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Robust Nonlinear Flight Control Using Embedded Vehicle Computer Model

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Abstract

Feedback linearization approach to nonlinear flight control system design depend upon the system model to find state dependent transformations that globally linearize the vehicle model. Finding the linearizing transformations can be extremely difficult in real flight vehicles due to the fact that the system models are often available only in the form of complex computer programs that have no direct analytical representation. On-line construction of approximate linearizing transformations by embedding computer models of the flight vehicle in the control loop is proposed in this paper. It is shown that the feedback linearizing computations can be carried out in a parallel manner, and can be used for the direct synthesis of stable flight control laws. The paper advances a method based on differential game theory for including robustness specifications in the control loop and also for systematically improving the robustness based on observed performance. The utility of the proposed approach is demonstrated using a high-fidelity computer simulation of a UH-60 helicopter. Computing resources on-board next generation aircraft make the proposed approach practical.

Introduction

Nonlinear control based on the theory of feedback linearization is gaining wider acceptance in the flight control community, as evidenced by the number of recent papers being published in this area[1-20]. The chief advantage of the feedback linearization approach is that it does not require gain scheduling to ensure the flight control system stability over the entire operational envelope of the flight vehicle. This method has been used to develop an array of flight control systems for aircraft and rotorcraft. These include trajectory following systems[1-8], stability augmentation systems[9-11], autopilots for implementing specific tasks such as flight test trajectory control[12,13], twin-lift rotorcraft control[14], and control of aircraft and missile flight at extreme angles of attack[15-18]. The feedback linearization approach has also been used to develop guidance laws for aircraft pursuit-evasion[19,20], and high angle of attack missile guidance[21].

Robustness aspects of the feedback linearized control laws have also been investigated to a certain extent using a Lyapunov function based approach[22], and more recently using a differential game theoretic approach[23]. A few authors have combined the feedback linearization technique with modern robust control methods such as H_∞ and the μ - synthesis techniques to yield robust nonlinear flight control systems, see Reference 16 for example.

The central part of the feedback linearization design approach is the synthesis of linearizing transformations that convert the aircraft nonlinear equations of motions into a decoupled, linear time-invariant form. The feedback linearizing transformations are constructed using the aerodynamic and the engine models, together with the equations of motion. While the feedback linearization of the equations of motion is direct, it is not the case with aerodynamics and engine models. These models are normally based on experimental data, and are often represented using large numerical tables and computer programs. These program modules are developed by specialists in aerodynamics and engine technologies, and are subject to change as additional data becomes available through static tests and flight tests.

In conventional aircraft configurations, the aerodynamic and engine models are simple enough to be represented algebraically, enabling the direct computation of linearizing transformations without extensive numerical manipulations. However, in more complex aircraft such as helicopters or high-performance aircraft, the aerodynamic and engine models are too complex to be amenable to algebraic manipulations. Extensive numerical computations are required in these cases to obtain the feedback linearizing transformations. An iterative scheme for carrying out these computations has been suggested previously[2-4]. However, on-line implementation of iterative methods is not advisable due to the convergence difficulties that can often arise in these methods.

More recently, a piecewise linear approximation has been successfully employed for the numerical computation of the feedback linearizing transformations[1]. In that approach, the aerodynamic models are constructed by trimming the aircraft at various flight conditions, and locally defined Jacobians are used to construct approximate models. These models are chained together to cover the entire flight envelope, providing an approximate means for feedback linearizing the vehicle dynamics. Reference 1 shows that such an approach can provide satisfactory performance even in a complex helicopter flight control system. However, the number of approximate models that needs to be stored on-board in order to meet a desired level of accuracy is yet unclear.

It has been demonstrated in various flight control problems that the feedback linearization task as well as the control synthesis can be considerably simplified by invoking the time-scale separation between the vehicle attitude and translational dynamics[1, 5, 6, 12, 17]. Time-scale separation results in a hierarchical control architecture, with the outer loop generating attitude commands in response to the position/velocity command inputs, and the inner loop following the attitude/attitude rate commands. Note that the proposed notion of time-scale separation is consistent with the number and type of control actuators normally available in flight vehicles. It may be observed that most flight vehicles incorporate actuators for generating three moment components, and a force generation actuator.

