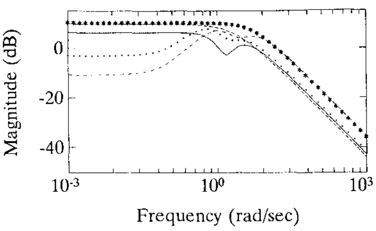

Fig. 2 Magnitude responses of uncertainties: $P_0(s) - P_1(s)$ (solid line); $P_0(s) - P_2(s)$ (dashed line); $P_0(s) - P_3(s)$ (dotted line); $P_0(s) - P_4(s)$ (dash-dotted line); uncertainty bound $r(s)$ (star line).

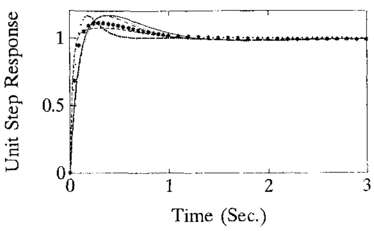

Fig. 3 Unit step responses: FC1 (solid line); FC2 (dashed line); FC3 (small-dotted line); FC4 (dash-dotted line); nominal system (star line); reference model (big-dotted line).

Robust Compensator Design with Desired Performance Requirements

In this section, the system performance will be considered. Here we use the model-matching approach to achieve the desired performance specification. It is seen that the order difference between the denominator and numerator of $T(s)$ in Eq. (17) is 1; the reference model is chosen as

$$T_m(s) = \frac{w_{sp}^2}{z_m} \frac{s + z_m}{s^2 + 2\zeta_{sp} w_{sp} s + w_{sp}^2} \tag{18}$$

Following the design specification,[4] ζ_{sp} and w_{sp} are chosen as 0.9 and 11, respectively. By adjusting the zero location $-z_m$ by the model pole-zero pattern,[5] it is found that, when $z_m = 6$, the peak time is 0.19 s and maximum overshoot is 16.5%. Thus the zero is chosen at -6; i.e., we have the reference model

$$T_m(s) = \frac{20.17(s + 6)}{s^2 + 19.8s + 121} \tag{19}$$

To minimize $\|T(s) - T_m(s)\|_2$ under the restriction that $U(s)$ is BR, for simplicity, let $b = \frac{1}{2}d$ such that $U(s)$ is always BR for all $d > 0$. By minimizing $\|T(s) - T_m(s)\|_2$ with respect to d, we have $d = 6.7$ and $b = 3.35$. Then, from Eq. (17), $T(s)$ is determined and the compensator will be

$$C(s) = \frac{-(1.1s^4 + 11.65s^3 + 41.6s^2 + 60.36s + 31.9)}{s(s^3 + 7.86s^2 + 8.06s + 1.78)} \tag{20}$$

By applying this compensator to different flight conditions, the simulation result is given in Fig. 3, which shows that this parametrized robust compensator can achieve satisfactory performance and robustness of this flight control system.

Conclusions

By using the U-parameter design method and model-matching approach, we have explored a simple parametrized robust compensator design method that shows satisfactory system performance and robustness for a flight control system through simulation. For the considered design example, the Barmish/Wei theory[6] and proportional-plus-integral controller could simultaneously stabilize the four given plants; however the U-parameter approach possesses the parametrized formulation of a simultaneous stabilization problem such that it can be easily applied for model-matching design to achieve the desired system performance.

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Methodology for Integration of Digital Control Loaders in Aircraft Simulators

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I. Introduction

IT is known and accepted that frequencies up to 50 Hz must be represented in simulating control feel. This translates into a frame rate of 500 Hz or more for digital electronics.[1] Only recently have moderately priced digital systems been able to achieve this performance. The control loader electronics in use today are still predominantly analog.

The analog computer of a control loader typically represents a generic quasilinear model of a control system.[1] The parameters are selected to suit the aircraft being simulated and adjusted to fit control system responses measured in flight or on the ground.[2–4] As delivered, the new digital loaders[5] are programmed to emulate the logic wired into their analog predecessors. The digital systems offer improved repeatability and reliability while delivering equivalent functionality. The implementation reported here exploits the digital system to model the actual linkage. The specific contributions made were 1) a commanded force equation derived from the difference of the aircraft and simulator dynamic equations, 2) a recursive formalism for treating the linkage, the mathematical formulation is by induction, which feeds into recursive code. (see Ref. 6 for details), and 3) a generic force loop to control the actuator and deliver the commanded force regardless of the control position and velocity.

