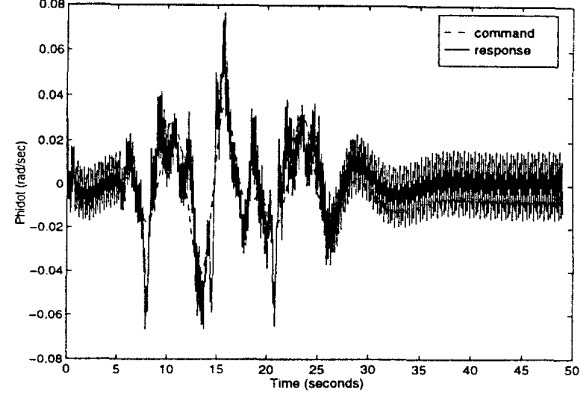


Figure 5: Euler Roll Rate History (Elliptical Turn, $k = 2800$)

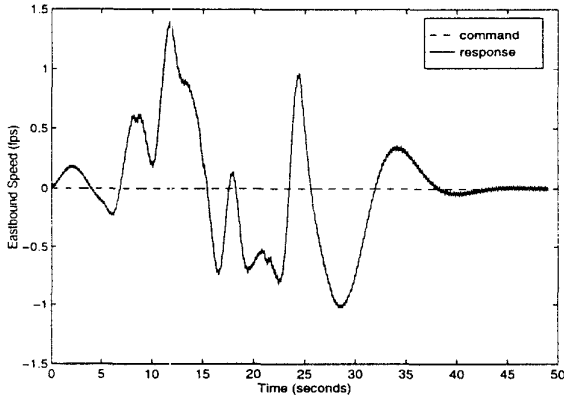


Figure 3: Eastbound Speed History (Elliptical Turn, $k = 2800$)

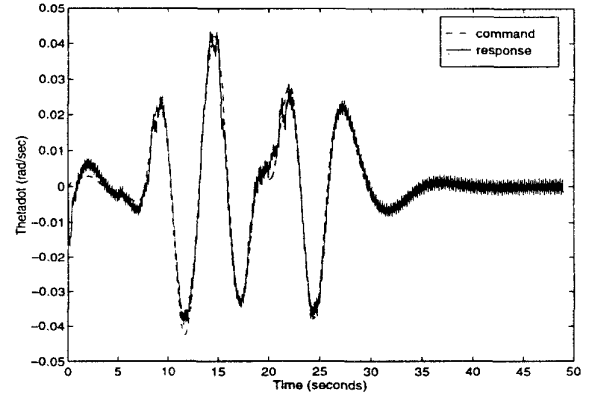


Figure 6: Euler Pitch Rate History (Elliptical Turn, $k = 2800$)

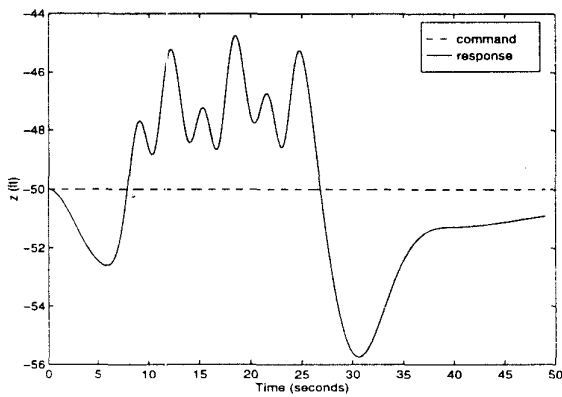


Figure 4: Altitude History (Elliptical Turn, $k = 2800$)

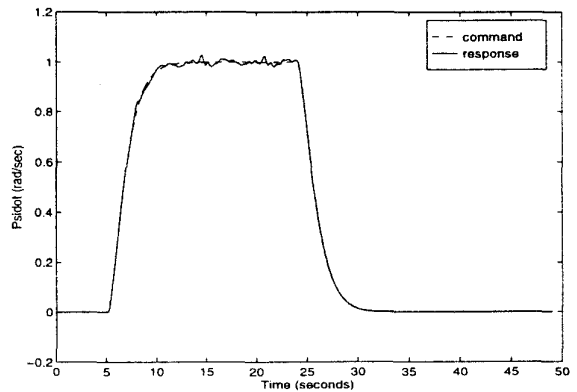


Figure 7: Euler Yaw Rate History (Elliptical Turn, $k = 200$)

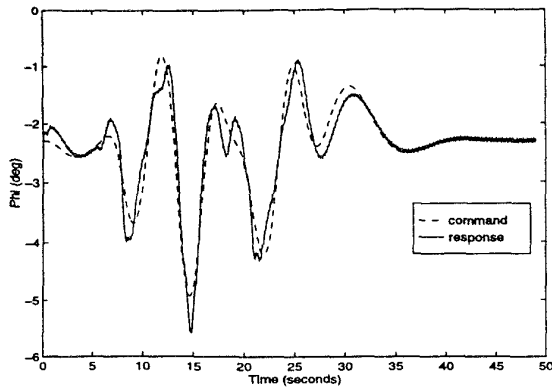


Figure 8: Euler Roll Attitude History (Elliptical Turn, $k = 2800$)