With the foregoing background, the objective of this paper is to advance a methodology that enables on-line synthesis of the feedback linearization maps by embedding portions of the flight vehicle simulation model in the feedback loop. The proposed method exploits the time-scale separation structure, and does not constrain the control engineer to follow any specific parametrization scheme for approximating the aerodynamic and the engine models. The feedback linearizing transformations are then to realize the desired flight control functions.

The methodology advanced in the present paper does not require any numerical iterations, and is suitable for implementation on a parallel processor. It is applicable to a large class of flight vehicles, and requires very little analytical effort for its implementation. Indeed, if a high-fidelity simulation of the flight vehicle is available, the flight control engineer does not need to devote any amount of time for synthesizing the linearizing transformations. The designers can focus all their skills on the feedback control system synthesis to meet the control system performance specifications. The transformations automatically synthesized by the proposed methodology will then ensure the flight control system stability and performance as the flight conditions change. The following sections describe the proposed method in further detail, and illustrates its application for designing the flight control system of a UH-60 helicopter using a high-fidelity simulation model of the vehicle.

A method based on differential game theory[23, 24] is proposed for the design of the feedback linearized flight control systems. This approach allows the inclusion of the errors in feedback linearizing transformations, and any other extraneous disturbances in the design process. An approach to iteratively improve the robustness of the control loop by estimating the residual errors is also advanced. The following sections will discuss each of these issues in further detail.

Flight Vehicle Models and Flight Control Architecture

The present work assumes that a six-degree-of-freedom rigid-body model adequately represents the aircraft dynamics. The equations of motion for a flight vehicle using the standard flight dynamic axes system can be expressed as[25]:

$$F_X = m(\dot{U}+WQ-VR)$$

$$F_y = m(\dot{V}+UR-WP)$$

$$F_z = m(\dot{W}+VP-UQ)$$

$$L = I_x \dot{P} - I_{xz} \dot{R} + Q R (I_z-I_y)-I_{xz} P Q$$

$$M = I_y \dot{Q} + R P (I_x-I_z) + I_{xz} (P^2-R^2)$$

$$N = - I_{xz} \dot{P} + I_z \dot{R} + P Q (I_y-I_x) + I_{xz} Q R$$

$$\dot{\theta} = Q \cos \phi - R \sin \phi$$

$$\dot{\psi} = (Q \sin \phi + R \cos \phi) \sec \theta$$

$$\dot{\phi} = P + (Q \sin \phi + R \cos \phi) \tan \theta$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = T \begin{bmatrix} U \\ V \\ W \end{bmatrix}$$

In these equations, U, V, W are the velocity components measured in the flight vehicle body axis system; P, Q, R are the components of the body rotational rate; F_X, F_Y, F_Z are the forces acting along the body axes; and m is the vehicle mass. I_X, I_Y, I_Z are the vehicle moments of inertia and I_{XZ} is the vehicle product of inertia. Note that these equations assume aircraft configuration symmetry about the vertical plane. Relaxing this assumption will increase the complexity of the rotational dynamic equations, but has no other impact on the following analysis. The variables ψ, θ, ϕ are the Euler angles describing the vehicle attitudes with respect to an earth-fixed coordinate system. The variables x, y, z are the components of the vehicle position vector with respect to the earth-fixed coordinate system. In certain flight control situations, it may be desirable to express the vehicle attitudes in terms of Quaternion parameters. The present methodology can be applied in such problems without extensive modifications. The transformation matrix T relating the body axis system to the earth-fixed coordinate system depends on the vehicle attitude dynamics[23]. The variables L, M, N are the roll, pitch, and yaw moments on the airframe due to aerodynamics, control actuators and the engine/rotor forces.

In addition to the vehicle six-degree-of-freedom, in flight vehicles such as rotorcraft, the dynamic model may include additional degrees of freedom arising from articulated rotors. With appropriate modifications, the proposed methodology can handle these additional degrees of freedom without difficulty, as will be demonstrated in one of the following sections.

