System Identification Requirements for High-Bandwidth Rotorcraft Flight Control System Design

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The application of system identification methods to high-bandwidth rotorcraft flight control system design is examined. Flight test and modeling requirements are illustrated using flight test data from a BO-105 hingeless rotor helicopter. The proposed approach involves the identification of nonparametric frequency-response models followed by parametric (transfer function and state space) model identification. Results for the BO-105 show the need for including coupled body/rotor flapping and lead-lag dynamics in the identification model structure to allow the accurate prediction of control system bandwidth limitations. Lower-order models are useful for estimating nominal control system performance only when the flight data used for the identification are band-limited to be consistent with the frequency range of applicability of the model. The flight test results presented in this paper are consistent with theoretical studies by previous researchers.

Nomenclature

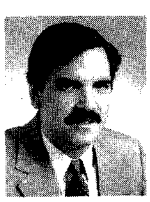
GM = gain margin (of open-loop response), dB
K_ϕ = roll angle feedback gain, %/rad
K_p = roll rate feedback gain, %/rad/s
L_p = roll damping derivative, 1/s
p = roll rate = $\dot{\phi}$ (linear model), rad/s
$\gamma^2_{\delta_a p}$ = coherence from lateral control inputs to roll rate outputs
δ_a = lateral control input, %
ζ = damping ratio
τ = time delay, s
τ_p = phase delay (of closed-loop response), s
$\Phi_{2\omega_{180}}$ = phase angle in degrees of closed-loop system when the frequency = $2 \times \omega_{180}$
ϕ = roll angle, rad
ϕ_c = roll angle command input to command model, rad
ϕ_e = roll angle error signal = $\phi_m - \phi$, rad
ϕ_m = roll angle command input to stability loop, rad
ω = frequency, rad/s
ω_{bw} = bandwidth frequency (of closed-loop response), rad/s; for attitude command systems, the bandwidth is defined as the frequency at which the phase angle is -135 deg
ω_c = design crossover frequency (of open-loop response) to give 45 deg phase margin, rad/s
ω_u = frequency at which instability occurs due to increasing feedback gain, rad/s (frequency value at which the root locus branch crosses the imaginary axis)
ω_{180} = frequency where the phase angle of closed-loop system is -180 deg, rad/s
ω_2 = upper frequency of transfer function fitting range, rad/s

Introduction

SYSTEM identification procedures provide an excellent tool for improving mathematical models used for rotorcraft flight control system design. Dedicated flight tests of a prototype helicopter can be conducted to update the flight mechanics models and to optimize control system gains early in the development process. Such an approach has already been taken by Kaletka and von Grunhagen[1] in the development of a fly-by-wire BO-105 and by Bosworth and West[2] in the development of the X-29A.

The identification of models for use in flight control system design involves requirements that are considerably different from those encountered in other applications such as piloted simulation and wind tunnel validation. Models identified for use in simulation and wind tunnel validation must be generally accurate over a wide spectrum of frequencies from trim (zero frequency) and phugoid (low frequency) to the dominant transient responses of the longitudinal short-period and roll-subsidence modes (mid/high frequency). Therefore, in terms of stability and control derivatives, the low-frequency parameters such as the speed derivatives may be just as important to a pilot's perception of simulation fidelity as an accurate value of roll damping.

Practical flight control system design requires models that are 1) highly accurate in the crossover frequency range—to exploit the maximum achievable performance from the helicopter—and 2) robust in the crossover range with respect to flight condition and input form and size—to ensure that



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closed-loop stability/performance is maintained; the control system design can be made sufficiently robust to compensate for poor model robustness, but at the expense of performance.

These requirements are especially difficult for advanced high-bandwidth control systems where the crossover range occurs at frequencies near the limit of current identification capabilities.

This paper examines in detail these requirements for system identification application to high-bandwidth flight control design. Much of this paper discusses the need in control system design for higher-order models that include rotor dynamics. It is interesting to note that the inclusion of rotor flapping dynamics in an optimal control system design methodology was investigated by Hall and Bryson[3] many years ago.

The roll response of the BO-105 helicopter (Fig. 1) at a trim condition of 40 m/s is used throughout to illustrate the main points of the analysis. The high-bandwidth/highly coupled rotor system of the BO-105 presents the control system designer with a "most difficult case" scenario. Flight data presented in this paper were collected by the DLR Institute for Flight Mechanics as part of the AGARD WG18 on rotorcraft system identification.

Simple Model-Following Control System

Figure 2 shows a simple design of the roll channel for the control system based on an explicit model-following concept. An attitude-command/attitude-hold configuration is shown, with only roll angle feedback for the present. The error signal is formed from the difference between the actual roll angle response and that of the desired command model.

The control law design problem for this simple system involves the selection of the stabilization loop gain K and an appropriate command model. Design requirements based on the U.S. military handling qualities specification[4] are for an overall closed-loop roll attitude bandwidth ϕ/ϕ_c (based on a 45 deg phase margin) in the range of $\omega_{bw} = 2$–4 rad/s. The desired stabilization loop bandwidth of ϕ/ϕ_m is selected as twice this range $(\omega_{bw})_{stab} = 4$–8 rad/s to achieve good model following and gust rejection.[5] This implies a stabilization loop crossover frequency (of ϕ/ϕ_e) in the same range, with associated satisfactory phase and gain margins. The following section addresses the identification and modeling aspects for achieving these desired stabilization loop characteristics ϕ/ϕ_m. Command model selection (ϕ_m/ϕ_c) is not addressed herein, because it is not an identification issue.

