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An Empirical Correction Method for Improving off-Axes Response Prediction in Component Type Flight Mechanics Helicopter Models

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Summary

Historically, component-type flight mechanics simulation models of helicopters have been unable to satisfactorily predict the roll response to pitch stick input and the pitch response to roll stick input off-axes responses. In the study presented here, simple first-order low-pass filtering of the elemental lift and drag forces was considered as a means of improving the correlation. The method was applied to a blade-element model of the AH-64 Apache, and responses of the modified model were compared with flight data in hover and forward flight. Results indicate that significant improvement in the off-axes responses can be achieved in hover. In forward flight, however, the best correlation in the longitudinal and lateral off-axes responses required different values of the filter time constant for each axis. A compromise value was selected and was shown to result in good overall improvement in the off-axes responses. The paper describes both the method and the model used for its implementation, and presents results obtained at hover and in forward flight.

Nomenclature

$c_{d_{filter}}$	filtered elemental drag coefficient
$c_{d_{table}}$	elemental drag coefficient from table
$c_{l_{filter}}$	filtered elemental lift coefficient
$c_{l_{table}}$	elemental lift coefficient from table
f_1	lift coefficient table
f_2	drag coefficient table
M	local Mach number of blade element
P	helicopter roll rate, deg/sec
Q	helicopter pitch rate, deg/sec
R	rotor radius, ft
V_0	longitudinal component of airspeed, ft/sec
α	angle of attack of blade element, deg
δ_{lat}	lateral stick input, in.
δ_{lon}	longitudinal stick input, in.
τ_a	first-order filter time constant, 1/sec
Ω	rotor rotational speed, rad/sec
u	advance ratio, nd
ψ_a	static aerodynamic phase lag, deg

Background

Component-type flight mechanics simulation models of most existing helicopters are unable to correctly predict the off-axes roll response to a longitudinal input and pitch response to a lateral input of the actual vehicle. Linear models, identified from flight data at a specific flight condition, correctly capture the off-axes behavior. Such identified models, however, are only applicable to flight near their reference condition and cannot be applied over the entire flight envelope. Further, they obviously cannot be used during the aircraft development phase, before flight data become available.

Simulation model fidelity is especially important for modern development programs where accurate on- and off-axes response prediction is required for high-bandwidth flight control design purposes (ref. 1). Some researchers speculate that the off-axes discrepancies of flight mechanics simulation models are due to inadequate modeling of the main rotor wake and dynamic inflow (refs. 2 and 3). Others suggest that the discrepancies are the result of insufficient modeling of rotor/fuselage interaction. Yet others propose that only by including blade flexibility can the off-axes discrepancies be corrected. The answer is not clear and has led to the conclusion, as voiced by Professor Curtiss of Princeton, that "off axis response characteristics of single rotor helicopters are not understood" (ref. 4).

In recent years, considerable research effort has been devoted to improving the modeling of the rotor wake. In 1994, Rosen and Isser developed a complex model of rotor wake distortion during pitch and roll motion of a hovering helicopter (ref. 5). This rigorous approach takes into account the influences of shed and trailing vortices together with geometric unsteady effects. It has shown promise in correctly predicting the off-axes responses of the AH-64 and the UH-60. However, to date, it has only been applied to the case of an isolated rotor in hover. Furthermore, the model is too complex to apply to flight mechanics models in its present form, especially if the model is intended for real time simulation.

To avoid this complexity, researchers at the Aeroflightdynamics Directorate (AFDD) have taken an empirical approach to improving the predictive capability of helicopter models. The goal is not to rigorously model the physics of the problem, but to develop simple modifications that would improve the off-axes correlation of existing and future component-type models. The work originated with the analysis of full scale wind-tunnel test data from the Sikorsky Bearingless Main Rotor (SBMR). That study showed that by increasing the swashplate phase angle used in the analysis model beyond its actual geometric value, it was possible to achieve much better correlation with the off-axes test data (ref. 6). Applying the same technique to a component type model of the UH-60, however, did not improve the off-axes correlation in free flight. The phasing of the swashplate only affects the rotor response to control inputs and not to shaft motion. It was, therefore, thought that for free flight it would be more appropriate to include this correction through an azimuthal rotation in the fixed-frame aerodynamic components, termed the "aerodynamic phase lag," ψ_a. The two correction approaches yield an identical improvement in the fixed-shaft, wind-tunnel case. The aerodynamic phase lag approach proved successful in subsequent identification studies of the UH-60 in hover and forward flight (Fletcher, ref. 7). Physical sources of this identified effective aerodynamic lag include: a) wake geometric distortion due to pitch and roll motion (refs. 5 and 8), b) increased two-dimensional (2-D) unsteady indicial response lag (Theodorsen type) under compressible flow conditions (ref. 9), and c) perhaps in-plane inflow swirl (ref. 2).

In a similar effort, Arnold et al. (ref. 3) have recently explored the effects of three possible methods of improving the off-axes response. These are, a) an extended version of momentum theory including wake distortion terms, b) a first-order aerodynamic lag model, and c) an aerodynamic phase correction. The latter two methods follow the empirical approach of AFDD (refs. 1 and 7). Arnold et al. have shown that all three approaches result

in similar improvements in the off-axes responses when applied to a simplified model of the coupled pitch and roll dynamics in hover. Also, they have shown that considerable improvement in correlation with flight data is achieved when the extended momentum theory approach is applied to an existing non-linear simulation model. The extended momentum theory work of Arnold parallels the work by Keller (ref. 8) who has shown that the inclusion of induced velocity variations due to shaft rate improves correlation in the pitch response to lateral cyclic inputs. Finally, Von Grunhagen (ref. 2) of the Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) has included apparent angular momentum, arising from the in-plane swirl of the wake, in the dynamic inflow equations and shown improvements in the off-axes prediction.