The feedback linearization approach transforms the aircraft dynamics into a linear time-invariant form using state variable feedback. The resulting model will consist of decoupled chains of integrators, with each chain being driven by one of the control variables. For instance, the attitude dynamics of a high-performance fixed-wing aircraft can be expressed in the form[9]:

$$\ddot{\theta} = U_1, \ \ddot{\psi} = U_2, \ \ddot{\phi} = U_3$$

with U_1, U_2, U_3 being the pseudo-control variables defined as:

$$U_1 = F_2 + G_2 \Delta\delta_e + G_3 \Delta\delta_a + G_4 \Delta\delta_r$$

$$U_2 = F_3 + G_5 \Delta\delta_e + G_6 \Delta\delta_a + G_7 \Delta\delta_r$$

$$U_3 = F_4 + G_8 \Delta\delta_e + G_9 \Delta\delta_a + G_{10} \Delta\delta_r$$

In these expressions, $\Delta\delta_e$, $\Delta\delta_r$, $\Delta\delta_a$ are the incremental values of elevator, rudder and aileron-differential tail deflections. The actual values of the control surface deflections are the sum of the nominal values and incremental control surface deflections. In the case of rotorcraft, the control variables $\Delta\delta_e$, $\Delta\delta_r$, $\Delta\delta_a$ can be considered to be the pitch cyclic, pedal displacement, and the roll cyclic. The variables F_2, F_3, F_4, $G_2 \ldots G_{10}$ denote state/control dependent nonlinear functions that can be computed using the aerodynamic and engine models. For conventional fixed-wing aircraft as well as rotorcraft, the incremental control variables appear linearly in the expressions for pseudo-control variables. Thus, if the pseudo-control variables are known, the incremental control variables can be extracted using linear algebraic methods. The incremental control values can then be combined with the measured actuator states to yield the actuator commands.

Note that the aircraft attitude dynamics is in linear, time-invariant form with respect to the pseudo-control variables U_1, U_2, U_3. Linear system theory[26] can be used to design control laws with respect to the pseudo-control variables that meet the desired time and frequency response specifications. Recent control methods such as H_∞ control theory[27] and the μ-synthesis method[28] can be used to ensure robust stability and performance. The attitude control system has the responsibility for stabilizing the airframe while tracking the attitude commands generated by the translational control law.

The control objectives of the translational control law in a conventional fixed-wing aircraft are to track the airspeed and heading angle commands while maintaining a desired altitude profile. In rotorcraft, the translational control systems may be required to track all the three position components, and/or velocity components. The control variables in the translational dynamics are the vehicle attitude components and the force generation actuator setting. The main engine thrust forms the force generator in fixed-wing aircraft, while the main rotor serves the force generation function in rotorcraft.

The translational control law can be derived by transforming the aircraft translational dynamics using feedback linearization maps and then designing control laws in terms of the pseudo-control variables. The pseudo-control variables can subsequently be transformed into attitude and force generator commands. The translational and rotational controls laws can then be integrated to obtain the overall flight control system. Details of feedback linearizing transformations for the translational dynamics and inverse transformation of the pseudo-control variables are discussed in References 1 and 6.

The separation of the flight vehicle rotational and translational control laws can be justified using singular perturbation theory[29, 30] and can be shown to yield low-order nonlinear controllers[1, 5-7, 11-13, 15, 17]. Further details on the time-scale separated flight control system design methodology can be found in References 6, 7, and 1. This methodology has been applied successfully for the design of several flight control systems. Examples include high-performance aircraft, high-angle-of-attack aircraft and missiles, and rotorcraft. Figure 1 shows the schematic arrangement of a time-scale separated flight control system.

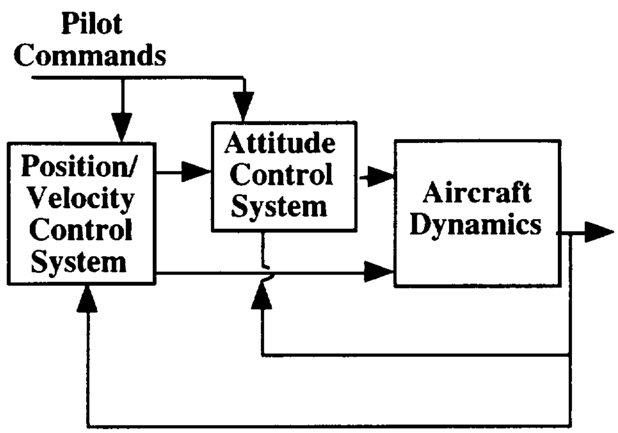

Fig. 1. Two Time-Scale Flight Control System Architecture

Numerical Methods for Feedback Linearization

From the foregoing discussions, it can be observed that the main effort involved in the synthesis of feedback linearized controllers is the construction of the linearization map. In the most general case, construction of the feedback linearization map will involve the use of numerical approximations. The numerical approximations can be based on one of the several parameterization schemes, including linear[1] and connectionist[31, 32] models.