Identification Models for Control System Design

Identification models for use in control system design can be categorized as nonparametric (e.g., frequency response) or parametric (e. g., transfer functions and state-space models). Both types of models are discussed in this section.

Fig. 1 BO-105 case study helicopter.

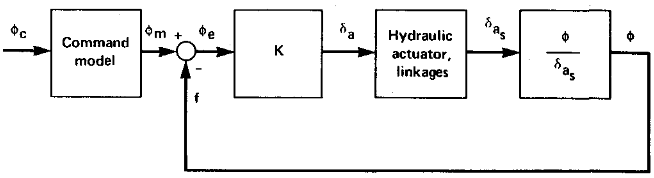

Fig. 2 Simple explicit model following control system.

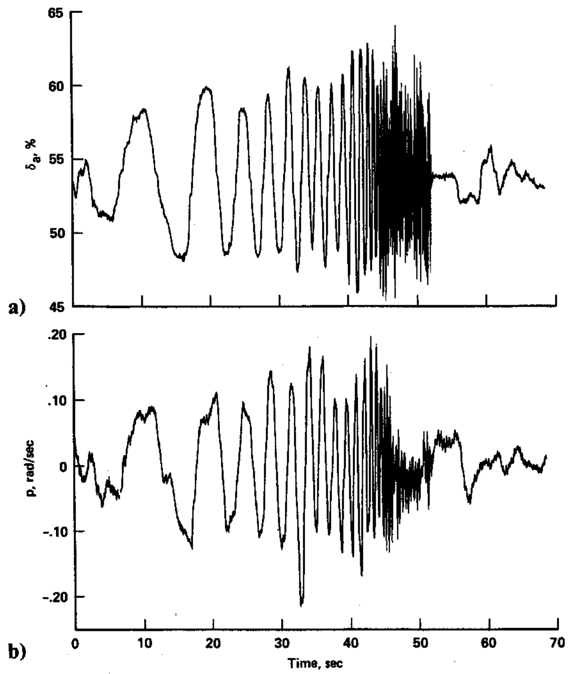

Fig. 3 Flight data of roll axis frequency sweep: a) pilot lateral stick input δ_a; b) roll rate p.

Nonparametric Frequency-Response Model

Nonparametric identification models are highly useful as starting points for control system design because they contain no inherent assumptions on model order or structure. The frequency response is complete and accurate (within the frequency range of good coherence) and provides the fundamental open-loop characteristics needed for both classical and modern frequency-domain-based design models. The identified frequency response is a describing function model of locally linearized nonlinear behavior. The severity of this assumption can be checked by comparing extracted describing functions for different input amplitudes.

A robust control system design requires a model that is accurate over a frequency range that spans the intended crossover region. However, the helicopter's dynamics and thus the achievable crossover frequency are unknown at this stage. Thus a nonparametric model that is accurate over a broad frequency range is desirable. Pilot-generated frequency sweeps are especially well suited for this purpose.[6,7] Piloted frequency sweeps of the BO-105 were conducted over a range of frequencies from 0.1 to 5 Hz (0.63-31.4 rad/s) to excite all the dynamic modes of concern (Fig. 3).

The identified open-loop (ϕ/δ_a) frequency response of the BO-105 body/rotor/actuator system for the 40 m/s flight condition shown in Fig. 4 was obtained using the spectral analysis techniques of Refs. 8 and 16. The spectral analysis was optimized for accuracy in the frequency range of 1-30 rad/s, which covers all modes of concern near the crossover range. The associated coherence (see Fig. 4c) indicates accurate identification in this frequency range. The Bode plot of Fig. 4 shows that with roll attitude feedback only, a maximum crossover frequency (ϕ/ϕ_e) of $\omega_c = 5.72$ rad/s can be achieved for phase and gain margins of 45 deg and 6 dB, respectively.

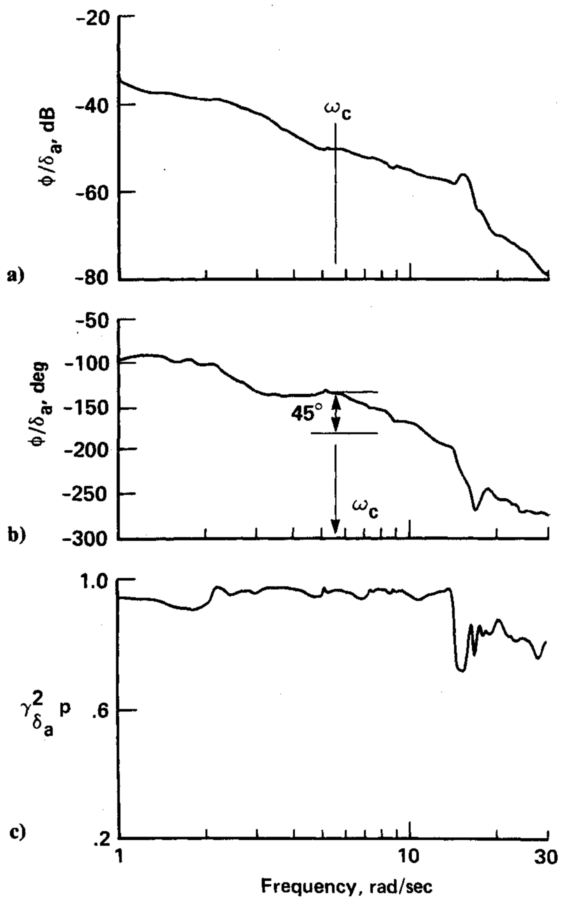

Fig. 4 **Frequency-response identification.**

These characteristics meet the design specifications for this simple system. However, roll rate feedback will be necessary to offset additional lags in a practical design implementation.[5]

Parametric Model

A parametric model of the roll response is useful to facilitate detailed control design studies. The fundamental considerations in deriving such a parametric model are 1) desired frequency range of validity, 2) model order, 3) estimate of model accuracy, and 4) model robustness.