In the effort presented here, the aerodynamic phase lag technique was applied to a blade-element model of the AH-64 known as Blade-Element Model for Apache (BEMAP) (ref. 10). Following the implementation of Arnold (method b above), first-order low-pass filtering of the lift and drag coefficients per blade element was used to implement the desired phasing. The time constant could then be varied until good off-axes correlation was achieved. Herein, the delay was applied to the lift and drag coefficients at the elemental level in an attempt to mimic the actual generation of the forces on the elements (similar to Theodorsen effect but of much higher delay). Also, in the current study the modification is applied to a full-flight-envelope flight-mechanics model, rather than the simplified representation of the pitch and roll responses used in reference 3.

This paper describes the details of the model and the aerodynamic phase lag correction technique. It also provides frequency-domain comparisons of the responses of the modified model with flight data in hover and forward flight. Summary results from SBMR and UH-60 work at AFDD are provided to show the general applicability of the technique, and trends in the empirical phase lag for a range of rotor geometries and flight conditions.

BEMAP

The BEMAP is a version of McDonnell Douglas Helicopter Systems' (MDHS) FLY Real Time (FLYRT) (ref. 11) in which the map-type main-rotor has been replaced with a blade-element type module (ref. 10). The new rotor module was developed following the general structure of the main-rotor module of Sikorsky's Gen Hel model of the UH-60 Black Hawk helicopter (ref. 12). The kinematic and inertial equations for modeling the AH-64 rotor were derived with the aid of the symbolic manipulation program MACSYMA (ref. 13) based on a

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flap-lag-pitch hinge arrangement and following the work of Chen (ref. 14). Though the Apache uses a flap-pitch-lag hinge arrangement, the simpler f-l-p sequence was used to avoid the added complexity of treating blade pitch as a degree of freedom (DOF).

Simple 2-D strip theory, augmented with yawed flow corrections and Pitt-Peters dynamic inflow, is used to calculate the aerodynamic forces generated by each blade element. The yawed flow corrections are applied as described in reference 12. The Pitt-Peters inflow model is based on the version outlined by Peters and Ha Quang (ref. 15). It was implemented as a modification of the implementation used by Ballin (ref. 16) in which the normal induced inflow is calculated based on the aerodynamic thrust coefficient using an iterative scheme. Lift and drag coefficients are extracted from bi-variate maps as functions of local angle of attack and Mach number. These coefficients are used to calculate the elemental lift and drag forces. The elemental forces are then summed over all the blade elements to calculate the aerodynamic forces and moments per blade. The aerodynamic forces and moments on each blade are then used, along with the inertial, gravitational, and flapping and lead-lag restraint forces and moments to calculate the flapping and lead-lag dynamics. Finally, the forces and moments are summed over all the blades to calculate the total forces and moments at the aircraft center of gravity.

The new rotor was integrated into FLYRT to create BEMAP. This also required the modification of the trim and equations-of-motion modules. The modules representing other components of the Apache helicopter, i.e., fuselage/empennage/wings, vertical tail/tail rotor, horizontal stabilator, and landing gears, however, were used directly from FLYRT (ref. 11). BEMAP was extensively validated against flight data as described in reference 10. Some of the same data will be used later in this paper as a basis of comparison to highlight off-axes improvements.

Implementation of the Aerodynamic Phase Lag

The delay, or effective phasing, of the elemental forces is accomplished by processing the lift and drag coefficients for each element through a first-order filter. As mentioned before, the lift and drag coefficients at each time step are found from lookup tables as functions of local angle of attack and Mach number at that element.

$$c_{l_{table}} = f_1(\alpha, M) \tag{1}$$

$$c_{d_{table}} = f_2(\alpha, M) \tag{2}$$

The angle of attack and Mach number are based on the local flow resulting from aircraft motion, blade rotation, blade flap, lead-lag, rotor inflow, and wind. The filtering is done for every blade element using:

$$\tau_a \dot{c}_{l_{filter}}(i,j) + c_{l_{filter}}(i,j) = c_{l_{table}}(i,j) \tag{3}$$

$$\tau_a \dot{c}_{d_{filter}}(i,j) + c_{d_{filter}}(i,j) = c_{d_{table}}(i,j) \tag{4}$$

where i is the blade index and j is the element index (1-4 and 1-5 respectively for this model). This filtering is depicted graphically in figure 1.
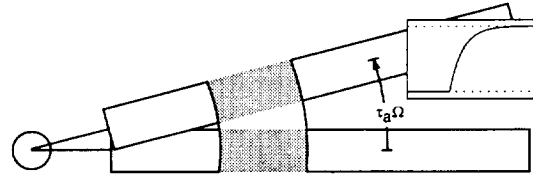

Figure 1. Implementation of first-order filter on lift and drag coefficients.

The time constant of the first-order filter, τ_a, is selected in terms of an equivalent static aerodynamic phase lag, ψ_a :

$$\tau_a = \frac{1}{\Omega} \tan \psi_a \tag{5}$$

so that this implementation (τ_a in rotating frame) and previous implementations (ψ_a in fixed frame) result in the same steady-state response (ref. 3).

For each airspeed (hover and 60 kts), the time constant was varied until the most improvement in the off-axes response was achieved. The aerodynamic lag was assumed independent of rotor azimuth for all airspeeds. This was considered to be a reasonable approach even though using first harmonic variation in τ_a for the lateral and longitudinal inputs might have resulted in better correlation in forward flight, as will be discussed later.

Generating Model Responses

A frequency-domain approach was taken in the evaluation of the model responses (with and without the aerodynamic phase lag correction) and for their comparison with flight data. Non-parametric frequency responses for the actual aircraft were already available from reference 10. Simulation model responses without the aerodynamic phase correction could also have been used from the same reference. The latter responses, however, were based on 6 DOF linear models generated using a simple numerical

perturbation technique. It was decided to employ a more rigorous approach for this effort.

The new approach basically mimics the process of frequency sweep testing of an actual aircraft. Instead of pilot-generated sweeps, however, computer generated sweeps were used. These were generated using a modified version of a FORTRAN code described in reference 6. Briefly, the code allows the user to 1) specify the total duration and sample rate, 2) the duration of initial and ending zero signal, 3) the duration of signal fade-in to maximum amplitude at a constant minimum frequency, and 4) the duration of signal fade-out at a constant maximum frequency. White noise of specified standard deviation can also be added to the fundamental signal to improve spectral content. In addition, white noise can be specified as the input to the three remaining controls and its standard deviation adjusted relative to the white noise used for the main control. Figure 2 shows a typical frequency sweep input used for this work.

