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# Identification and Simulation Evaluation of a Combat Helicopter in Hover

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**Frequency-domain parameter identification techniques were used to develop a hover mathematical model of the AH-64 Apache helicopter from flight data. The unstable AH-64 bare-airframe characteristics, without a stability augmentation system, were parameterized in the conventional stability-derivative form. To improve the model's vertical response, a simple transfer-function model approximating the effects of dynamic inflow was developed. The model, with and without stability augmentation, was then evaluated by AH-64 pilots in a moving-base simulation. It was the opinion of the pilots that the simulation was a satisfactory representation of the aircraft for the tasks of interest. The principal negative comment was that height control was more difficult in the simulation than in the aircraft.**

## Nomenclature

| | |
|---|---|
| $a_x, a_y, a_z$ | = longitudinal, lateral, and vertical applied specific force, ft/s$^2$ |
| del | = delayed |
| $j$ | = complex variable, $\sqrt{-1}$ |
| $L, M, N$ | = roll, pitch, and yaw applied specific moments, rad/s$^2$ |
| lon, lat, ped, col | = longitudinal, lateral, directional, and vertical cockpit inputs, in. |
| $p, q, r$ | = roll, pitch, and yaw angular rate perturbations, rad/s |
| $u, v, w$ | = longitudinal, lateral, and vertical airspeed perturbations, ft/s |
| $X, Y, Z$ | = longitudinal, lateral, and vertical applied specific force perturbations, ft/s$^2$ |
| $\delta$ | = control input, in. |
| $\theta$ | = pitch angle perturbation, rad |
| $\dot{\theta}$ | = pitch rate perturbation, rad/s |
| $\tau$ | = time delay, sec |
| $\phi$ | = roll angle perturbation, rad |
| $\dot{\phi}$ | = roll rate perturbations, rad/s |
| $\omega$ | = frequency, rad/s |

## Introduction

OBTAINING accurate mathematical models of actual flight vehicles is important for many reasons. The models are used for crew training in simulation, pilot handling–qualities evaluations in simulation, control-system design, display-system design, and evaluation of simulator visual- and motion-system fidelity. The development of these models may arise from 1) analysis of the known physics, 2) empirical compilation of acquired vehicle flight data (such as in function tables), or 3) a combination of both the analytical and the empirical methods. This paper describes an application of the third method to the development of an AH-64 Apache hover model.

The model was developed to support the design of new hover-display dynamics for the Apache. Accurate vehicle-response models are used in two ways for current hover-display design methods. First, they are used to provide predictive velocity information on the pilot's display, thus greatly improving the display's utility to the pilot. Second, the availability of an accurate model allows a credible analytical evaluation of the pilot-vehicle-display closed-loop dynamics during display design trade-offs prior to piloted evaluation.[1,2]

Different levels of model complexity are available to accomplish the Apache display design and evaluation. A full-envelope, rotor-map mathematical model of the AH-64 exists and has been compared with flight data.[3] This complex model has the difficult goal of matching the vehicle characteristics over the full flight envelope. In Ref. 3 it is shown that whereas the model is adequate in pitch and yaw for primary axis inputs, it has deficiencies in predicting the primary roll and vertical responses as well as pitch/roll cross-coupling.

Instead of using the complex full-flight-envelope model for the study described herein, the authors decided to develop a simpler model that more closely matched the on- and off-axis flight characteristics in the near-hover flight regime of interest for the display research. The model developed was an extended six-degree-of-freedom stability-derivative characterization extracted from an extensive flight data base using system identification techniques. There were four motivating factors for taking this approach. First, Ames Research Center has developed and applied procedures[4–7] for easily identifying multi-input, multi-output models (for vehicles such as the Bell XV-15, Bell 214ST, MBB BO-105, and the Sikorsky UH-60) using frequency-domain techniques. These techniques are now assembled in a package called Comprehensive Identification from FrEquency Responses (CIFER®). Second, a parametric, linear model (such as a low-order transfer function) eases the display design. Otherwise, it would have been necessary to extract a linear

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model from the complex nonlinear model by using methods similar to those described herein for the flight-test data. Third, previous attempts to develop bare-airframe, unstable helicopter models at hover have been generally unsuccessful because of poor data or because of difficulties in applying the identification method. The availability of a newly acquired and comprehensive data base for the AH-64 and the recently completed CIFER system presented an opportunity to advance the state of the art in helicopter system identification. Fourth, once a model is developed with the Apache's Digital Automatic Stabilization Equipment (DASE) off, that is, a DASE-off model, the DASE can be easily added by combining the known control laws with the DASE-off model.

This paper first discusses the basic identification techniques used in the extraction of a seven-degree-of-freedom (7-DOF) mathematical model (six rigid-body degrees of freedom and one for dynamic inflow) of the AH-64 in hover. The identified model is then validated against flight-test data not used in the identification process. In addition, the identified model is compared with a linearized version of a complex nonlinear model of the AH-64. Then, a pilot-in-the-loop moving-base simulation is described, which is followed by pilot comments on the qualitative impression of the model's fidelity. Finally the results and comments are discussed.

## Identification Technique

The frequency-domain system identification method described in Ref. 6 and shown in Fig. 1 was used. Only a brief outline of the method will be given here. The identification process comprises three major steps: 1) the identification of the correct output/input nonparametric frequency responses, 2) the development of a parametric state-space stability-derivative model that best matches the frequency responses, and 3) the verification of the resulting stability-derivative model with flight-data responses not used in the identification process.