Frequency Range of Validity

The frequency range of model validity should extend substantially on either side of the crossover frequency. As a rule of thumb, dynamics modes with frequencies of 0.3-3.0 times the crossover frequency will contribute substantially to the closed-loop response. In the present case, this indicates that the parametric model should be valid in the frequency range of 2-18 rad/s, which includes all of the classical attitude response modes (short period, dutch roll, and roll subsidence), the regressing rotor modes (flapping and lead-lag), and the dynamic inflow (for lower speed conditions). Accurate characterization outside of this frequency range is not important to control system design for the design bandwidth selected here. Closed-loop control suppresses all low frequency open-loop response, so that accurate knowledge of the speed derivatives (phugoid and spiral dynamics) is of little importance.

Model Order

The model order must be high enough to capture the important dynamic characteristics in the frequency range of model validity. In the frequency domain, this means a sufficient number of states to achieve a "good fit" of the nonparametric response of Fig. 4 are needed in the desired frequency range. However, if the model order is excessive, model parameters will exhibit large variability to small changes in flight condition, input form, and input size, which will compromise robustness.[9]

Estimate of Model Accuracy

Flight control design requires an estimate of the accuracy of the aerodynamic parameters. Modern multi-input/multi-output methods that feed back all outputs to all controls require a consistent level of accuracy in the characterization of all of the on- and off-axis responses. Metrics such as the Cramer-Rao lower bound, multi-run scatter, and frequency-response errors are useful for assessing model accuracy.

Model Robustness

Models must be robust with respect to flight condition, input form, and input size. Model structure determination methods are useful in reducing parameter insensitivity and correlation, which in turn improves model robustness. Also, model verification with alternative input forms and magnitudes are useful in this regard.

High-Order Model for Roll Response

A seventh-order model is selected as the "baseline model" that captures the key dynamics in the frequency range of concern (2-18 rad/s): 1) coupled roll/rotor flapping dynamics (second order), 2) lead-lag/air resonance (second order), 3) dutch roll dynamics (second order), 4) roll angle integration (first order), and 5) actuator dynamics (equivalent time delay).

Dynamics inflow modes are not explicitly included in the preceding list because of their small influence at this forward flight speed (40 m/s). (Implicit effects of inflow on the rotor modes are captured in matching the frequency-response data.) The roll angle response to lateral stick transfer function for the

Table 1 Roll response models, ϕ/δ_a

Mode	Fitting range	Transfer function[a]	Fit cost
Baseline model seventh order	1-30 rad/s	$\dfrac{2.62[0.413,\ 3.07][0.0696,\ 16.2]e^{-0.0225s}}{(0)[0.277,\ 2.75][0.0421,\ 15.8][0.509,\ 13.7]}$	12.1
Coupled body/rotor fifth order	1-30 rad/s	$\dfrac{2.47[0.490,\ 3.11]e^{-0.0218s}}{(0)[0.319,\ 2.71][0.413,\ 13.5]}$	26.8
Broadband quasisteady fourth order	1-30 rad/s	$\dfrac{0.200[0.283,\ 2.04]e^{-0.0743s}}{(0)[0.214,\ 2.13](9.87)}$	102.3
13 rad/s band-limited quasisteady second order	1-13 rad/s	$\dfrac{0.300e^{-0.0838s}}{(0)(14.6)}$	44.2

[a]Shorthand notation: $[\zeta,\omega]$ implies $s^2+2\zeta\omega s+\omega^2$, ζ = damping ratio, ω = undamped natural frequency (rad/s); and $(1/T)$ implies $s+(1/T)$, rad/s.

Table 2 Comparison of performance estimates

Model	Open-loop metrics, ϕ/ϕ_e			Closed-loop metrics, ϕ/ϕ_m	
	ω_c, rad/s	GM, dB	ω_u, rad/s	ω_{bw}, rad/s	τ_p, s
Data	5.72	6.39	11.4	8.58	0.0658
Baseline model	5.32	6.51	11.8	9.46	0.0659
Coupled body/rotor	5.33	5.70	11.5	9.62	0.0682
Broadband quasisteady	4.28	10.2	10.2	6.98	0.0545
13 rad/s band-limited	5.26	7.96	11.1	8.33	0.0600

baseline model is then fourth-order numerator and seventh-order denominator. The model parameters shown in Table 1 were obtained from a frequency response fit of Fig. 4 from 1 to 30 rad/s using 50 points. The frequency-response comparison with the data is seen in Fig. 5 to characterize the dynamics accurately in the range of concern, thus, indicating that the model is of sufficiently high order. The mismatch near the lead-lag mode (13 rad/s) reflects the reduced accuracy (lower coherence) of the flight data in this frequency range (Fig. 4). The 45-deg phase margin crossover frequency for the baseline model is taken from Fig. 5 as $\omega_c = 5.32$ rad/s, which is within 7% of the data, and the baseline gain margin and the frequency for closed-loop instability (ω_u) matches the data (see Table 2).