Figure 2. Typical computer generated frequency sweep input including white noise.

The sweeps were used as inputs to the model, one axis at a time, and model responses recorded. The main difficulty with running frequency sweeps through an unpiloted simulation model is maintaining attitude and airspeed close to initial trim. Given the long duration of a typical sweep (90 sec), some additional control has to be provided. This

was added in the form of low-gain rate and attitude feedback loops on roll, pitch, and yaw (fig. 3), similar to the work by Ballin et al. (ref. 16). These loops have no effect on the extracted dynamic response obtained from multi-input/multi-output spectral analysis, since the frequency responses are based on the total input to the mixer (Sum4, Sum5, and Sum6 in fig. 3).

Figure 3. Feedback loops to maintain attitude during frequency sweep.

First, 6 DOF linear models of the simulation were generated, using standard linear perturbation techniques, at the airspeeds of interest. These where then used, in MATLAB®, to find suitable rate and attitude feedback gains (fig. 3). The simulation was then modified with the new feedback loops and exercised with typical frequency sweeps to insure that attitude and airspeed excursions were limited to acceptable levels. Finally, test data were taken at hover and 60 kts with and without the aerodynamic phase lag correction.

Model time histories generated above where then processed through the Comprehensive Identification from FrEquency Responses (CIFER®) (ref. 17) tool to generate Bode plots for comparison with flight data. For each case, two 90 sec runs were concatenated to give a total run length of 180 sec. Five windows, varying from 5 to 40 sec in length, were used to process the data. The larger windows were used to provide good low frequency coverage while the smaller windows provided good averaging and high frequency identification accuracy. The data was further processed to eliminate the effects of off-axes inputs and to combine the results from all the windows. In some

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cases the entire process (starting from the generation of inputs) was repeated because the model results did not have sufficient coherence in the frequency region of interest (1 to 10 rad/sec). Nevertheless, in a few of the cases good coherence could not be achieved across the entire frequency region of interest even after several attempts.

Figure 4 shows a comparison of the frequency response curves obtained using the identification approach with curves obtained using the 6 DOF linear-perturbation-model approach. As expected, the two approaches show similar results in the mid-frequencies while the new approach is clearly superior at higher frequencies, capturing the regressing rotor dynamics.
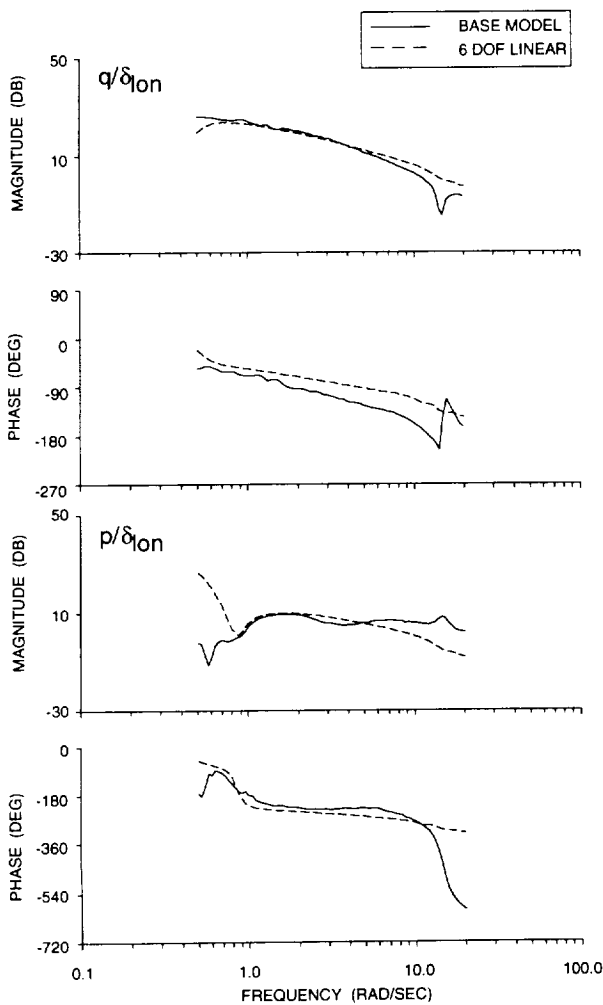
Figure 4. Results of new frequency response generation approach vs. the old 6 DOF approach.

Comparison of Model Responses with Flight Data

Hover

The responses of the modified AH-64 model were compared with available flight data in the frequency domain. Results in hover indicate that using a time constant equivalent to an aerodynamic phase lag of $\psi_a = 36$ deg, the modified AH-64 model correlates significantly better with the flight data. Figure 5(a) depicts the on-axes roll-rate to lateral input response of the model in hover, with and without the aerodynamic phase lag correction. As may be seen, the on-axes response of the baseline simulation model is quite good. Within the frequency range of interest (between 1 and 10 rad/sec for flight mechanics models), the baseline model shows very good correlation in both phase and magnitude. It is also seen that the addition of the aerodynamic phase lag does not degrade the on-axes correlation.

Figure 5(b) depicts the off-axes pitch-rate responses to the same lateral input. It may be seen that the baseline simulation model exhibits the familiar inability to match the off-axes response as indicated by the up to 180 deg mismatch in the phase correlation. Figure 5(b) also shows that the addition of the 36 deg of aerodynamic lag almost completely corrects the phase correlation error in the 1-5 rad/sec frequency range where flight data has acceptable coherence, without degrading the magnitude correlation. Note that the coherence of the off-axes flight data is significantly lower than the on-axes data and falls below the acceptable values for a portion of the 1 to 10 rad/sec interest region. This is caused by low output signal magnitude and may be due to the large moment of inertia of the aircraft in pitch. Nevertheless, the general trend of improvement in correlation should be valid.