A trial implementation was made at the University of Alabama Flight Dynamics Laboratory (UA FDL). A force feel system was integrated for the longitudinal cyclic in the UH1 fixed base simulator using a McFadden 192B[5] digital control loader.

Our purpose was to model the control system as accurately as the hardware of the digital loader allowed (without assist from the simulation host and/or other computers). Lack of access to a simulator that requires and supports extreme fidelity, or to a flying UH1, limits the scope of our validation to checking that the implementation was

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complete and free of objectionable features. This was verified in a flight test by a qualified pilot.

The new method is complementary to the traditional. The generic model requires limited data that is easily collected, given access to the aircraft. The full model requires design data available only to the manufacturer. The fidelity of the linear generic model is usually adequate, but the full specific model must be as good or better. Increased fidelity should be most significant in simulating aircraft of high maneuverability and agility, typically, fixed wing.

II. Commanded Force Equation

Flight controls and their linkage tend to be complicated mechanical systems. Lagrange's equations are recognized as a preferred tool of analysis.[7] We state the equations twice: for flight and for the simulator,

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L^{\mathrm{flt}}}{\partial \dot{q}_i} - \frac{\partial L^{\mathrm{flt}}}{\partial q_i} = F^{\mathrm{flt}}_{\mathrm{friction}\,i} + F^{\mathrm{flt}}_{\mathrm{aero}\,i} + F^{\mathrm{flt}}_{\mathrm{inertia}\,i} + F^{\mathrm{flt}}_{\mathrm{spring}\,i} + F^{\mathrm{flt}}_{\mathrm{pilot}\,i} \qquad (i = 1, \ldots, n) \tag{1}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L^{\mathrm{sim}}}{\partial \dot{q}_i} - \frac{\partial L^{\mathrm{sim}}}{\partial q_i} = F^{\mathrm{sim}}_{\mathrm{friction}\,i} + F^{\mathrm{sim}}_{\mathrm{loader}\,i} + F^{\mathrm{sim}}_{\mathrm{inertia}\,i} + F^{\mathrm{sim}}_{\mathrm{spring}\,i} + F^{\mathrm{sim}}_{\mathrm{pilot}\,i} \qquad (i = 1, \ldots, n) \tag{2}$$

Next subtract Eq. (1) from Eq. (2). We postulate that the control motions and the pilot force inputs in the simulator are the same as in flight. The unknown pilot inputs cancel. One can now solve for the control loader input:

$$F^{\mathrm{sim}}_{\mathrm{loader}\,i} = F^{\mathrm{flt}}_{\mathrm{aero}\,i} + F^{\mathrm{flt}}_{\mathrm{spring}\,i} - F^{\mathrm{sim}}_{\mathrm{spring}\,i} + F^{\mathrm{flt}}_{\mathrm{friction}\,i} - F^{\mathrm{sim}}_{\mathrm{friction}\,i} + F^{\mathrm{flt}}_{\mathrm{inertia}\,i} - F^{\mathrm{sim}}_{\mathrm{inertia}\,i} + \left(\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial}{\partial \dot{q}_i} - \frac{\partial}{\partial q_i}\right)(L^{\mathrm{flt}} - L^{\mathrm{sim}}) \tag{3}$$

The index i goes over the degrees of freedom of the pilot control system. These would normally be longitudinal stick, lateral stick, rudder pedals, and throttle or collective ($n = 4$). The trial implementation was restricted to the longitudinal cyclic ($n = 1$).

For traditional reversible controls in airplanes, $F^{\mathrm{flt}}_{\mathrm{aero}\,i}$ is the most significant term on the right-hand side of Eq. (3). The main function of the loader is to reproduce the aerodynamic force. A simple minded approach to control feel might apply this term and neglect all others. With irreversible controls, the spring force that substitutes for aerodynamic feel becomes most significant. Nevertheless, the other terms, representing friction, effects of flight loads on the controls, and effects of inertia in the control linkage against pilot inputs, contribute to pilot perception and affect fidelity. In helicopters it is common for the pilot to disable the spring force and minimize the friction, leaving only these residual terms.