The first step is accomplished by having the pilot generate a progressive low-to-high-frequency stick input over the frequency range to be modeled. For the Apache data taken, this range encompasses 0.1–30 rad/s. The input is such that the vehicle starts and ends in trim. A fast Fourier transform, using chirp $z$–transforms,[8] is calculated from these data for each input/output combination. The matrix of frequency responses between the input $x$ and the output $y$ is determined by multiplying the inverse of the input spectral-density matrix by the cross-spectral-density matrix,

$$H(\omega) = [G_{xx}(\omega)]^{-1} G_{xy}(\omega) \tag{1}$$

This matrix calculation yields the correct single-input, single-output frequency responses when multiple control inputs are present and partially correlated in the test data, which is usually the case for helicopter tests. For single input tests, Eq. (1) reduces to the more familiar scalar relationship. After these frequency responses are calculated, the second step is to hypothesize a state-space stability-derivative model based on a physical understanding of the vehicle's primary flight dynamics. An optimization scheme employing a secant search then minimizes the error in both magnitude and phase between the free model parameters and the frequency responses. Confidence analyses are performed on each converged result by using the following theoretical accuracy metrics: Cramer-Rao bounds, insensitivities, and correlations between free model parameters. Insensitive parameters and selected parameters in those sets that are highly correlated are eliminated, and the optimization scheme is repeated.

The final step, after a satisfactory model has been determined, is to drive the model with flight-test doublet inputs (which were not used in the identification process) for comparison with flight-test responses. This final step is a verification of both the model structure and its values.

## Application to an AH-64 Helicopter

Figure 2 (from Ref. 9) shows the principal dimensions of the AH-64 Apache. The vehicle is a single-main-rotor, twin-engine, tandem-seat helicopter. The flight data were collected at the U.S. Army Airworthiness Qualification Test Directorate at Edwards, California, on August 22, 1990. The aircraft serial number was 84-24256. Gross weight at takeoff was 16,100 lb with a center of gravity (c.g.) at 204.4 in. Ambient temperature and pressure were 58°F and 30.06 in. of Hg, respectively. The vehicle was configured with eight Hellfire missiles inboard and two 19-shot pods outboard. Data were taken out of ground effect with the DASE on and off. DASE-off data were used primarily for the identification, since the DASE's inherent stabilization properties tend to partially suppress the vehicle's low-frequency modes that one wants to identify.

Frequency sweeps were input in each axis separately whereas data were recorded for four inputs and eight outputs. An example of the flight data used to generate frequency responses for the model determination is shown in Fig. 3. The aircraft-body-vertical accelerometer signal is shown as one of the eight outputs, with the cockpit-collective lever as the input. Here the mean and slope were removed from the data for the future spectral calculations.

The identified $a_z(j\omega)/\delta_{col}(j\omega)$ frequency response of the aircraft is shown in Fig. 4. Here the effects of the $a_z$ response owing to the

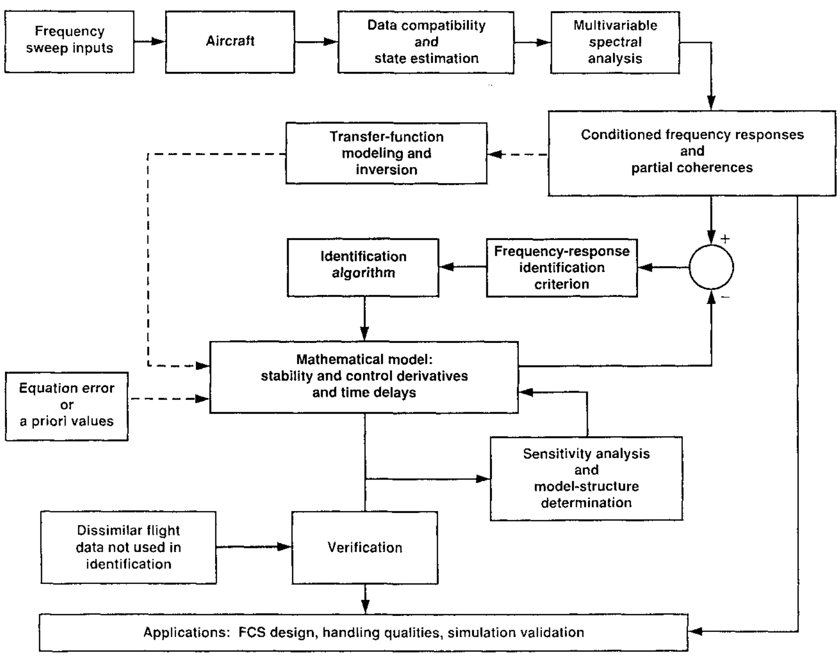



**Fig. 1 Identification process.**

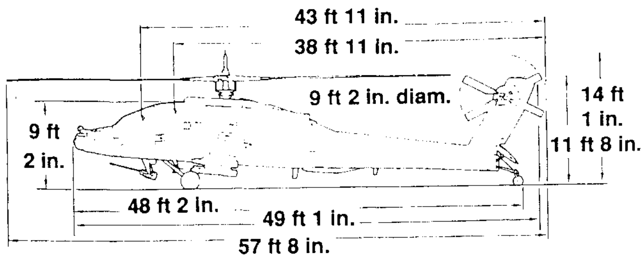



**Fig. 2 Principal dimensions of AH-64.**

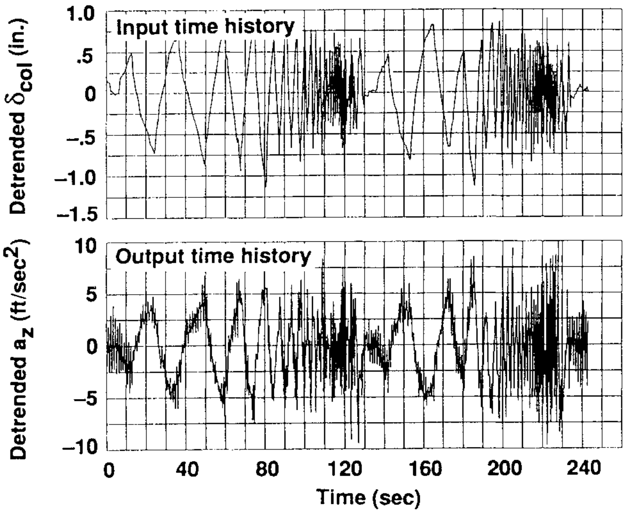



**Fig. 3 Example flight-test input.**

**Table 1 Responses used in model development**

| Output | lon | lat | ped | col |
|---|---|---|---|---|
| $u$ | ✓ | | | ✓ |
| $v$ | | ✓ | ✓ | |
| $p$ | | ✓ | ✓ | |
| $q$ | ✓ | ✓ | | |
| $r$ | | ✓ | ✓ | ✓ |
| $a_x$ | ✓ | ✓ | | ✓ |
| $a_y$ | | ✓ | ✓ | ✓ |
| $a_z$ | | | | ✓ |