Moving on to pitch inputs, figure 6(a) depicts the on-axes pitch-rate to longitudinal input response of the model in hover, with and without the aerodynamic lag correction. The on-axes response of the baseline simulation model is again good. Within the frequency range of 1 and 10 rad/sec, the baseline model shows very good correlation in both phase and magnitude. Also, the addition of the filter does not degrade the on-axes correlation.

Figure 6(b) depicts the off-axes roll-rate responses to the same longitudinal input. Here, unlike in the lateral input case, the coherence of the off-axes flight data is adequate, probably because the roll moment of inertia of the aircraft is small (compared to pitch). Again, the baseline simulation model exhibits the familiar inability to correctly
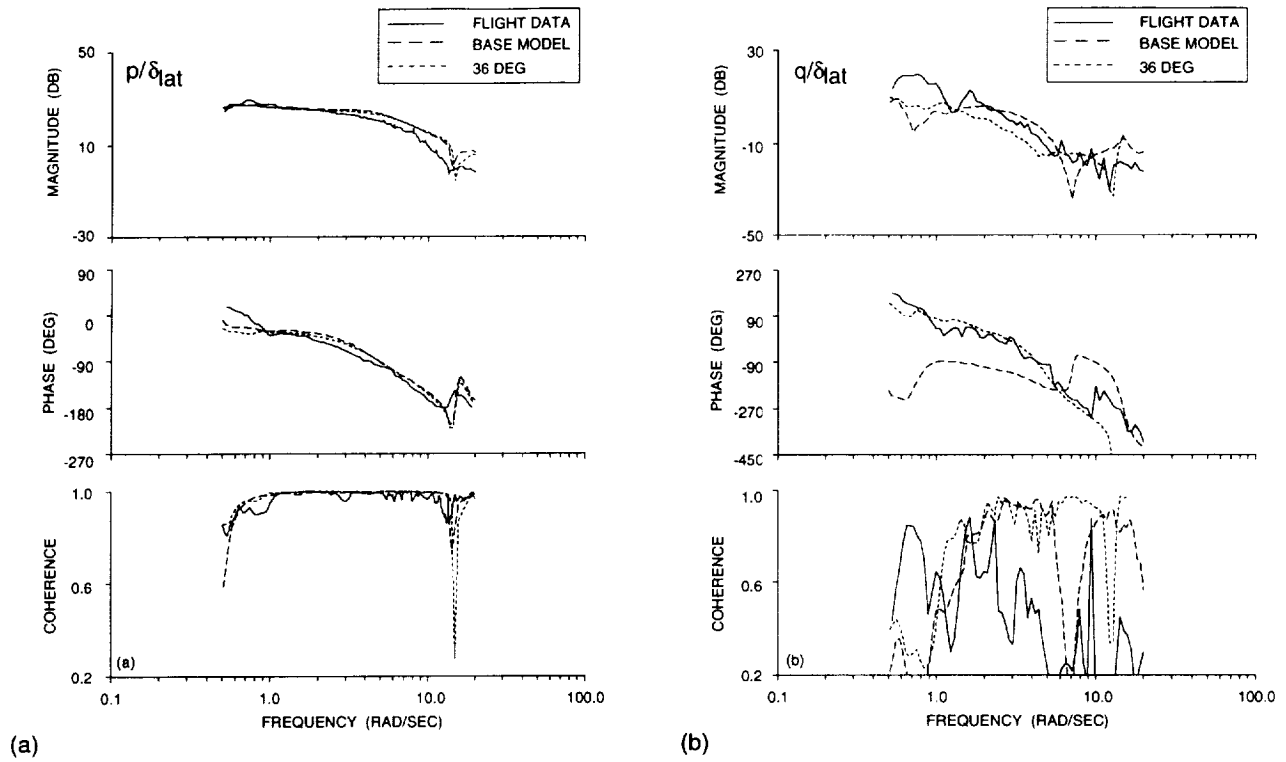
Figure 5. (a) Roll-rate response to lateral input at hover, (b) pitch-rate response to lateral input at hover.
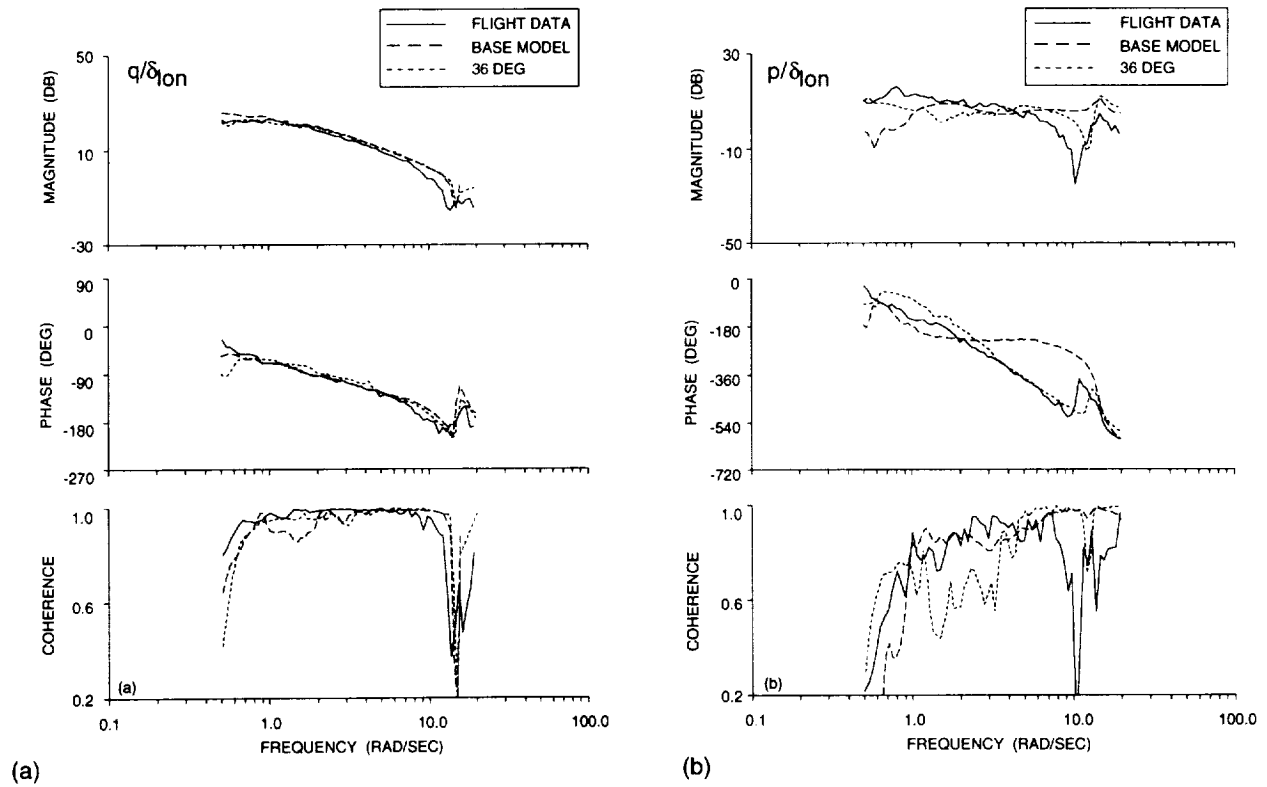