The linear parameterization scheme has its basis in Taylor series approximation. Indeed, most of the currently operational flight control systems are designed using Taylor series linearized aircraft models. The difference between the conventional approach and the linearly parameterized feedback linearization approach is that the latter does not linearize the equations of motion. Instead, linearized aerodynamic and engine models are used in conjunction with the nonlinear equations of motion to derive flight control laws. This approach produces global stability guarantees, while avoiding the time-consuming gain scheduling step inherent in the conventional design technique. Moreover, the feedback linearization approach completely avoids the questions about the number and distribution of linearization conditions within the flight envelope required to ensure satisfactory closed-loop response.

The connectionist methods to feedback linearization are of more recent origin. These methods attempt to generate feedback linearization maps by first training a nonlinear network using a simulation model and then employing the resulting network in the control loop. These methods often incorporate on-line learning loops to continuously improve the feedback linearization maps. Choosing the number and type of learning elements to represent the feedback linearization map is the main issue that needs to be resolved while using connectionist approaches.

The approach advanced in the present paper exploits the fact that every flight vehicle development program produces a high-fidelity simulation of the vehicle dynamics to enable various trade studies, and for pilot training. The simulation model is continuously being refined as additional information becomes available. This being the case, if the feedback linearization methodology can be directly tied to the high fidelity simulation, the flight control system development can proceed in parallel with the simulation model refinement. The simulation model as well as the feedback linearization methodology will become more and more refined as additional data becomes available. As the aircraft development approaches maturity, the flight control system will also become mature.

Such an approach can be realized by employing the force/moment computer simulation code modules for the generation of feedback linearizing transformations. Note that the feedback linearization methodology requires the capability for determining the value of the control variables that can produce a desired set of forces and moments, given the current values of the state and control variables. In the most general case, since the control variables appear nonlinearly in the force/moment computer models, these computations would require numerical iterations. Due to the potential for divergence, iterative numerical solutions are not attractive for on-line implementation.

An alternative methodology is to employ the force/moment computational code modules to synthesize instantaneous affine models of the forces and moments in which the control variables are forced to appear linearly. Feedback linearization maps can be constructed from the affine models using linear algebraic methods. Such an approximation can be constructed by replicating the force/moment computation modules of the aircraft simulation models in the on-board computer and exciting each copy with different sets of inputs. For instance, one of the force/moment modules would receive the current states and the current value of controls as the inputs, while

Given an affine model, the feedback linearizing transformation consists of determining the incremental values of control variables ΔU required to realize commanded values of the forces and moments. For instance, the incremental control settings required to generate a commanded moment vector M_c can be computed as:

$$\Delta U = g(X, U)^{-1} [M_c - f(X, U)]$$

Note that the process requires the invertability of the g(X, U) matrix, which corresponds to the controllability condition for the feedback linearized flight vehicle attitude dynamics. Additional control logic will need to be incorporated in these calculations to handle actuator saturation constraints.

The performance of the feedback linearized flight control system depends to a certain extent on the fidelity of feedback linearizing transformations. The accuracy of the feedback linearizing transformations can be assessed from the fact that the flight vehicle dynamics together with the linearizing transformation must provide the response of a chain of integrators. Specifically, in time-scale separated control laws, the attitude dynamics should have the response of a double integrator, while the translational dynamics will have a first or second-order integrator response based on whether a velocity command or position command system is being employed. Any observed deviation from this expected dynamic behavior can be used to quantify the errors in the feedback linearizing map. The control system can be made robust against the observed errors using any modern robust control technique.