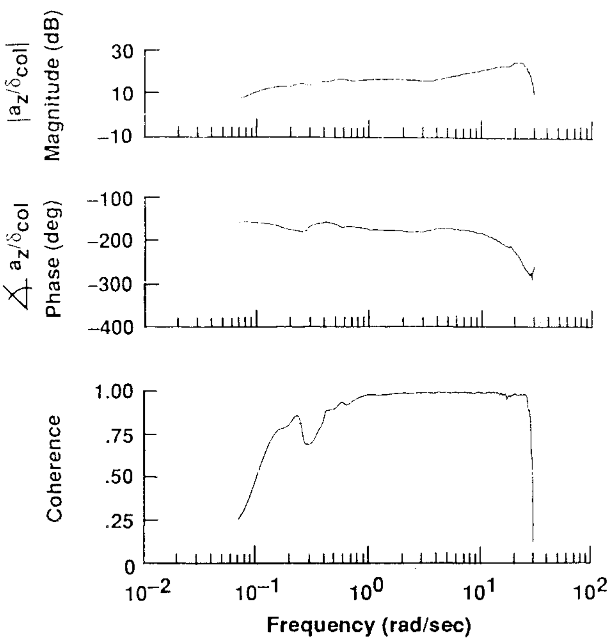



**Fig. 4 Vertical acceleration-to-collective frequency response.**

other three cockpit control inputs have been removed by Eq. (1). The bottom plot in Fig. 4 is the partial coherence function, which is a measure of the linearity between the input and the output; it shows that a good frequency-response identification was achieved in the frequency range of 0.15–25 rad/s for this input/output pair.[6] Important dynamic information may be gleaned from this frequency-response plot. Over a broad frequency range (0.2–3 rad/s) the magnitude response is flat (14 dB) and the phase curve is −180 deg. These characteristics show that positive (up) collective stick inputs produce a constant upward (negative $Z$-axis) acceleration of $a_z/\delta_{col} = -5.3$ ft/s$^2$/in. At high frequency, the significant peaking in the magnitude response reflects the effect of the rotor's coupled flap/inflow dynamics,[10] whereas at low frequency, the magnitude attenuation and phase increase reflect the quasi-steady vehicle heave damping. Thirty-two such AH-64 hover frequency responses for eight outputs from four inputs were identified. The eight outputs were $u$, $v$, $p$, $q$, $r$, $a_x$, $a_y$, and $a_z$. The four inputs were $\delta_{lon}$, $\delta_{lat}$, $\delta_{ped}$, and $\delta_{col}$.

Eighteen of these 32 responses were selected for the stability-derivative identification using the coherence function as the primary indicator of the response's relevance for the model. For example, little to no pitch rate results from pedal input, so this response pair has very poor coherence (no input-to-output transfer). Thus, $q/\delta_{ped}$ was not used in the model determination. The responses that were used in the model development are shown in Table 1. Although, in many instances, the flight data had spectral content out to 30 rad/s, the identification range for this 7-DOF model typically extended only to 10 rad/s (except for the vertical axis, which is discussed later). This maximum frequency is usually acceptable for flight simulation handling qualities investigations.

Table 2 summarizes the resulting ninth-order stability-derivative model for the DASE-off configuration. Also listed are identified time delays for each axis that approximate the unmodeled high-frequency modes, such as the swashplate actuators and the main-rotor dynamics. The lead/lag filter on the collective term into the vertical axis is an approximation of the dynamic inflow to be discussed later.

Example comparisons of the flight and model frequency responses are shown in Fig. 5. The best and worst fits in the frequency domain, as well as two principal on-axis angular responses, are shown. The $a_y/\delta_{ped}$ response had the best fit, and the $q/\delta_{lat}$ response had the worst fit. The quality of all the remaining 16 fits lies between these two bounds.

Figures 6–9 compare the time responses predicted by the identified linear model (referred to as the identified model) with both flight-test data and a linearized six-degree-of-freedom model extracted from the nonlinear full-flight envelope of Ref. 3 (referred to as the linearized full-envelope model). The linearized full-envelope model was extracted from the complex model by using a forward-difference method. Each figure in succession depicts responses to longitudinal, lateral, directional, and vertical doublets. These flight data were not used in the identified model's identification, so they are a good indication of the identified model's fidelity. In the figures, note that initial conditions in the model attitudes and linear accelerations may be different between the linear models and the flight data. These initial conditions are selected for each linear model based upon a least-squares fit between the linear and flight-test response. These initial condition selections are necessary to eliminate the difficulties that measurement biases introduce when comparing models with unstable modes as is the case with the AH-64.

For the longitudinal input in Fig. 6, both the on-axis ($q/\delta_{lon}$) and the off-axis ($p/\delta_{lon}$) angular responses of the identified model match flight data well. The longitudinal-acceleration response of the identified model is almost identical to the flight-test response. Though the on-axis response of the linearized full-envelope model matches flight data well, the off-axis response is out of phase with the flight-test response.