The transfer function model indicates a highly coupled body-roll/rotor-flapping mode ($\zeta = 0.51$, $\omega = 13.7$ rad/s) as is expected for the hingeless rotor system (high effective hinge offset) of the BO-105. Helicopters with low effective hinge offset rotors (or equivalently low flapping stiffness), such as some articulated systems, will generally exhibit two essentially decoupled first-order modes: 1) body angular damping (L_p, M_q) and 2) first-order rotor regressing. The decoupled rotor mode is often modeled by an effective time delay. The degree of body/rotor coupling is determined by the flapping stiffness as illustrated in Fig. 6 from Heffley.[10] The lead-lag mode is very lightly damped ($\zeta = 0.0421$) due only to structural damping of the hingeless rotor and the low aerodynamic damping. The total modal damping ($\sigma = -\zeta\omega = -0.666$ rad/s) agrees very well with previously published experimental data.[11] Significant roll/yaw coupling is apparent from the separation of the complex pole/zero combination of the dutch roll mode. Finally, the equivalent time delay corresponds well to known control system hydraulics and linkage lags.

Figure 7 shows the root locus for variation in the roll angle gain K_ϕ (of Fig. 2). The pole at the origin moves to the crossover range, and the dutch-roll mode is driven into the neighboring zero in the stable manner. The lead-lag mode is also driven toward the neighboring complex zero and is slightly stabilized ($\zeta = 0.0440$) for the nominal crossover frequency ($\omega_c = 5.32$). The attitude feedback gain K_ϕ is limited by the destabilization of the rotor/flapping mode. Added time delay

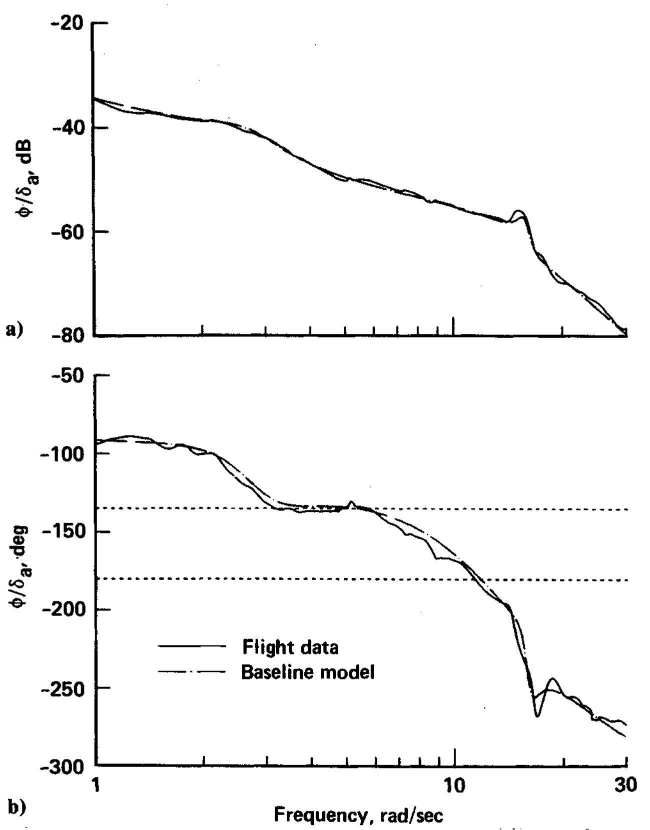

Fig. 5 Comparison of baseline model (seventh-order) and flight data.