Figure 6. (a) Pitch-rate response to longitudinal input at hover, (b) roll-rate response to longitudinal input at hover.

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model the off-axes response. The figure shows that as 10 rad/sec is approached, the phase correlation error is 180 deg. This means that at those frequencies, the baseline model essentially goes the wrong way. The figure also shows that the addition of the 36 deg of lag again results in a significant improvement in the phase correlation. Furthermore, this is achieved without any degradation of the magnitude response. As a matter of fact, the magnitude response is slightly improved.

Forward Flight at 60 Kts

The results of using the aerodynamic phase lag correction to improve the correlation at 60 kts were mixed. It was obvious from the start that the filter time constant used in hover would not be applicable to 60 kts and that a smaller value would be needed. A range of values, from 15 to 30 deg, were therefore investigated. Results indicated that different amounts of aerodynamic phase lag would be needed in each axis to obtain the best correlation. An aerodynamic phase lag of 24 deg was shown to result in the best correlation of the pitch-rate response to lateral input, as shown in figure 7. On the other hand, the baseline simulation model (without any aerodynamic phase lag correction) showed the best correlation of the roll-rate
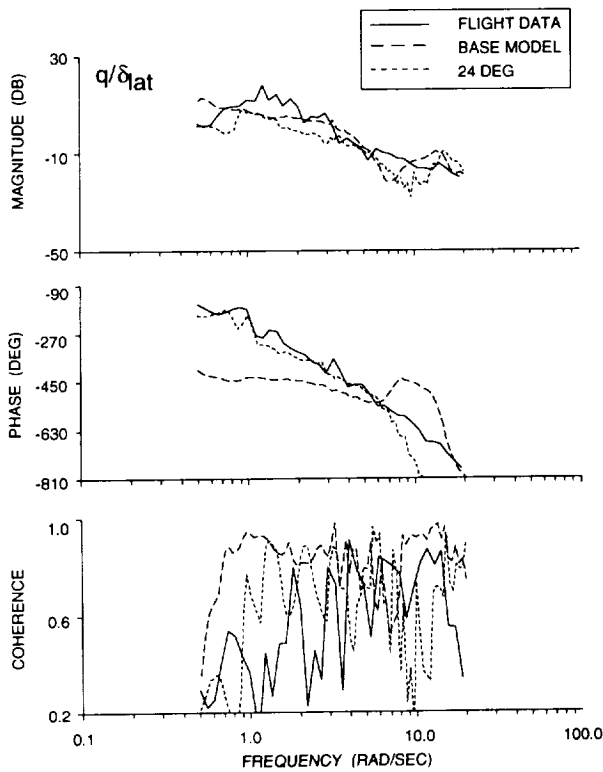
Figure 7. Pitch-rate response to lateral input at 60 kts.

response to longitudinal input. This suggests that a first harmonic variation of the value of the aerodynamic lag may be the optimum solution. For this study, however, the implementation required that the same delay value be used in both axes. Therefore, a compromise value of the aerodynamic phase lag had to be found. The goal was to provide improvement in the pitch-rate to lateral input response without degrading the roll-rate to longitudinal input response of the baseline model. Sample runs showed 19 deg to be this compromise value. The forward flight results that follow are therefore for 19 deg of aerodynamic phase lag correction.

Figure 8(a) depicts the on-axes roll-rate to lateral input response of the model at 60 kts with and without the aerodynamic phase lag correction. As may be seen, the on-axes response of the baseline simulation model is quite good. Within the frequency range of interest, the baseline model shows good correlation in both phase and magnitude and the addition of the filter does not degrade the correlation.

Figure 8(b) depicts the off-axes pitch-rate responses to the same lateral input. The baseline simulation model again exhibits poor prediction of the off-axes response. The mismatch in the phase response correlation is again up to 180 deg at some frequencies. The results also show that the addition of the 19 deg of equivalent phase lag significantly improves the phase response correlation while degrading the magnitude correlation somewhat. As in hover, the coherence of the off-axes flight data is low and falls below acceptable values for a portion of the 1 to 10 rad/sec interest region. Again, this may be attributed to low signal magnitude caused by high inertia in pitch.

Figure 9(a) depicts the on-axes pitch-rate to longitudinal input response of the model at 60 kts with and without the aerodynamic phase lag correction. The figure shows that the on-axes response of the baseline simulation model is quite good. Within the frequency range of interest, the baseline model shows very good correlation in both phase and magnitude and the addition of the correction does not degrade the on-axes correlation.