During actual flight tests, observed errors in the feedback linearizing maps can be used to refine the simulation model. The refined simulation model can subsequently be used for improving the numerical feedback linearization module. In this way, the proposed methodology can help improve the fidelity of the simulation model, and consequently the flight control system.

At each sample instant, the commanded forces and moments are generated by the pseudo-control loops are used in conjunction with the on-line computed feedback linearization transformations to compute the incremental values of the control variables. The sum of the current and incremental values of the control variables are then used as the commands to the flight vehicle. The resulting flight control system will have a structure as shown in Figure 2.

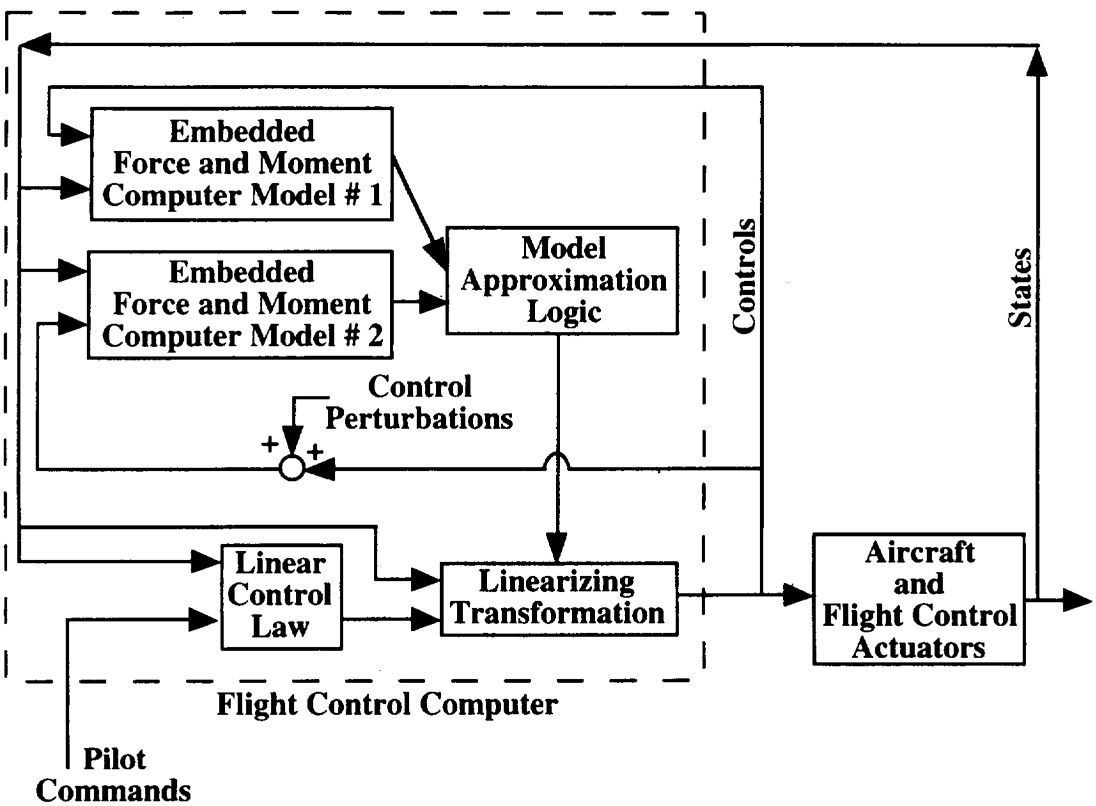

Fig. 2. Flight Control Using Embedded Vehicle Model

Note that the proposed flight control architecture will require a significantly more powerful flight control computer than those currently in use on-board aircraft. In view of the state of the art in digital computer technology, no technological advances are required to meet the increased computational demand. The proposed flight control logic will be applied to a realistic flight vehicle model in the following section. Simulation results will be presented to illustrate the system performance.