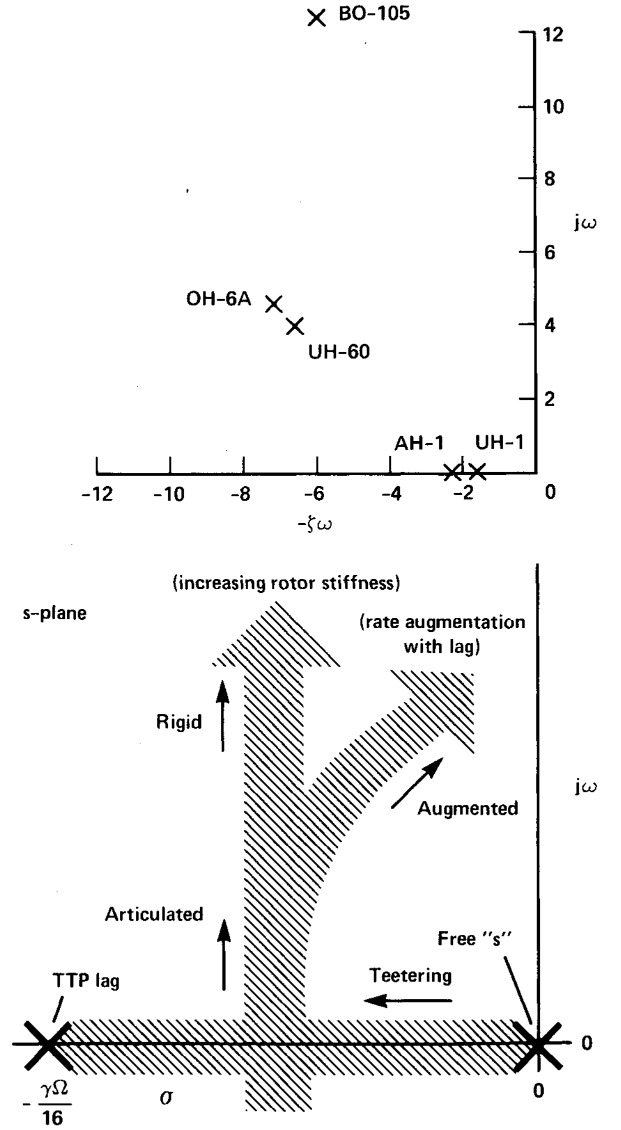

Fig. 6 Short-term eigenvalue locations as a function of flapping stiffness (from Ref. 10).

to account for unmodeled dynamics does not change these results significantly.

The closed-loop frequency response of ϕ/ϕ_m (from Fig. 2) shown in Fig. 8 for $K_\phi = 322.9\%/\text{rad}$ indicates that good model following will be achieved out to the desired stabilization-loop bandwidth frequency (4-6 rad/s). The closed-loop data curve also shown in the figure was generated by calculating KG/[1 + KG] for each frequency, using the open-loop data curve of Fig. 4. The good agreement between the closed-loop baseline model response and the (calculated) data over the broad frequency range (1-30 rad/s) further demonstrates the validity of the seventh-order model for predicting high-bandwidth flight control system performance.

Two important quantitative metrics of closed-loop performance (ϕ/ϕ_m) are bandwidth (ω_{bw}) and phase delay (τ_p). Closed-loop bandwidth ω_{bw} is defined in the handling-qualities community[4] as the frequency at which phase margin of the closed-loop response, ϕ/ϕ_m in this case, is 45 deg. (This definition applies for attitude command systems as in the present study.) The phase delay is a measure of the phase rolloff near the bandwidth frequency and reflects the total effective time

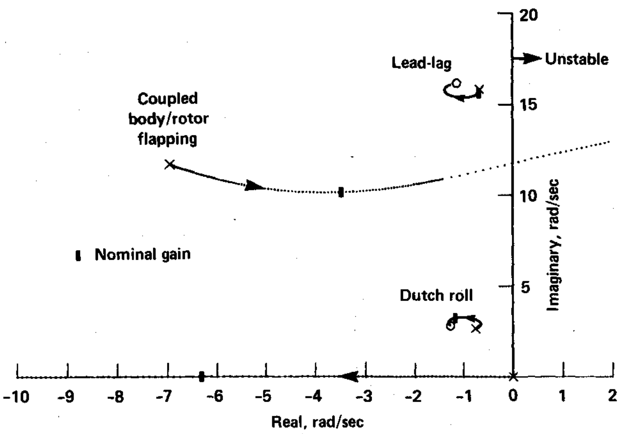

Fig. 7 Stabilization loop root locus, varying roll attitude feedback gain K_ϕ.

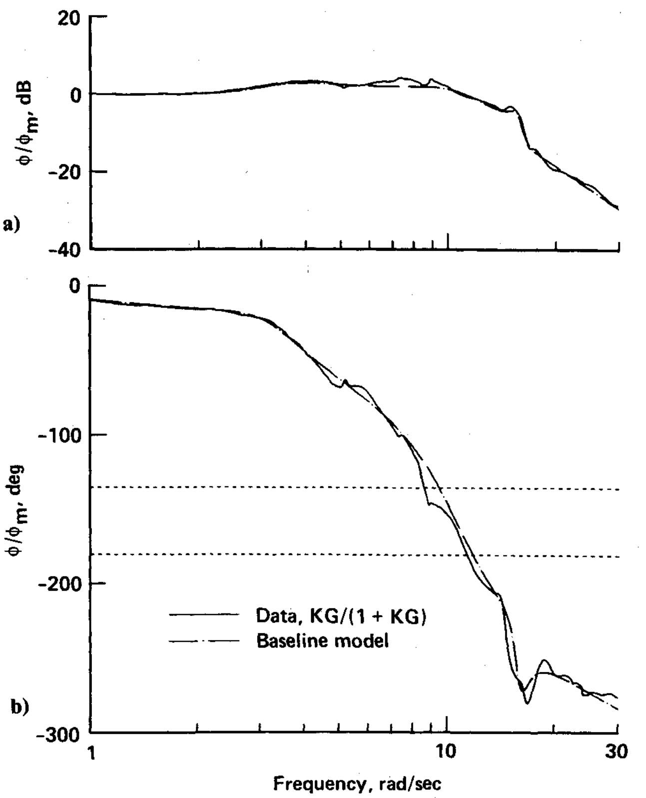

Fig. 8 Comparison of closed-loop response ϕ/ϕ_m of baseline model vs data.