Figure 7 shows the responses to lateral-cyclic inputs. Both of the on-axis ($p/\delta_{lat}$) responses match well. The off-axis ($q/\delta_{lat}$) response of the identified model closely matches the flight data, even though this response had the poorest relative fit in the frequency domain (Fig. 5). For this lateral doublet, the input spectrum has its predominant power in the frequency range of 1.6 rad/s and higher; the frequency-response fit is good in this range. This time-domain matching would most likely be worse if a lower fre-

**Table 2 AH-64 hover mathematical model**

$$
\begin{bmatrix} \dot u \\ \dot v \\ \dot w \\ \dot p \\ \dot q \\ \dot r \\ \dot\theta \\ \dot\phi \end{bmatrix}
=
\begin{bmatrix}
-0.020 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & -32.2 & 0.0 \\
0.0 & -0.279 & 0.0 & -1.56 & 0.0 & 0.0 & 0.0 & 32.2 \\
0.0 & 0.0 & -0.122 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & -0.00425 & 0.0 & -1.83 & 1.04 & 0.0 & 0.0 & 0.0 \\
0.000844 & 0.00710 & -0.00514 & -0.227 & -0.419 & -0.090 & 0.0 & 0.0 \\
0.0 & -0.00301 & 0.0 & -0.309 & 0.0 & -0.270 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 1.0 & 0.0 & 0.0 & 0.0 & 0.0
\end{bmatrix}
\begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \\ \theta \\ \phi \end{bmatrix}
+
\begin{bmatrix}
-1.48 & -0.194 & 0.0 & 0.835 & 0.0 \\
0.0 & 0.496 & -2.79 & -0.856 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & -14.6 \\
-0.104 & 0.834 & -0.401 & 0.0 & 0.0 \\
0.235 & 0.0592 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.104 & 0.494 & 0.266 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0
\end{bmatrix}
\begin{bmatrix} \delta_{\mathrm{lon}_{\mathrm{del}}} \\ \delta_{\mathrm{lat}_{\mathrm{del}}} \\ \delta_{\mathrm{ped}_{\mathrm{del}}} \\ \delta_{\mathrm{col}_{\mathrm{del}}} \\ \delta_{\mathrm{col}_{\mathrm{del}_{\mathrm{lead\ lag}}}} \end{bmatrix}
$$

$$\delta_{\mathrm{lon}_{\mathrm{del}}}(s) = e^{-0.088s}\delta_{\mathrm{lon}}(s)$$
$$\delta_{\mathrm{lat}_{\mathrm{del}}}(s) = e^{-0.121s}\delta_{lat}(s)$$
$$\delta_{\mathrm{ped}_{\mathrm{del}}}(s) = e^{-0.079s}\delta_{\mathrm{ped}}(s)$$
$$\delta_{\mathrm{col}_{\mathrm{del}}}(s) = e^{-0.061s}\delta_{\mathrm{col}}(s)$$
$$\delta_{\mathrm{col}_{\mathrm{del}_{\mathrm{lead\ lag}}}}(s) = \frac{s+4.8}{s+12.9}\delta_{\mathrm{col}_{\mathrm{del}}}(s)$$

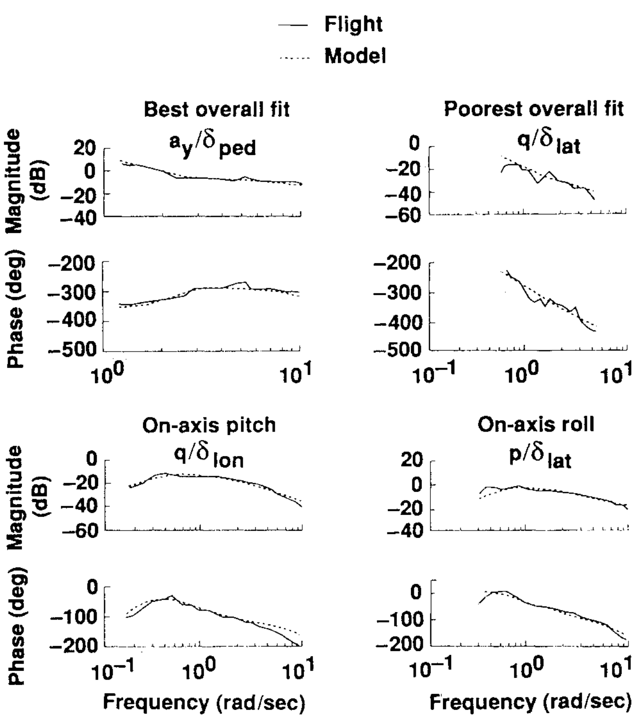



Fig. 5 Example frequency-response fits.

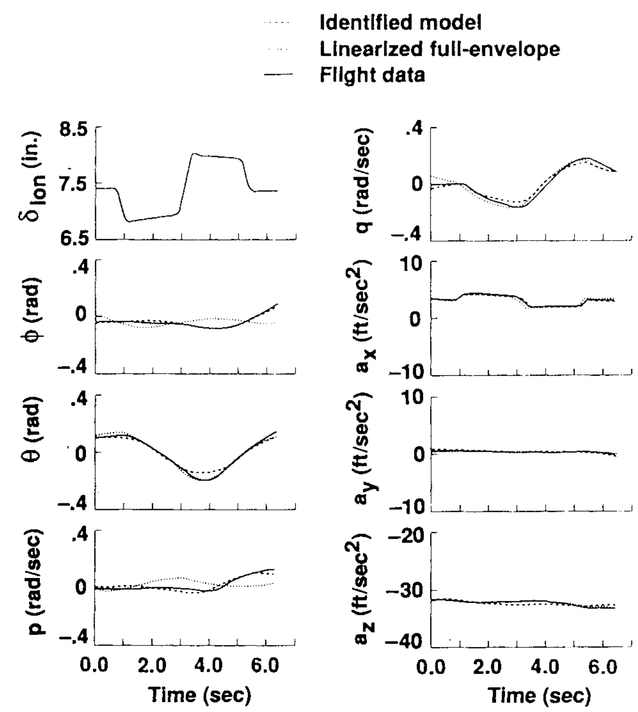



Fig. 6 Flight vs two linear models for a longitudinal doublet: DASE-off.

quency doublet was used, since for this case the model errors increase at low frequencies (less than 1 rad/s). Again, the linearized full-envelope model off-axis responses are out of phase with the flight-test data.