Figure 9(b) depicts the off-axes roll-rate responses to the same longitudinal input. As mentioned previously, the baseline simulation model does a good job of duplicating the phase of the response throughout the frequency range of interest. However, the magnitude response correlation is quite poor. Adding 19 deg of aerodynamic lag degrades the phase correlation above 6 rad/sec while improving the magnitude correlation considerably beyond 2 rad/sec. Note that again, as in hover, the coherence of the flight data in the roll-to-pitch off-axes response is much better than the pitch-to-roll case.
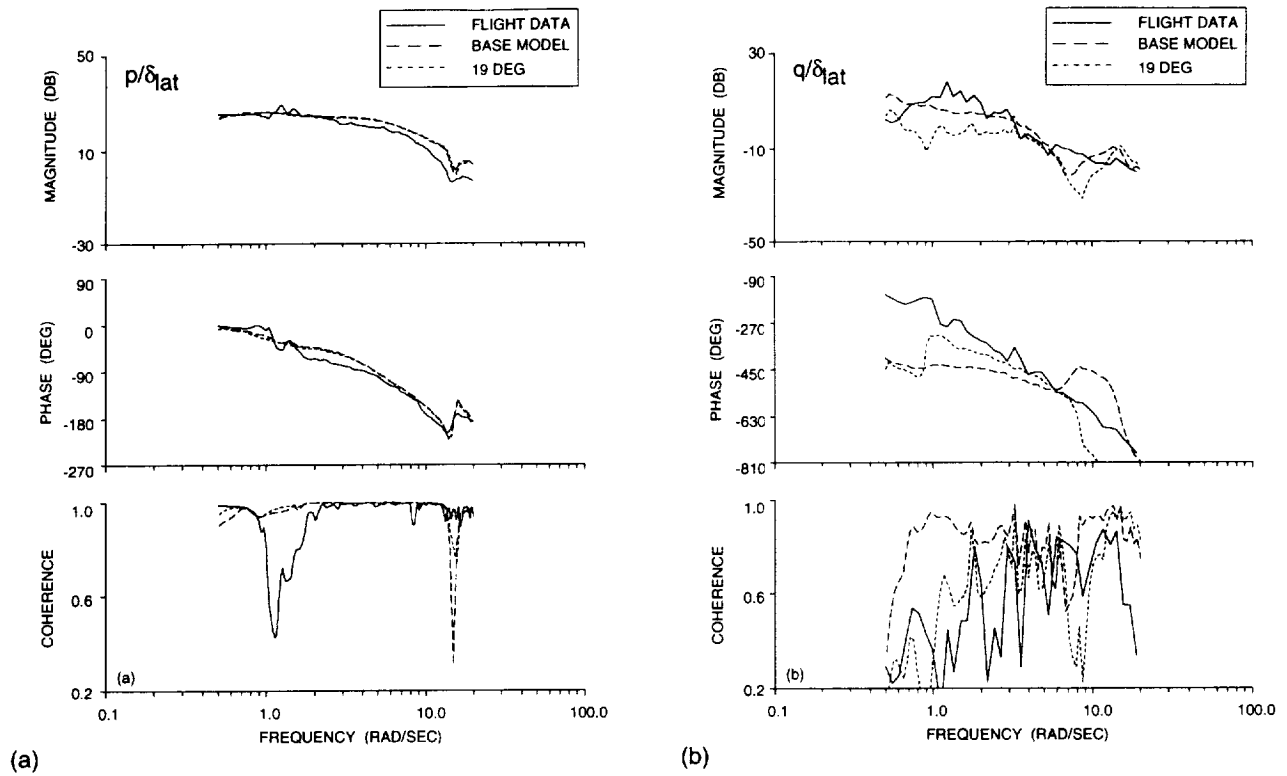
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Figure 8. (a) Roll-rate response to lateral input at 60 kts, (b) pitch-rate response to lateral input at 60 kts.
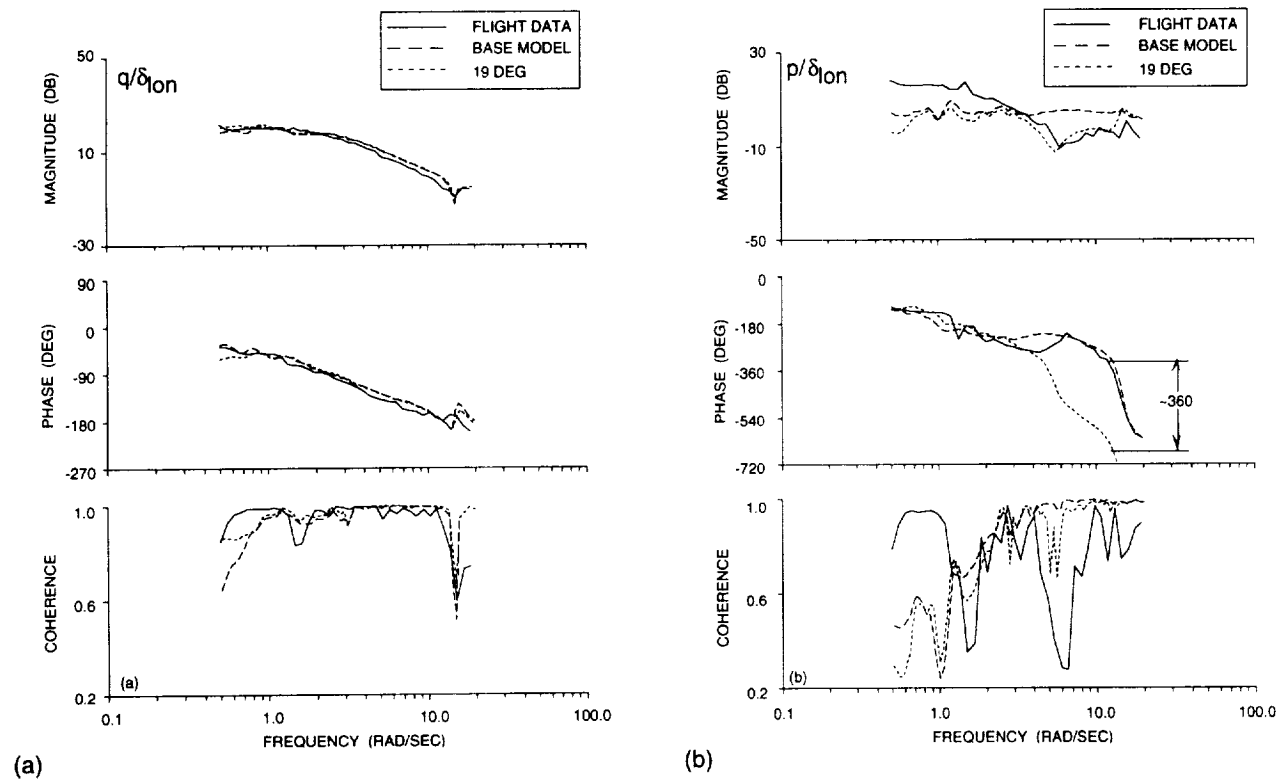