Application Example: Flight Control System for a UH-60 Rotorcraft

The proposed methodology is next employed for the development of a flight control system for the UH-60 rotorcraft. A sketch of the UH-60 helicopter is presented in Figure 3. The GENHEL simulation model[34, 35] of this helicopter forms the basis for the present flight control law development. The GENHEL simulation program incorporates six degrees of freedom rigid body model of a single main rotor helicopter. The model is applicable over the full operational range of airspeed, angle of attack and angle of sideslip. The main rotor hub rotational, flapping and lead-lag degrees of freedom are included in the model. Blade element theory[36] is used to model each main rotor blade. Detailed models of the engine, drive train and rotor inflow models are included in the simulation. Additionally, the aerodynamic interference effects between the main rotor, tail rotor and the fuselage are also incorporated. Over the past several years, the GENHEL program has undergone several improvement and validation cycles, and is considered to be a high fidelity representation of the operational UH-60 rotorcraft.

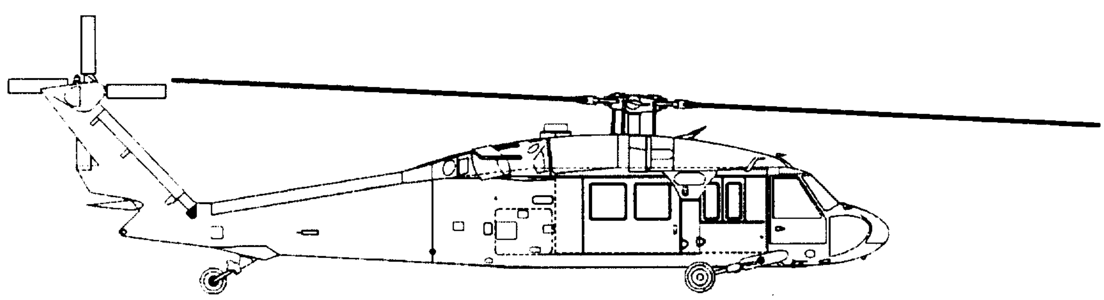

Figure 3. Side View of the UH-60 Rotorcraft

Copies of the computer code implementing the forces and moments in the GENHEL program used to carry out the computations required for feedback linearization. Note that in actual application, multiple copies of the force/moment module will be used to perform the calculations on a parallel computer. The forces and moments corresponding to the nominal values of states and controls, as well as those corresponding to the perturbed values of control are computed. Nominal and perturbed values of the forces and moments are then used to form the affine force/moment model approximations that form the basis for feedback linearization.

For the present research, the main rotor state variables are not fed back into the feedback linearization module. Thus, the rotor states in the GENHEL simulation are different from those used to compute the forces and moments for control law computations.

As a first step in the validation procedure, the numerical feedback linearization module is run in parallel with the GENHEL simulation. Various inputs are applied to determine the differences between the two models. Figures 4 shows the comparison between the Z-body axis component of the force computed in the GENHEL simulation and that computed using the approximate affine model when subjected to a pitch cyclic doublet input. The pitch cyclic input is applied at 5 seconds and removed after two seconds. It can be observed that the numerical feedback linearization module captures essential trends in the vehicle forces and moments.