The identified model response to directional inputs in Fig. 8 captures the on-axis yaw rate ($r/\delta_{\mathrm{ped}}$) very well. The identified model's roll-rate response also matches well; this response is primarily caused by the vertical displacement of the tail rotor from the roll axis. The linearized full-envelope model does not match the flight data as well as the identified model does in the $p$, $r$, and $a_y$ responses.

The identified model's vertical-axis-acceleration response to collective input in Fig. 9 matches the overshoots in the flight data almost perfectly; the overshoots are due to a dynamic inflow effect. Note that the identified model has a low value of $Z_w$ ($-0.122$ s$^{-1}$ in Table 2). The vertical-acceleration response is consistent with this low value, for the acceleration does not decay over the 2 s of doublet input as expected with a $Z_w \approx -0.3$ s$^{-1}$ that is typically determined from momentum theory. Other identification efforts have noted this reduction in identified $Z_w$ when compared with momentum theory.[11] A contributing source of this discrepancy might be the omission of the effect of varying rotor speed on thrust. For this modeling, an assumption of constant rotor speed was used. The linearized full-envelope model captures two-thirds of the overshoot of the $a_z$ response but does not match the remaining dynamics, since another state is required as later described. The angular responses to

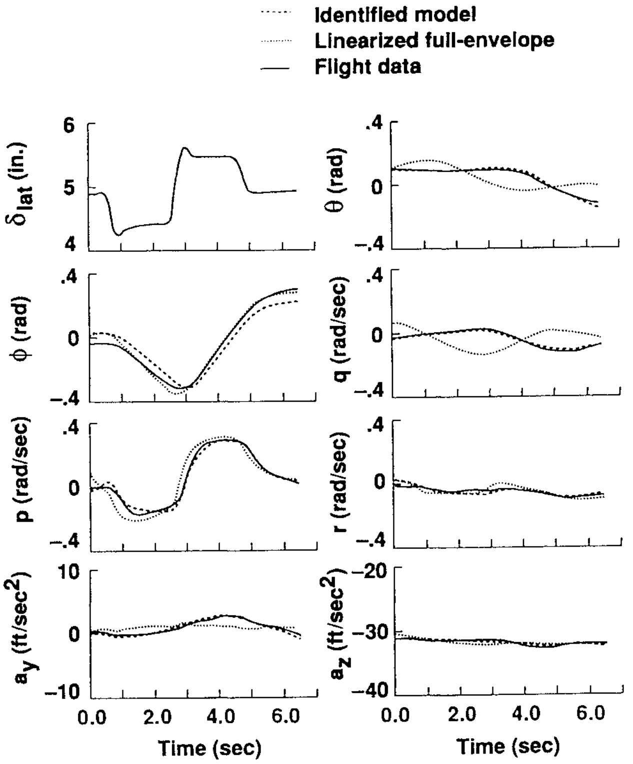



Fig. 7 Flight vs two linear models for a lateral doublet: DASE-off.

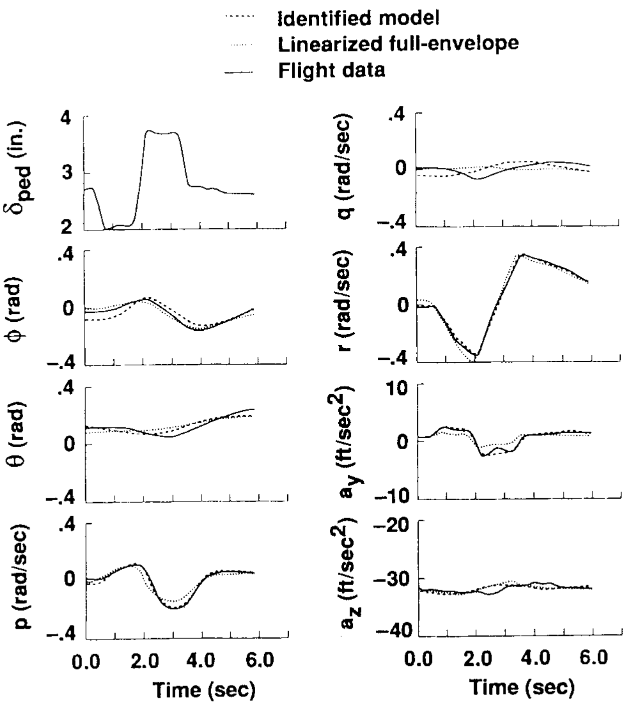



Fig. 8 Flight vs two linear models for a directional doublet: DASE-off.

collective input of the linearized full-envelope model do not match as well as the identified model.

Notice that although the on-axis responses of the linearized full-envelope model shown here are satisfactory (except for the vertical), the principal deficiencies were in the off-axis responses. These trends are consistent with those noted in the Introduction, which adds confidence in the linear characterization of the full-envelope model for comparison purposes. The time responses show that, for this restricted flight regime, the identified model is a better representation of the principal flight dynamics than the linearized full-envelope model. This is important to note, because the trend in vehicle modeling is to use the most complex model available whereas at times

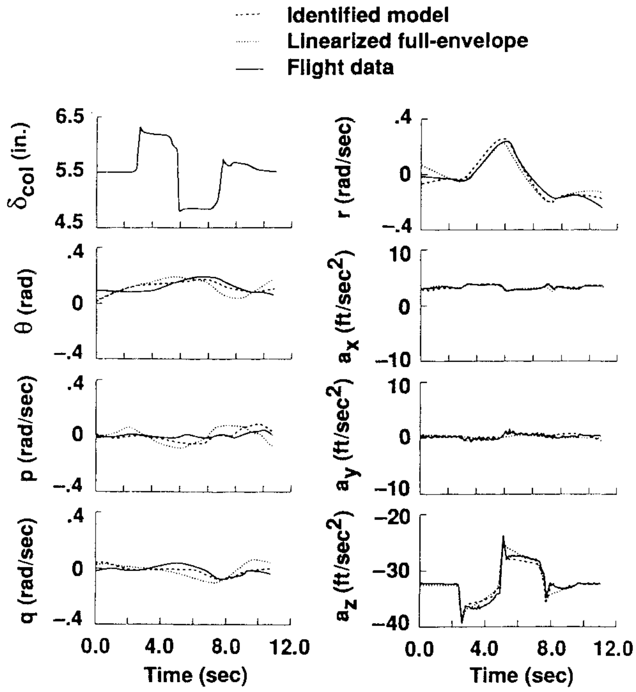



Fig. 9 Flight vs two linear models for a vertical doublet: DASE-off.

a simple model may be more accurate over the frequency range of interest.