Figure 9 (a) Pitch-rate response to longitudinal input at 60 kts, (b) roll-rate response to longitudinal input at 60 kts.

A closer examination of figure 9(b) indicates that the corrected-model actually matches the off-axes dynamics of the aircraft much better than upon initial examination. Looking at the magnitude plot for the corrected-model, it can be seen that a pair of lightly-damped complex zeroes are indicated at a frequency of about 6 rad/sec. This matches the flight data which also indicates a pair of lightly damped zeroes at about the same frequency. The phase results match at low frequency and are simply offset by 360 deg at high frequency. The difference indicates that whereas the lightly-damped flight-data-zeros contribute a rapid phase lead, the corrected-model-zeros contribute a rapid phase lag over the same frequency interval. These characteristics indicate that relative to the flight data zeroes, the corrected-model-zeroes have essentially the same natural frequency, but are shifted slightly to the right of the imaginary axis (on the complex plane). This is verified by reversing the phase contribution of the corrected-model zeroes to represent the case of complex zeroes located at the mirror image position (fig. 10). This mirror image shift of the zeroes does not affect the magnitude curve.
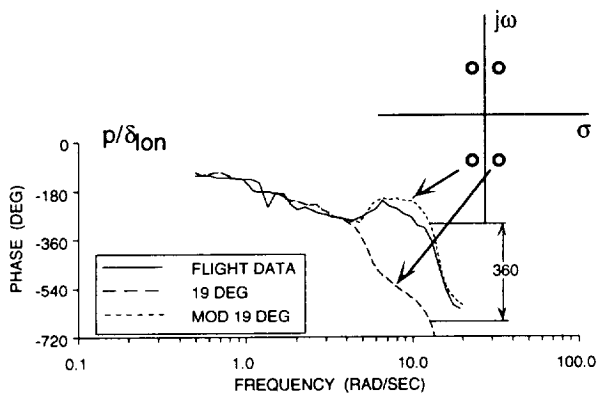

Figure 10. Effect of minimum-phase versus nonminimum-phase zeros.

As may be seen from figure 10, the adjusted phase response matches the flight data well, verifying the shift in the real-part of the complex zeroes as the cause of the original discrepancy. Numerical investigations conducted by the authors suggest that a physical source of the discrepancy in the damping of the zeros may be an error in the assumed pitch-flap coupling, δ_3. Though the physical δ_3 angle for the AH-64 rotor is zero, there can be a contribution to the effective δ_3 from control linkage geometry and shaft flexibility. In any case, the influence of a slight error in the predicted damping ratio of the coupling response zeros is probably of little practical significance.

Thus overall, the corrected model can be said to match the response of the aircraft better than the original model, and the compromise lag value of 19 deg is quite satisfactory.

The baseline simulation model results from figure 9(b) together with the 24 deg of aerodynamic lag correction results from figure 7 highlight the need for different values of aerodynamic phase lag in each axis to achieve best correlation. One potential solution to this problem might be to implement the aerodynamic phase lag as a first harmonic function of the rotor azimuth. This would be consistent with the first harmonic nature of dominant inflow dynamics. Note, however, that other effects, such as insufficient modeling of the interaction of the main rotor wake with the tail surfaces (ref. 18), may also contribute to this apparent need for different Aerodynamic Phase lag values for the two coupling responses.

DISCUSSION

The simulation results in this study show that considerable improvement in the AH-64 off-axis response modeling can be achieved with a very simple empirical correction to the blade element aerodynamic calculations. However, the current results were obtained by tuning the aerodynamic phase lag to existing flight test data for this specific helicopter. The broad applicability of this technique to the simulation of new helicopters requires a validated "carpet-plot," that maps the variation of ψ_a for a range of key configuration parameters. In this section, we begin the construction of such a carpet-plot with the incorporation of data from the current study on the AH-64, previous results from UH-60 flight tests, and the SBMR wind-tunnel tests. This combined presentation of results also permits an understanding of the key physical sources for the aerodynamic lag effect.

Collection of Existing Results

The empirical values of ψ_a for the AH-64 obtained in the current study are shown in figure 11 as a function of non-dimensional advance ratio, $\mu = V_0/(\Omega R)$ Also shown are the UH-60 results of Fletcher (ref. 7) for hover and 80 kts ($\mu = 0.19$).

There is close agreement of the hover results for the AH-64 and the UH-60, which have very close values of hinge off-set. (AH-64: $\varepsilon = 0.038$; UH-60: $\varepsilon = 0.047$). The phase lag values also compare favorably for forward flight when linearly interpolated for the same advance ratio. Clearly, the aerodynamic phase lag correction washes out with advance ratio, as do the dynamic inflow effects in general.
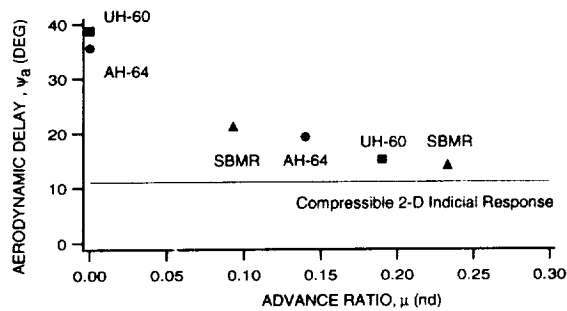
Figure 11. Variation of aerodynamic lag correction with advance ratio from various sources.