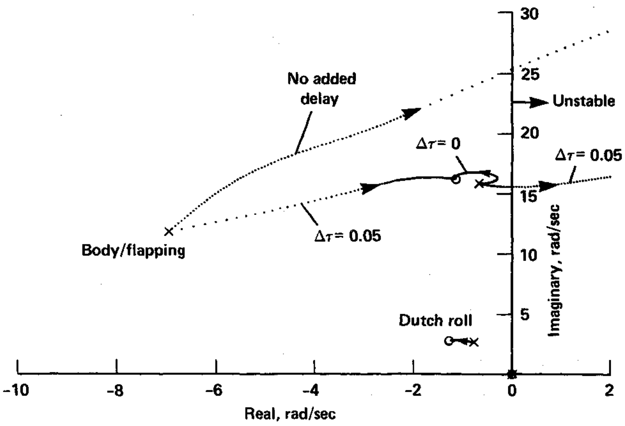

Fig. 9 Stabilization-loop root locus varying roll rate gain K_p.

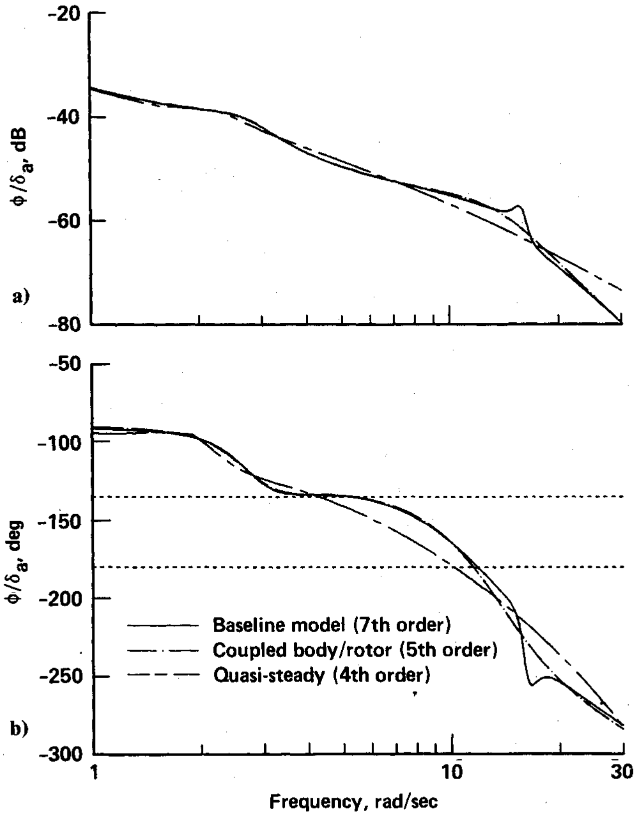

Fig. 10 Lower-order broadband models.

delay of the high-frequency dynamic elements (rotor and actuator in this simple case). The phase delay is defined as[4]

$$\tau_p = -\frac{\Phi_{2\omega_{180}} + 180 \text{ deg}}{57.3 \times 2\omega_{180}}$$

The bandwidth and phase delay metrics are well predicted by the higher-order model as shown in Table 2.

An additional feedback of roll rate will be required in the control system to offset lags and time delays associated with practical design implementation. Figure 9 shows a root locus for variation of roll rate feedback gain K_p. For no additional time delay, rotor/flapping mode stability remains the limitation on rate feedback gain, although the lead-lag mode damping is clearly reduced for moderate gain levels. When 50 ms of additional time delay are included to account for filters and computational delay in a practical digital control system implementation,[5] the lead-lag mode becomes rapidly destabilized and sets the limit on rate feedback. (A lag and a pure delay have the same effect on destabilizing the lead-lag mode for this case.) This result illustrates the need for accurate knowledge of the lead-lag dynamics in high-bandwidth control system design. Analytical studies by Diftler,[12] Miller and White,[13] and Curtiss[14] have made the same conclusions. A flight test investigation by Chen and Hindson[15] using a variable-stability CH47 helicopter demonstrated the importance of rotor dynamics and control system lags in determining feedback gain bandwidth limits.

Lower-Order Models for Broadband Roll Response

Two levels of approximation that are commonly made in formulating models for identification are considered in this section: 1) omit lead-lag dynamics (fifth order) and 2) quasisteady rotor dynamics (fourth order).

A fifth-order roll-attitude response model was obtained by refitting the frequency response data without the lead-lag mode (see Table 1). The transfer function result is consistent with the seventh-order model, with only slight variations in the remaining parameters. This indicates that the lead-lag/air-resonance mode can be modeled as a one-way-coupled (parasitic mode), similar in nature to an aircraft structural mode. Thus, the lead-lag transfer functions (quadratic dipoles) could be appended onto an eight degree-of-freedom identification model (flapping dynamics only). This approach has been successfully applied in the state-model identification of BO-105 dynamics.[16]

The frequency-response matches of the fifth-order model matches the high-order model very well (see Fig. 10), except of course for the omission of the lead-lag mode. The fitting error shown in Table 1 indicates only a slight degradation relative to the seventh-order model. The roll angle gain is again limited by destabilization of the coupled roll/flapping mode. Of course, roll rate limitations due to lead-lag instability will not be detected by this model. Comparison of the closed-loop response (ϕ/ϕ_m) of the fifth-order and the seventh-order model (see Fig. 11) shows that the reduced-order model is very accurate except for the lead-lag mode omission. The quantitative metrics match the baseline model results (see Table 2).