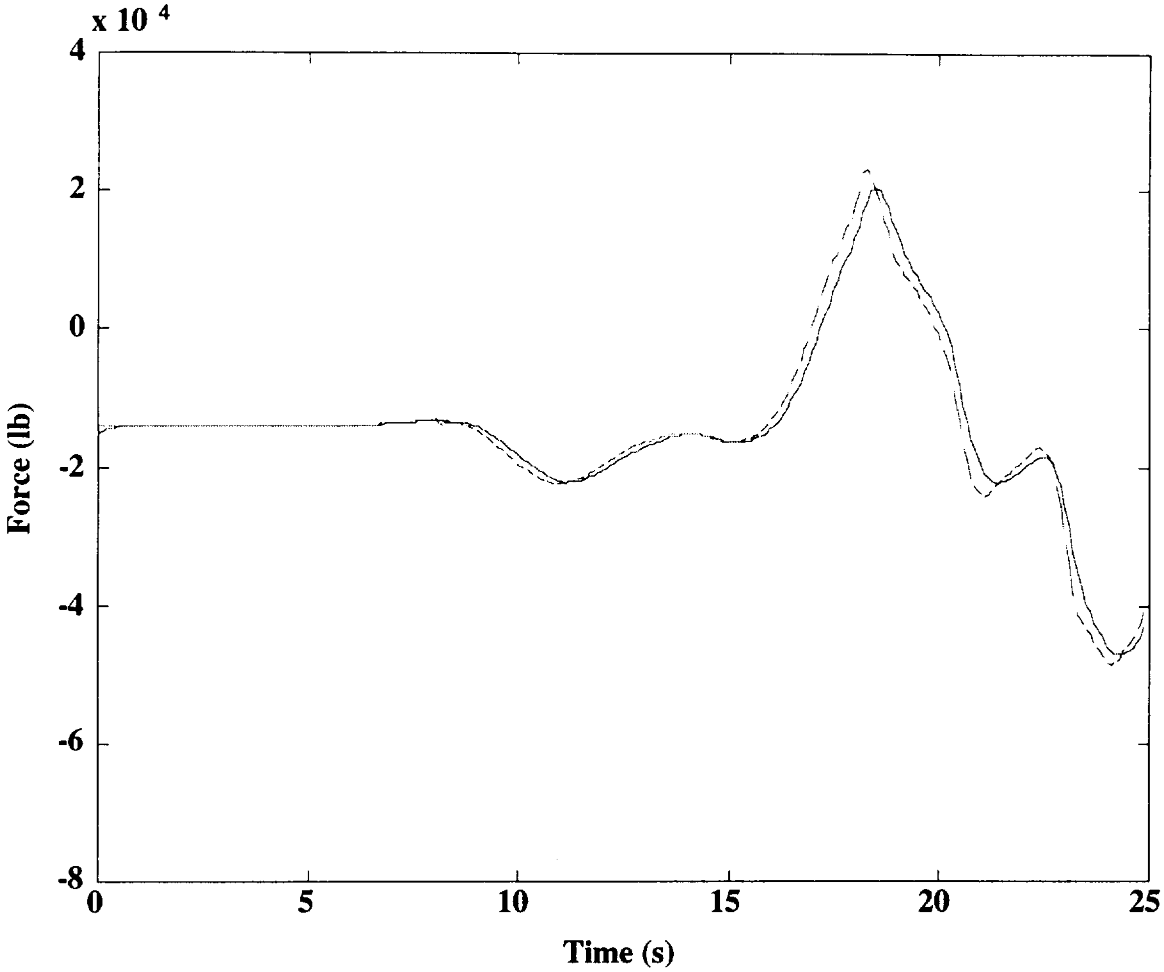

Fig. 4. Comparison between the Force Component along the Z Body Axis

Solid Line: GENHEL Simulation

Dotted Line: Embedded Model

The attitude control loop is next closed using the affine model approximation. As in Reference 1, the attitude and rate gains are chosen to locate the closed loop system poles at -2.7 ± 0.842j corresponding to Level 1 flying qualities[37] for attitude-command/attitude-hold rotorcraft flight control system.

As an example of the system performance, the step response for the roll attitude control system is shown in Figure 5. This figure shows the response of the actual feedback linearized system including all the errors in approximations, together with the response that would have resulted if the feedback linearization maps were exact. It can be observed that the two responses are extremely close, denoting that the present feedback linearization approach is capable of delivering satisfactory performance in the presence of modeling uncertainties.