The initial identification study of the SBMR dynamic response wind-tunnel data (ref. 6) implemented an off-axis correction in terms of an adjustment to the swashplate phasing. These low-speed ($\mu = 0.093$) results were later updated (ref. 19) to account for SBMR feathering axis geometry that actually caused the geometric swashplate rigging to be -14 deg, rather than the design value of -9 deg indicated in the original study (ref. 6). The SBMR analysis was subsequently broadened to include the forward flight test data at 100 kts ($\mu = 0.233$) and an identification model structure based on aerodynamic phase lag ψ_a, rather than equivalent swashplate phasing. The SBMR aerodynamic phase lag results for the two test conditions analyzed ($\mu = 0.093$ and ($\mu = 0.233$) are shown in figure 11. The SBMR results show the same wash-out trend with advance ratio as seen for the AH-64 and the UH-60. Unfortunately, sufficient data to determine a possible relationship between ψ_a and hinge-offset (SBMR: $\varepsilon = 0.095$) is not currently available.

Physical Sources of Aerodynamic Phase Lag

The test data obtained to date and presented in figure 11 provide a start to the broad carpet-plot needed for general application of the aerodynamic phase lag technique. However, an understanding of the physical sources for the lag is important for the development of theoretical models for correlation with the test data and to fill in the carpet-plot over a detailed grid of helicopter configuration parameters.

While the results display a strong sensitivity of aerodynamic lag with advance ratio for low speed conditions, the correction values clearly wash-out with higher advance ratios. The data suggest that the phase lag reaches a high-speed asymptotic value of about $\psi_a = 13$ deg. Since dynamic inflow effects also wash-out with advance ratio, and are essentially negligible beyond $\mu = 0.15$–0.2, this residual 13 deg aerodynamic lag is not caused by the geometric distortion of the dynamic wake as modeled by

Rosen and Keller (refs. 5 and 8). The source of the residual delay is rather an additional aerodynamic effect which is not currently included in flight mechanics simulation models.

One possible source of the residual aerodynamic phase lag is the 2-D unsteady aerodynamic indicial response, which was not included in the AH-64 or UH-60 simulation models, and is generally neglected for helicopter flight mechanics since the 1/rev incompressible contribution is very small. For example, the classical Theodorsen delay for a reduced frequency equivalent to 1/rev motion is about 5 deg based on tip speed and about 9 deg based on the speed at the 3/4 radius location (ref. 20). Leishman has shown (ref. 9) a strong dependency of the effective indicial delay on Mach number, although the database of experimental test results presented for low reduced frequency is quite limited. Linear interpolation of the reference 9 data based on flow conditions at the 3/4R indicate an indicial lag of about 11 deg. This corresponds well with the residual (asymptotic) aerodynamic phase lag indicated in figure 11.

If we accept the 2-D indicial contribution to the total aerodynamic phase lag to be 11 deg independent of advance ratio, the contribution to the delay by wake distortion effects at hover is about 25 deg (average of the AH-64 and UH-60 hover results). The simple theoretical model by Arnold et al. (ref. 3) of the dynamic wake distortion for the UH-60 in hover yields an equivalent phase lag contribution of 26.5 deg, which is now in very good agreement with the experimental results.

This discussion suggests that the dominant physical sources of aerodynamic phase lag are the dynamic wake distortion due to rotor cyclic flapping, and the 2-D compressible indicial response. It would be very interesting to correlate theoretical models of wake distortion at forward flight conditions, and for rotors with higher effective hinge-offsets for comparison with the results shown in figure 11. Additional test data at intermediate values of hinge-offset and advance ratio are also needed to fill in and validate the small sample of experimental results currently available. The goal is a validated carpet plot of aerodynamic phase lag for use in future simulation models of new helicopter configurations.

CONCLUSIONS

1. A significant improvement in the roll response to longitudinal input and pitch response to lateral input modeling accuracy of a blade-element simulation model of the AH-64 was achieved by incorporating a simple aerodynamic phase lag correction. Including this

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correction did not degrade the satisfactory on-axis response correlation.

2.   At hover, a single value of the aerodynamic lag corrected both the roll response to longitudinal input and pitch response to lateral input coupled responses. At 60 kts, the optimum phase lag value is different for the two coupled responses, and a single value selected as a compromise to yield the best overall result. This characteristic suggests a possible refinement based on a first harmonic variation of phase lag with azimuth, which would be consistent with the first harmonic nature of dominant inflow dynamics.

3.   The AH-64 results show a wash-out in the required aerodynamic phase lag value with advance ratio. There is close agreement with identification results for the UH-60, which has comparable hinge-offset. Sikorsky Bearingless Main Rotor (SBMR) results also exhibit this trend.

4.   The primary physical sources of aerodynamic phase lag are considered to be: 1) dynamic wake distortion due to angular velocity motion of the tip-path plane, and; 2) compressible two-dimensional (2-D) unsteady indicial response. The theoretical values for these two contributions match the available test data well.

5.   Future efforts should focus on determining and validating a comprehensive carpet-plot of aerodynamic phase lag for use in future simulation models of new helicopter configurations.

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Historically, component-type flight mechanics simulation models of helicopters have been unable to satisfactorily predict the roll response to pitch stick input and the pitch response to roll stick input off-axes responses. In the study presented here, simple first-order low-pass filtering of the elemental lift and drag forces was considered as a means of improving the correlation. The method was applied to a blade-element model of the AH-64 APache, and responses of the modified model were compared with flight data in hover and forward flight. Results indicate that significant improvement in the off-axes responses can be achieved in hover. In forward flight, however, the best correlation in the longitudinal and lateral off-axes responses required different values of the filter time constant for each axis. A compromise value was selected and was shown to result in good overall improvement in the off-axes responses. The paper describes both the method and the model used for its implementation, and presents results obtained at hover and in forward flight.

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