A fourth-order model is obtained by adopting a quasisteady assumption for the roll dynamics and treating the rotor as an equivalent time delay. The resulting transfer function model fit is given in Table 1. The time delay of 0.0743 s now accounts for 0.023 s from the hydraulics/actuator system and 0.051 s from the effective rotor delay. The quasisteady roll damping mode is estimated at $L_p = -9.87$ rad/s. The dutch roll pole/zero quadratic has been detuned for this single axis fit. (This could be improved by considering a simultaneous match of β/δ_r, which will enforce the correct dutch roll location.[8]) The frequency response of this model is seen in Fig. 10 to be a poor approximation, especially at a higher frequency, as expected by the adoption of a crude rotor flapping approximation. This is further emphasized by the three-fold increase in the fitting cost relative to the fifth-order model (see Table 1). The 45-deg phase margin crossover frequency is underpredicted by 20% relative to the baseline model, whereas the gain margin is overpredicted by 57% (see Table 2).

The root locus vs attitude gain for this model (see Fig. 12) indicates that the gain limitation is due to the destabilization of a coupled second-order pure rigid body mode. Thus, the quasisteady fails to capture key dynamics of the coupled roll/flapping mode. Finally, the closed-loop bandwidth is underestimated by 26% as indicated in Fig. 11 and Table 2. Overall, the use of the fourth-order model to match the full frequency range (1–30 rad/s) is seen to be inappropriate.

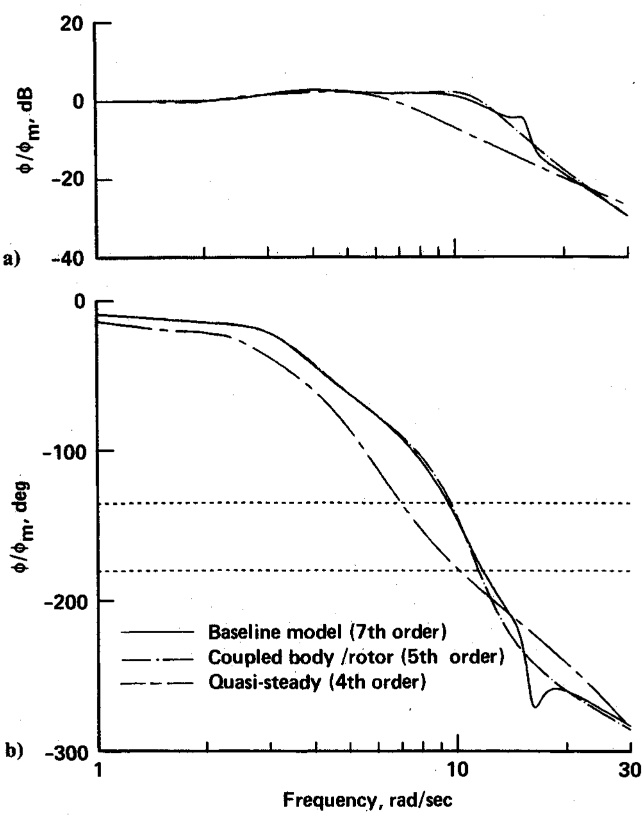

Fig. 11 Closed-loop responses of lower-order broadband models.

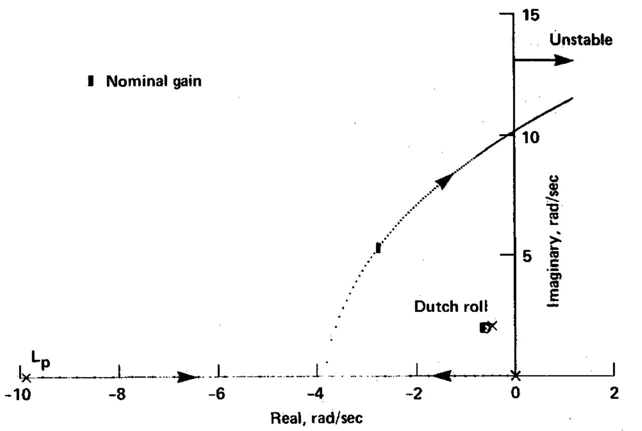

Fig. 12 Stabilization-loop root locus for fifth-order (quasisteady) model varying attitude gain K_ϕ.

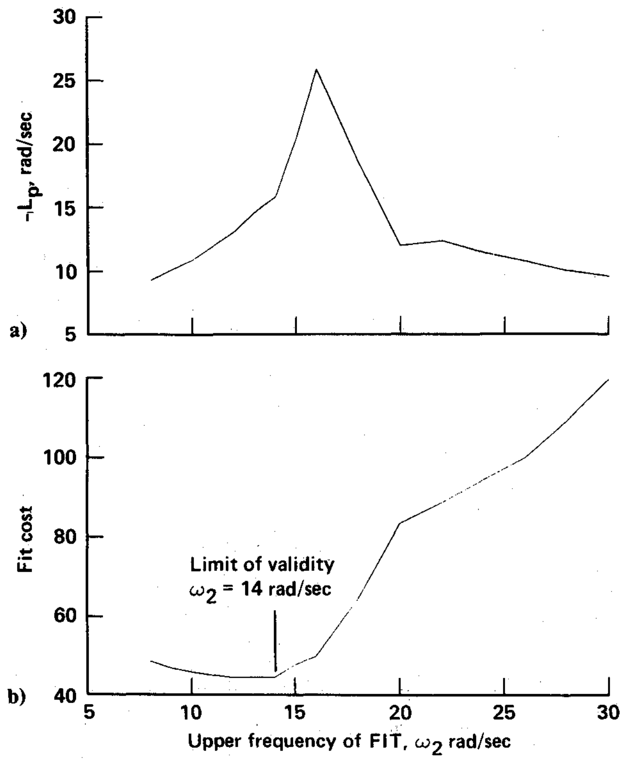

Fig. 13 Effect of upper frequency limit ω_2 on quasisteady identification; lower limit of fit is fixed, $\omega_1 = 1$ rad/s.