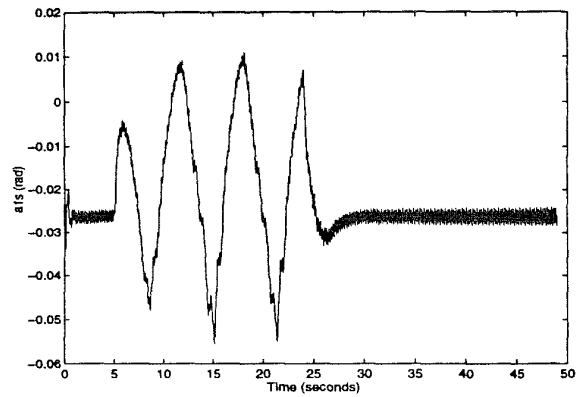


Figure 11: Time History of Lateral Cyclic (Elliptical Turn, $k = 2800$)

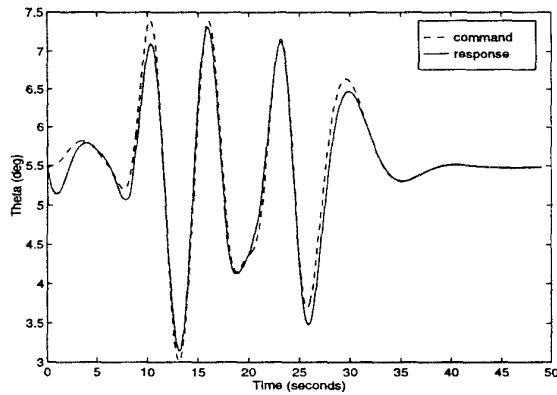


Figure 9: Euler Pitch Attitude History (Elliptical Turn, $k = 2800$)

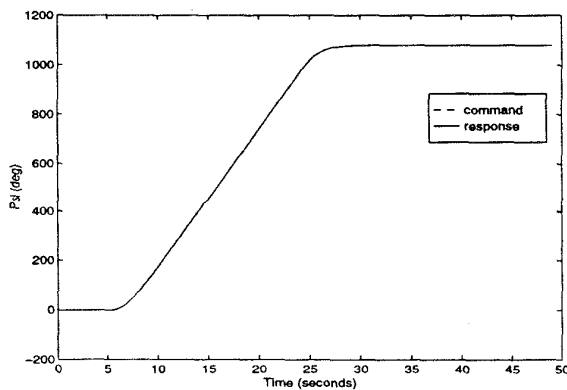


Figure 10: Euler Yaw Attitude History (Elliptical Turn, $k = 2800$)

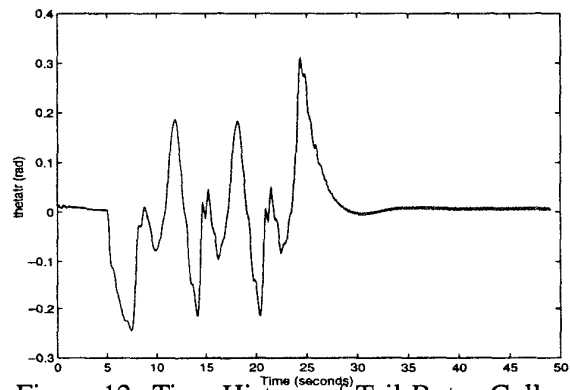


Figure 12: Time History of Tail Rotor Collective Pitch (Elliptical Turn, $k = 2800$)

tio was specified for the fast dynamics, in order to damp out the transmission of the higher frequency unmodeled dynamics. Results show very small tracking errors in both inner and outer loop commanded variables throughout the maneuver. The vehicle remained demonstrably stable throughout the maneuver and all controls remained within their allowable limits. The higher order unmodeled dynamics manifest in the system only as low magnitude harmonic vibrations overlaid onto the system responses, although these dynamics are not accounted for in the stability theory.

6. ACKNOWLEDGMENT

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8. BIOGRAPHY

Jesse Leitner received the BS degree in Aerospace Engineering from the University of Texas at Austin in 1990 and the MS and PhD degrees from Georgia Tech in 1992 and 1995, respectively. He is currently an Aerospace Engineer with the Air Force Research Laboratory at Kirtland AFB, Albuquerque, NM. His current areas of interest are in nonlinear, adaptive control, and neural networks, with application to spacecraft GN&C, and control of optical systems, and helicopter flight control.

Anthony Calise is a Professor of Aerospace Engineering at the Georgia Institute of Technology. Prior to joining the faculty at Georgia Tech, Dr. Calise was a Professor Mechanical Engineering at Drexel University for 8 years. He also worked for 10 years in industry for the Raytheon Missile Systems Division and Dynamics Research Corporation, where he was involved with analysis and design of inertial navigation systems, optimal missile guidance and aircraft flight path optimization. He is the author of over 150 technical reports and papers. He is a fellow of the AIAA and former Associate Editor for the *Journal of Guidance, Control, and Dynamics* and for the *IEEE Control Systems Magazine*.

J. V. R. Prasad has been an Associate Professor of Aerospace Engineering at the Georgia Institute of Technology since 1993, where he has been on the faculty since completing his PhD in 1985. He has been the recipient of a number of awards, including the Sigma Xi 1992 Junior Faculty Award; the 1992-93 Lilly Teaching Fellow Award; and the advisor for the Best Ph.D. Thesis award by Sigma Xi, to name a few. Dr.

Prasad is a Senior Member of AIAA; a Member of AHS; and Member and Chairman of the American Helicopter Society Technical Committee on Handling Qualities. He has authored or coauthored numerous technical papers on helicopter dynamics and nonlinear control, employing such methods as neural networks and fuzzy logic.