The modeling of the effect of dynamic inflow in the vertical response was initially neglected. Dynamic inflow accounts for the fact that the induced velocity change at the rotor does not occur instantaneously.[12] The dynamic lag associated with the acceleration of a large air mass results in an angle-of-attack change at the rotor blade. For a collective input, the angle-of-attack perturbation is initially due to the immediate collective pitch change; this initial angle of attack is then reduced by the change in inflow during the climb, so that there is more initial thrust than steady-state thrust. This increase in initial thrust is reflected in the high-frequency peaking of the $a_z/\delta_{col}$ magnitude plot of Fig. 4. Dynamic inflow has previously been approximated with an equivalent system model that adds a lead term (a zero) and a pure delay in the $w/\delta_{col}$ response.[11] The same method was applied here, except the addition of a zero was accompanied by a pole instead of a pure delay. Over the frequency range of interest (less than 25 rad/s), this lead/lag approximation was deemed acceptable.

The identification process was repeated with this lead/lag filter added to the parametric model structure, and its effect in the vertical axis is shown the Fig. 10 "before" and "after" plots. The filter's values are given at the bottom of Table 2. The before dynamic-inflow plot was developed using an $a_z/\delta_{col}$ frequency-response fit range up to 10 rad/s. As shown, the sharp initial overshoot was not captured with the eighth-order model without the dynamic-inflow approximation. Pilots will often note in moving-base simulations that they do not feel a "kick in the pants" on the initial collective input. In the after dynamic-inflow plot, the $a_z/\delta_{col}$ fit range was extended to 25 rad/s, and the lead/lag filter is included in the parameterization of the model. Note that this simple approximation captured the initial overshoot almost perfectly, whereas the fit is slightly sacrificed after the overshoot. The effect of this lead/lag filter in the vertical axis is stabilizing for height control here, since the pilot-in-the-loop phase margin is improved. This improvement was noticed immediately during the initial development using fixed-base evaluations.

It should be emphasized that this stability-derivative model is for the hover environs only and is valid to less than approximately 15 knots. For this near-hover flight regime, the AH-64 DASE control system was closed around the eighth-order stability-derivative model with the dynamic-inflow approximation. The diagrams of the pitch, roll, and yaw DASE are given in Ref. 13.

This control system, in its primary mode, uses a shaped combination of high-passed pilot stick-and-pedal positions and angular-rate feedbacks. The DASE is a limited-authority (approximately 10% of the actuator authority in each axis) series system. For necessary brevity, time history comparisons between flight tests with the DASE-on and the model with the DASE-on may be found in Ref. 14.

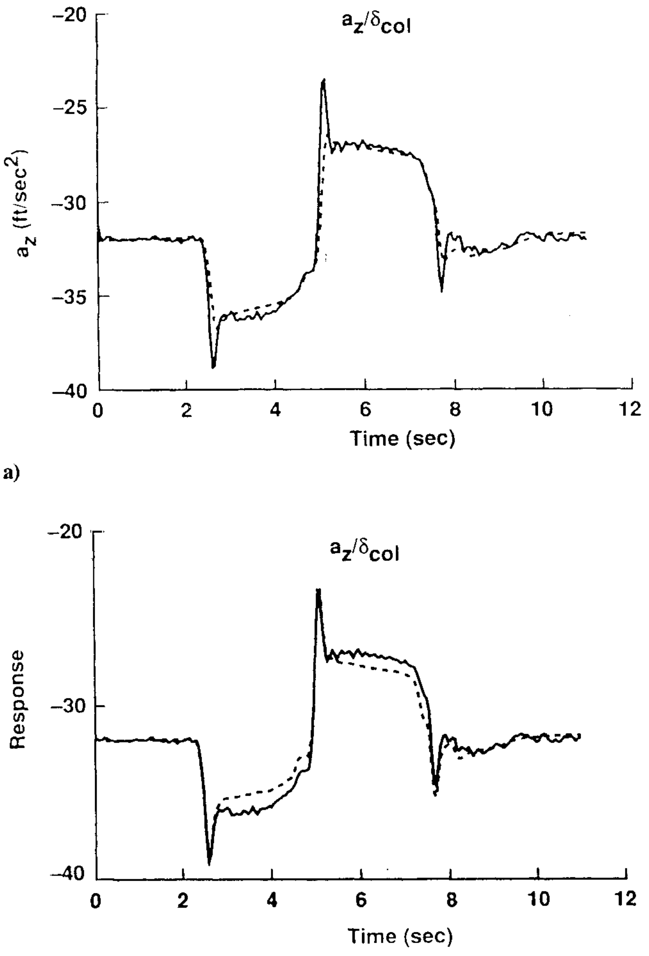



**Fig. 10 Effects of dynamic inflow addition: a) before and b) after.**

## Evaluation of Identified Model

### Simulation Setup

The Vertical Motion Simulator at Ames Research Center was used for subjective model evaluation. This large-amplitude motion system has operational linear displacements of ±22, ±15, and ±3 ft in the vertical, lateral, and longitudinal degrees of freedom, respectively. The operational pitch, roll, and yaw angular displacements are ±14, ±14, and ±19 deg, respectively.