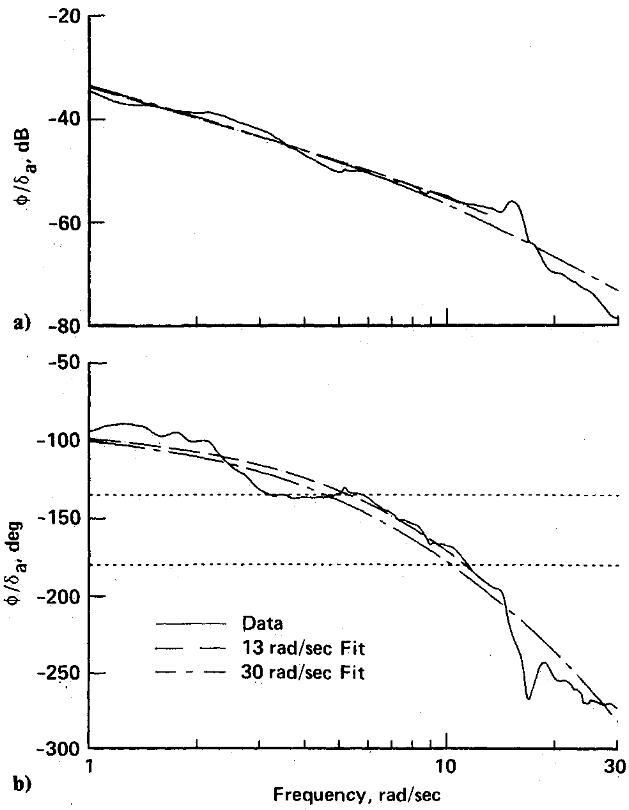

Fig. 14 Band-limited and broadband quasisteady models.

Quasisteady Models for Low-Frequency Roll Response

The utility of the quasisteady approximation in characterizing the lower-frequency dynamics was investigated. For this study, the dutch roll dynamics were omitted. Figure 13 shows the variation L_p and the fitting cost for changes in the upper fitting frequency ω_2 from 8 to 30 rad/s. The roll damping rises from $L_p = -9.3$ for $\omega_2 = 8$ rad/s, to $L_p = -20.4$ for $\omega_2 = 15$ rad/s; however, the cost function remains fairly constant in this range. For ω_2 beyond 14 rad/s, the cost function rises dramatically, indicating a poor characterization of the dynamic response. Note that for the $\omega_2 = 30$ rad/s, the roll damping drops to $L_p = -9.6$, which closely corresponds to the fourth-order model of Table 2. The extreme sensitivity in the model parameters and cost function for values of ω_2 greater than 14 rad/s shows that this frequency is the limit of the validity of the quasisteady assumption. For ω_2 below 14 rad/s, the cost function remains fairly constant at CF = 45, which roughly corresponds with the fifth-order fitting error; the higher-order model is more accurate as expected. The variability in L_p seen even for $\omega_2 = 7$-13 rad/s will be limited by the simultaneous fit of multiple responses in the full model identification.[16] The ϕ/δ_a frequency response for the $\omega_2 = 13$ rad/s case is shown in Fig. 14 to have comparable accuracy as the baseline model in the range of 1-13 rad/s (except for the omission of the dutch roll mode). The estimated crossover frequency is nearly identical to the high-order baseline model. Also, the closed-loop performance metrics are much closer to the baseline model than was the fourth-order model (see Table 2). The first-order model for $\omega_2 = 30$ rad/s, also shown in Fig. 14, is seen to poorly characterize the response at both low and high frequency. The frequency range of the fit is clearly inappropriate for the quasisteady model structure. A similar analysis conducted on the pitch response indicates a useful bandwidth for the quasisteady assumption of 13 rad/s. Thus, the overall useful bandwidth of the quasisteady model structure is 13 rad/s.

This analysis indicates that improved utility of the quasisteady models can be achieved if the data are band-limited to below the rotor-flapping frequency (13 rad/s in this case) before the identification is completed. This band limitation is easily accomplished in frequency-domain identification methods, since the fitting range is an explicit function of frequency.[16,17] In time-domain methods, the data should be filtered to eliminate the high-frequency dynamics.[6] Although the coupled rotor/flapping instability can still not be replicated with such band-limited quasisteady models, the nominal control system performance may be adequately estimated.

Conclusions

An accurate model for helicopter control system studies requires coupled body/rotor flapping and lead-lag dynamics. The lead-lag response may be treated as a one-way coupled parasitic mode for the case study evaluated herein.

For a single-rotor hingeless helicopter, the coupled body/rotor-flapping mode limits the gain on attitude feedback, whereas the lead-lag mode limits the gain on attitude-rate feedback.

Quasisteady models that approximate the rotor response by an equivalent delay are useful for estimating nominal control system performance if the data used in the identification are band-limited to frequencies below the coupled body/rotor response.

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