III. Linkage Model and Low-Level Loop

A mechanical control linkage, such as that in the UH1, typically consists of a series of belcranks (some of them attached to torque tubes) connected by pushrods. For the purpose of analysis the linkage is decomposed into "stages." Each stage consists of a control rod connected to a rotating arm. The control linkage of the longitudinal cyclic in the UH1 helicopter and in the UA FDL UH1 simulator are shown in Fig. 1. In this instance, the simulator was made from a helicopter hull, leading to commonality in part of the linkage. The general method does not depend on this coincidence.

Note that the sequence of simulator stages starts at the actuator arm and leads to the cyclic stick. The sequence for the aircraft starts at the stick and leads to the swashplate actuator valve. The sensor mounted on the actuator is the source of all data on the momentary position, rate, and acceleration of the linkage. These are the inputs to stage 0 of the simulator linkage. The position, rate, and acceleration of the cyclic stick that come out of the simulator computation serve as input values for the aircraft linkage.

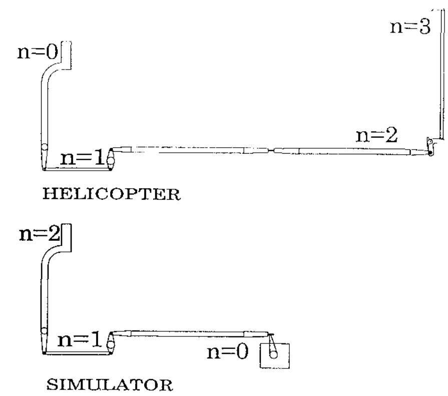

Fig. 1 Stages of the control linkage in helicopter and simulator.

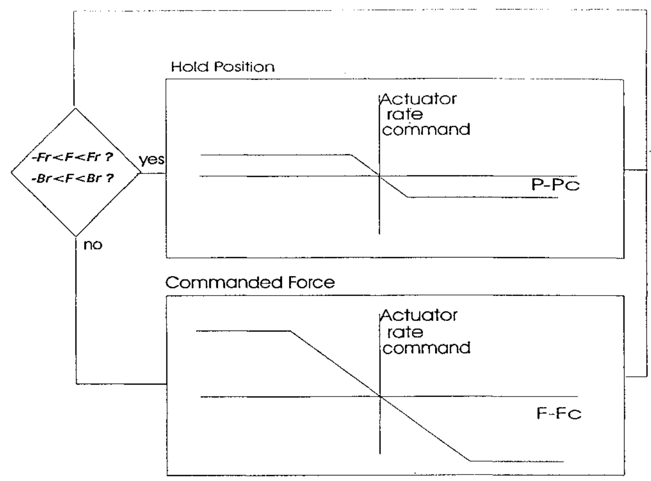

Fig. 2 Low-level loop.

All expressions necessary in Eq. (3), including first and second time derivatives of the arm angles can be obtained by purely algebraic operations based on the treatment of a single stage. The complete linkage is treated by induction.[6]

The computations in the trial implementation are carried out by a C program. A stage structure (object) is used, with linkage data stored in a linked list of stages. In each simulation frame, the generic code goes over the linked list and accumulates the contribution of each stage at the same time as it inductively derives stage parameters.

The outputs of the linkage model are 1) commanded moment, 2) friction, and 3) breakout. Each represents the difference between the aircraft and simulator physical system. These outputs are converted into a rate command for the actuator by a low-level loop (LLL) running at the maximum available frame rate.

Basically, the LLL is a force loop. Commanded force is subtracted from measured force to form an error. A command is generated that is proportional to the error up to some limiting value. The LLL reverts to the hold position mode whenever the force error falls below the friction value. It returns to the commanded force mode when the force error rises above the breakout (Fig. 2).

IV. Trial Implementation

The control loader used was a McFadden 192B.[5] In this system, a Banshee board[8] with a TMS320C30 microprocessor controls the analog equipment. The system came complete with Banshee software, authored in C by Katirai at McFadden. The software set a frame rate of 5000 Hz. It provided a digital emulation of McFadden's earlier analog systems, divided into five tasks and running at 1000 Hz.

We retained Katirai's housekeeping and communications shell including the 200-μs frames. The computational content was stripped and replaced. The linkage model, segmented into eight tasks, achieved a frame rate of 625 Hz. The LLL ran at 5000 Hz.