The simulation environment is shown in Fig. 11. From left to right, the pilot puts a force into the stick, which displaces according to the identified-stick-model characteristics given in Ref. 14. Cockpit-stick displacements then drive the 7-DOF model. Model outputs are fed back through the DASE control laws. Model outputs are then washed out (high passed) before being sent to the motion system. These washouts will be discussed later. Aircraft states are also sent to the Singer-Link DIG 1 four-channel visual system that sends three channels to the three cockpit windows and one to a helmet-mounted display (HMD). The aircraft states are processed to drive superimposed symbols on the HMD. The delay in the visual channel is 83 ms; visual-scene time-delay compensation was not available for this simulation, a result of the use of the head-tracked forward-looking infrared (FLIR) image presentation on the HMD. From these simulation elements, the pilot receives four principal cues: 1) vehicle-motion cues, 2) visual-scene cues, 3) display-symbol cues, and 4) stick-position and force cues. Also present was simulated AH-64 cockpit sound.

Since the simulator-cab motion is restricted by the limits noted previously, digital high-pass filters wash out model accelerations before they are sent to drive the motion system. The principal motion washout filters for the angular and linear axes (other motion logic such as roll/sway coordination will not be discussed) are shown in Fig. 12. The filters are second order with a damping ratio of 0.7. For this experiment, the high-frequency gain was set to 1.0 for all the filters. Thus, at frequencies beyond the filter natural frequency, the pilot will feel the full accelerations that the mathematical model is calculating. For low-frequency longitudinal and lateral accelerations from the model, the motion system slowly tilts to use gravity components to simulate the applied forces. For the remaining four axes, at frequencies below the natural frequency, the pilot feels less acceleration with an accompanying phase distortion. When assessing the fidelity of the model, these filter values are quite important. Their characteristics may be superimposed on frequency responses such as those shown in Fig. 5 to assess which part of the vehicle spectra the pilot feels. Below the washout natural frequency, the pilot must determine the fidelity of the mathematical models by using visual cues.

After the high-passed motion commands are determined, they are sent to the motion hardware. The motion system is a large actuation system with its concomitant lags. The lags of the motion system in the pilot's four control axes (pitch, roll, yaw, and vertical) were

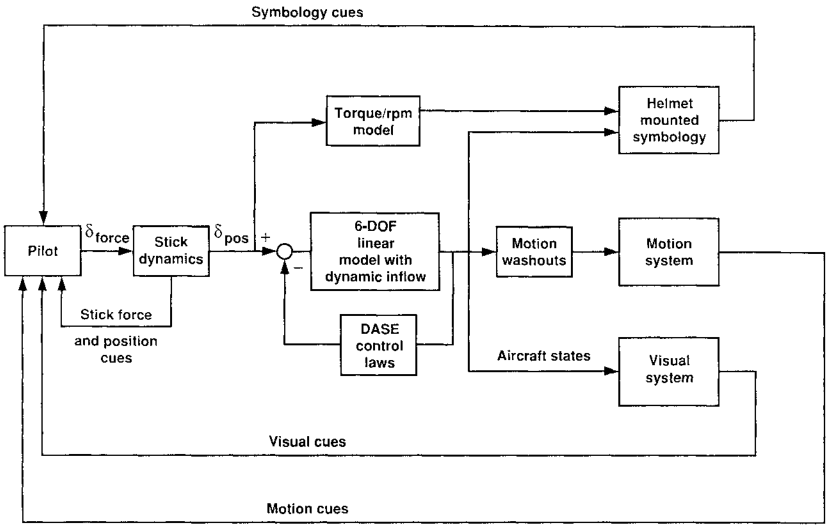
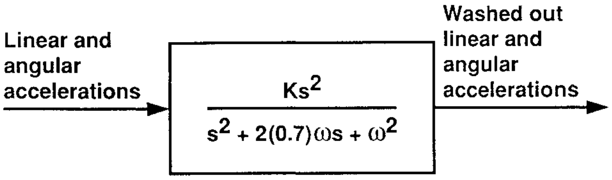



**Fig. 11 Simulation environment.**




| | K | ω rad/sec |
|---|---|---|
| $\dot{p}$ | 1 | 0.40 |
| $\dot{q}$ | 1 | 0.40 |
| $\dot{r}$ | 1 | 0.40 |
| $a_x$ | 1 | 2.00 |
| $a_y$ | 1 | 0.60 |
| $a_z$ | 1 | 0.25 |

**Fig. 12 Motion washouts.**

modeled as effective time delays, and values were identified from simulator data. Rather than add the time delays of the mathematical model identified in Table 2 to the unavoidable motion time delays, the Table 2 delays were reduced by the amount of delay identified in the motion system. A full discussion of these modifications is given in Ref. 14.

The simulation was flown by 11 pilots, 4 of whom were qualified in the AH-64; 3 were from the U.S. Army and the fourth from McDonnell Douglas. Ten of the 11 pilots were test pilots. Pilots performed several maneuvers, including precision hover, pedal turns, bob-ups, and sidesteps. Ideally, one would evaluate the model against an actual vehicle in back-to-back simulation and flight test for a precisely defined task. Then, pilot-vehicle performance comparisons between simulation and flight plus subjective pilot opinion ratings could be gathered. Here, the evaluation of the model was secondary to the simulation's primary objective of display design and evaluation. Also, an AH-64 was not available for back-to-back testing. Thus, pilot comments based on recollection of the vehicle's flying characteristics were the basis for assessing the model's fidelity. However, one pilot was able to fly the simulator, examine some particular items later in an AH-64 flight, and then return to the simulator for another session.

### Pilot Comments

All the comments are from the four AH-64 qualified pilots flying near-hover maneuvers up to 15 knots. In most cases, the pilot was presented with the FLIR image and superimposed symbols on the HMD. The quoted comments are broken down into general comments and comments for each axis.

*General*

"The simulation is a realistic representation of the workload in the airplane." "The model seems to act like an AH-64." "The simulated aircraft response is representative [of the aircraft]." "The cross-coupling seems right." "The simulation seems much more Apache-like than the Army's Combat Mission Simulator." "Feels kind of like being in a rocky rowboat . . . difficult to be smooth . . . getting some jerkiness." "Sensitivity and damping in the angular axes seem pretty good; I'm surprised." "Velocity response to pitch and roll attitudes seems too low; that is, too much attitude is required to accelerate and maintain velocity." "Within the constraints of the tasks required for the simulation, the model is quite good . . . outside of approximately 6 knots, the model comes apart." "Cyclic feels very representative . . . deadband in cyclic feels like the aircraft . . . pedals seem right also, although it is difficult to tell if they are exactly correct . . . they are representative."