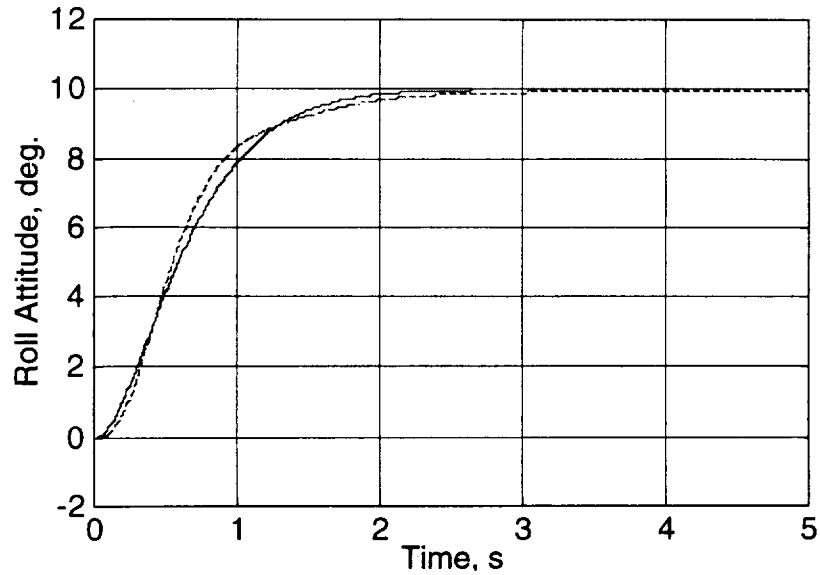

Fig. 5. Step Response of the Roll Attitude Control Loop

Solid Line: Perfect Feedback Linearization

Dotted Line: Actual Feedback Linearization

Further characterization of the feedback linearized flight control system is provided in Figure 6. In this figure, closed-loop frequency response of the ideal and actual systems are compared. These frequency responses were obtained by exciting the closed-loop systems to chirp[38] signals in the range of 0.04 Hz through 5 Hz. The output of the control system is then separated into magnitude and phase components via the fast Fourier transform. It may be observed that the frequency reponses are very close to each other till about 2 Hz. Beyond this, the actual model shows a more complex behavior. Thus, the control system design methodology must ensure that the closed loop system is robust with respect to unmodeled dynamics beyond 2 Hz. Modern robust control techniques[23, 24, 27, 28] can be used to yield such designs.

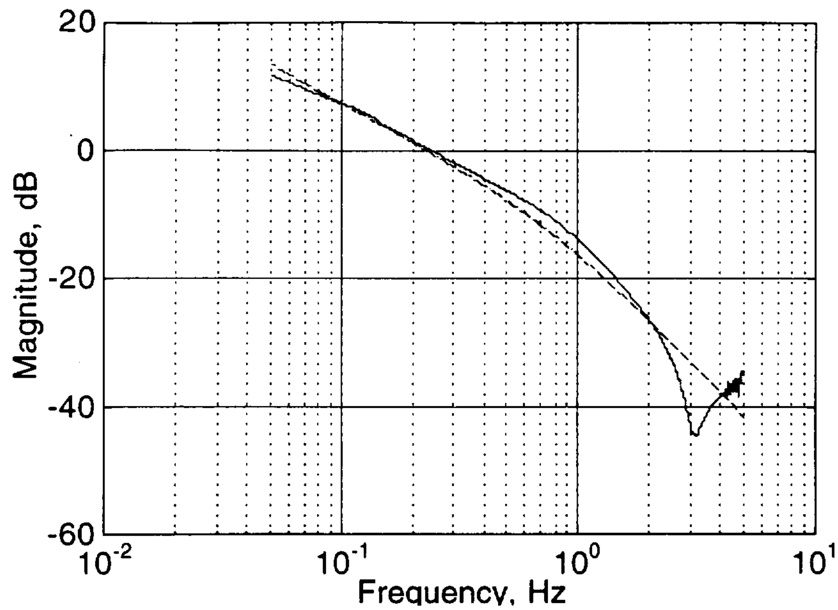

Fig. 6. Closed Loop Frequency Response of the

Roll Attitude Control System

Solid Line: Perfect Feedback Linearization

Dotted Line: Actual Feedback Linearization

Conclusions

A flight control methodology that embeds the vehicle model in the control loop to perform automatic feedback linearization was discussed in this paper. The proposed approach takes advantage of the fact that high-fidelity simulations are available in most flight vehicle development programs. Consequently, highly accurate feedback linearizing transformations can be synthesized by directly incorporating computer code modules from the vehicle simulation for the control law computations. The proposed method constructs, in real-time, an instantaneous affine approximation of the flight vehicle model using the computer code modules from the simulation. The affine model is then used to construct the instantaneous feedback linearizing transformations. Flight control laws are designed using the feedback linearized vehicle models. The control variables are then transformed using the inverse transformations to generate control commands to the flight vehicle. Since the proposed methodology accomplishes automatic feedback linearization, it frees the analyst to focus on meeting the flight control specifications using advanced control design methods. The method advanced in this paper is applicable to a large class of flight vehicles.

The feasibility of the concept was demonstrated by designing a flight control system for the UH-60 helicopter using a high-fidelity simulation model.

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