Table 1 Typical control loader forces

n_x	n_z	Force, lb Total	Maneuver increment
0	1	0.58	0
0	3	0.73	0.15
0.5	1	3.09	2.52

The effect of the loader on pilot perception was tested in a series of simulated "flights" piloted by Capt. Mark Jackson of the U.S. Army. The scenario was selected so as to induce significant flight loads. It consisted of takeoff, vertical climb to 50 ft, rapid acceleration to 80 knots, a 180-deg turn to the right at a bank of at least 60 deg, return to the airport, rapid deceleration to hover, and landing. This typically lasted 3 min and 15 s. The pilot elected to fly with the trim off.

The flight sequence was practiced with an early version of the control model with which the pilot was already familiar. Once proficiency was achieved, six flights were made with five variations in the loader program: 1) early version (gain factors not at their correct final values), 2) full model, 3) full model except that gain for control acceleration was set to zero, 4) full model except that gain for flight acceleration was set to zero, and 5) dummy, control loader applying no force.

The order of the six flights was 1, 3, 2, 5, 4, 2. The pilot did not know what each run represented. He was asked to rate the control feel subjectively. The results were 1) good; 2) great, good; 3) good; 4) good; and 5) poor. The full loader model 2 was included twice. Not surprisingly, it got two different ratings in the subjective evaluation. Still, the full model rated higher than any other.

Table 1 presents typical values of commanded force at the cyclic grip. The control loader produces a force also when the cyclic stick is accelerated; 1 g at the grip gives rise to 0.50 lb from the loader. This makes up for the difference in linkage inertia between simulator and aircraft. For further details of the trial implementation see Ref. 6.

V. Conclusions

The new method requires more detailed data on the control system than the traditional and has the capability of delivering higher fidelity. The contemporary McFadden digital loader can support the new method. The effort of modeling and programming is moderate.

Acknowledgments

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Improved Literal Approximation for Lateral-Directional Dynamics of Rigid Aircraft

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Introduction

THE literal (analytical) approximations for the spiral, roll convergence, and dutch roll modes are traditionally obtained by discarding some of the dynamic equations and certain degrees of freedom associated with the lateral-directional dynamics of a rigid airplane. In most cases, this leads to an "overdecoupling" of the lateral-directional dynamics, resulting in approximations that are rather inaccurate for both the spiral eigenvalue λ_s and the dutch roll damping $2\zeta_{\mathrm{DR}}\omega_{n_{\mathrm{DR}}}$ and are at best reasonable for the roll convergence eigenvalue λ_r and the dutch roll frequency $\omega^2_{n_{\mathrm{DR}}}$. In this Note, the literal approximation method developed by Newman and Schmidt[1] and Livneh and Schmidt[2] is used to generate one set of unified approximations for the lateral-directional dynamics of six different rigid airplanes with a total of 16 sets of flight conditions.[3,4] Various observations regarding the interrelations between the unified and the traditional approximations are drawn, and a short analysis of the errors associated with the unified vs the literal approximations is provided.

Formulation and Traditional Approximations for Lateral-Directional Dynamics

The characteristic polynomial corresponding to the Laplace transform of the linearized equations of motion for the lateral-directional dynamics of a rigid airplane is given[4] by

$$D(s) = \det\begin{bmatrix} sU_1 - Y_\beta & -[g\cos(\theta_1) + sY_p] & s(U_1 - Y_r) \\ -L_\beta & s^2 - L_p s & -\left(s^2 A_1 + sL_r\right) \\ -N_\beta & -\left[s^2 B_1 + N_p s\right] & s^2 - sN_r \end{bmatrix}$$

$$= (1 - A_1B_1)U_1 s(s+\lambda_s)(s+\lambda_r)\left(s^2 + 2\zeta_{\mathrm{DR}}\omega_{n_{\mathrm{DR}}}s + \omega^2_{n_{\mathrm{DR}}}\right)$$

$$= 0 \tag{1}$$

where U_1 is the flight vehicle airspeed, g is the acceleration of gravity, θ_1 is the pitch angle, and s is the Laplace transform variable. The three triads $(Y_\beta, L_\beta, N_\beta)$, (Y_p, L_p, N_p), and (Y_r, L_r, N_r) correspond to the side acceleration, rolling moment, and yawing moment per the perturbed sideslip angle β, perturbed roll rate p, and perturbed yaw rate r, respectively. The dimensionless inertia quantities A_1 and B_1 are given by $A_1 \equiv I_{xz}/I_{xx}$ and $B_1 \equiv I_{xz}/I_{zz}$, where I_{xx} and I_{zz} are the moments of inertia about the X and Z stability axes, respectively, and I_{xz} is the product of inertia about the X, Z

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