*Pitch*

"With DASE-off, there is a slight pilot-induced-oscillation (PIO) tendency, which is difficult to damp out; this is not in the aircraft. It could be a simulator artifact due to the poor field of view and visual scene content." "With DASE-off, the simulation requires more attention than does the aircraft; sensitivity feels about right." "With the DASE-on, the attitude response feels less sensitive than the aircraft . . . within the constraints of the task, the response is good." "Seems to be slightly too much pitch (nose-up) and roll (left) attitude for a stable no-wind hover."

*Roll*

"With the DASE-off, the simulation does not have a PIO tendency, although the aircraft does." "Within the constraints of the task, the roll response feels good." "Little bit jerky laterally in the hover turn [in simulation]." "Simulation feels more damped than the aircraft with the DASE-on, but it is tangled up with the motion system." "Slight DASE-on PIO tendency when aggressive; like the aircraft."

*Yaw*

"Simulation is like the aircraft in that the aircraft seems to wrap-up in yaw for a control input and build to a point where you have to recover [DASE-on]." "Sensitivity is good." "Trim excursions cause a little more heading control than is required in the aircraft." "DASE-on yaw/heave coupling is less in the aircraft . . . [simulation] has too much yaw response to collective [with DASE-on]." "DASE-off coupling from collective is good."

*Vertical*

"Vertical [acceleration] response to collective is good." "Vertical axis seems like it is more work [in simulation]." "It seems like the aircraft does not develop the [vertical] rates that the simulation does." "Seems like a lot more power input requirements to hold altitude [in simulation]." "Altitude control is my biggest heartache [in the simulator]." "The aircraft is more damped, but the simulation forces attention to the heave axis, which is realistic." "Cannot seem to find a torque setting that will stabilize the altitude." "Aircraft feels slightly more damped than simulation, but not enough to require a change . . . I would not alter the model." "Collective activity required is very representative."

## Discussion

Although there were some negative comments (e.g., the vertical axis), the overall impression of the model was favorable. As expected, the pilots had difficulty in attributing deficiencies to specific components of the simulation. This difficulty results from their indirect observation of what the mathematical model is actually doing. Their contact with the model, relative to what they sense in the aircraft, is through imperfect visual and motion cues. The simulation visual scene was untextured and had 83 ms of time delay. The motion system can only represent motion fidelity above the washout filter natural frequencies. In addition, as mentioned earlier, the directional and vertical axes suffer from hardware delays that are in excess of those identified for the mathematical model. These visual and motion effects are mentioned, not to lay blame for simulation deficiencies elsewhere than on the mathematical model, but to point up the fact that these non-mathematical-model deficiencies will have an effect on even a perfect model. Quantification of some of these degrading effects has been examined in previous experiments.[15] Each paragraph below presents a discussion of the individual sets of comments.

For the general comments, the "rocky rowboat" feeling may be due to imperfect phasing between the angular and linear motions. The simulation center of rotation is below the pilot, so linear motion has to cancel the resulting angular-induced linear motion. Although compensation in software is designed to match the responses, some jerkiness is present. The "approximately 6 knots" boundary on the model may have been chosen by the pilot, because the display evaluation tasks were designed to keep a displayed velocity vector symbol within its limits on the display, which was 6 knots.

The DASE-off PIO tendency would not appear to be a mathematical model deficiency upon examination of Figs. 5 and 6. From Fig. 5, the model-phase response is even slightly better than that of the aircraft. The trim attitudes in pitch and roll were taken directly from stable hover flight data. The trim attitudes used were 6.5 deg of pitch and −2.5 deg of roll. These trims did vary in the flight data as winds and weight changed, and instrument biases also may exist.

No conclusion can be drawn from differences in the $p/\delta_{lat}$ responses of Fig. 5 that would explain differences in PIO tendencies. One might attribute the increased PIO tendency in pitch to a simulation artifact, but that conclusion would be inconsistent with a decreased PIO tendency in simulation for roll. The pilot recognized some motion-system effects, such as those discussed earlier, in the roll axis.

The positive comment on DASE-off coupling from collective input is consistent with Fig. 9, except the model leads the aircraft because of unmodeled dynamics that couple between the rotor rpm and the yaw axis.

The vertical-acceleration response to collective input sensitivity is consistent with the response in Fig. 10. The other comments refer to the perceived (and actual) poor vertical damping of the mathematical model. A consistent pilot comment concerned the inability to set a torque to stabilize altitude. This comment appears to indicate that the pilot is trying to fly when out of ground effect with in-ground-effect techniques. Simulation of ground effects was not included in the model, because the tasks and evaluations were performed at a height of one rotor diameter from the ground. At this height, ground effect is minimal. When out of ground effect, the torque reading is effectively an acceleration command. Even with a vertical damping typically predicted from momentum theory ($-0.3\ s^{-1}$), pilots would not be able to maintain tight altitude control out of ground effect by setting torque. So, some of the negative comments on the vertical axes may have been technique related, since hovering operations are typically conducted at heights with some ground effect aiding in height stabilization. This explanation may not of itself be adequate, since achieving acceptable simulated height dynamics that also match flight data has been a difficulty for the helicopter community.

## Conclusions

A 7-DOF rigid-body hover model of the AH-64 Apache helicopter was developed using frequency-domain system identification techniques on flight data. The model was developed for use in the testing of a hover-display design but is applicable to any handling-qualities hover simulation. The model was evaluated by four contractor and government AH-64 pilots. Overall impressions of the model were favorable, with the most consistent negative comment being a difficulty in controlling the height axis. The mathematical model presented here should be very useful to future control and display designers in that it satisfactorily represents a current-generation helicopter in hover.

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