ON THE CALCULATION OF THE RESPONSE OF HELICOPTERS TO CONTROL INPUTS

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ABSTRACT

In the past few years a number of studies have provided accurate flight test data for the control response of single rotor helicopters over a wide frequency range. These measured responses have been compared to theory in a number of studies. Various differences between theory and experiment appear in all of these studies. This paper examines some of these differences, provides a quantitative explanation of one prominent difference, associated with the contribution of the lag degree of freedom, and suggests areas for further investigation. The discussion is directed towards articulated rotor helicopters. Flight test data from the UH-60, CH-53 and AH-64 helicopters, much of it taken for express purpose of evaluating the control response, and correlation with theory, as well as the use of parameter identification methods, is considered. Results for flight conditions near hover are emphasized.

INTRODUCTION

A large number of studies have appeared in the past few years directed towards solving the difficult problem of modelling the response of single rotor helicopters to control inputs over a reasonably large frequency range,as necessary for the design of modern automatic flight control systems. For many years,with the technology available, it was satisfactory to use for design a model which was reasonably accurate over the range of frequencies which included the quasi-static body modes. While the possible importance of the flapping dynamics to automatic flight control system design has been recognized for some years [1] it has only received increased attention relatively recently [2,3]. For many early helicopter designs the influence of the flapping dynamics could be largely viewed as a cascaded problem, i.e., a rapid rotor plane response followed by a slower fuselage response, more recent helicopter designs with larger hinge offset, or hingeless blades exhibit a faster body response and consequently modes which involve coupling between flapping and body motion [4,5]. The roll response of many contemporary helicopters shows a distinctly second order nature due to this coupling. Much more recently it has been recognized that the lag degrees of freedom must be considered in the design of high performance flight control systems as well [5,6,7]. Thus a high order model is necessary to describe all of these dynamics of importance to the problem. Differences between experiment and theory exist and often it is difficult to identify the sources of the discrepancies due to the complexity of the models. In many instances, the models are non-linear,although there appears to be much experimental evidence indicating that the discrepancies between theory and experiment are not due to the non-linear nature of the problem, but rather to a lack of understanding of some aspect of the physics of the problem. The high order of the analytical models has made the development of parameter identification methods difficult and challenging. Considerable progress has been made in this area recently, and some results associated with aspects of the rotor body dynamics are becoming available. However,without a detailed physical model, it is often difficult to associate results from parameter identification studies with sources of error in the analytical models.

However, with accurate experimental flight test data available for the response of helicopters to control inputs over a relatively wide frequency range, comparison of these data with various theories has indicated that there are a variety of discrepancies between theory and experiment over much of the frequency range of interest. At high frequencies (10-20 r/s), a problem that stands out in a number of studies (8,9,10,11) is the inability to predict the contribution of the lag motion to the body response to cyclic control inputs. In each of these references, similar discrepancies between theory and experiment are noted. Flight data are from two different helicopters, and the theories are different. The flight test data generally indicate that the contribution of the regressing lag mode, which shows up as a notch in the amplitude of the frequency response, occurs at a frequency considerably below that indicated by theoretical predictions. Note that this result corresponds to a higher lag frequency in the rotating frame. Agreement between experiment and theory is obtained in [9] by adding an artificial lag spring which does not exist on the actual helicopter, and consequently does not lead to any increased understanding of the problem or the real source of the difference between theory and experiment. This problem is considered in detail below.

A second area to be discussed is the modelling of the roll and pitch response to lateral and longitudinal control inputs over the first few seconds of the response, the characteristic that tends to be of most importance in handling qualities. The influence of dynamic inflow modelling on the results is examined. There appears to be some confusion about the role played by this effect in the response, as well as the range of parameters to be expected. The most difficult discrepancy to explain between between theory and experiment is related to the coupling effects, or the off axis response.

DISCUSSION

Lag Dynamics

References 8, 9, 10, and 11 all show significant differences between theory and experiment associated with a notch characteristic in the frequency response produced by the presence of the rotor cyclic lag degrees of freedom, which, in effect correspond to translation of the rotor center of mass, consequently producing fuselage response. This characteristic is usually more evident in the roll rate frequency response due to the lower roll moment of inertia which results in a larger roll excitation due to cyclic lag motion. This discrepancy in frequency between theory and experiment is very similar in all of these studies. This difference seems rather surprising since the frequency is primarily located by the relatively simple mechanics of the uncoupled lag motion as indicated below.

In the frequency band of 10-20 rad per/sec, the regressing lag mode contributes significantly to the helicopter response and should not be ignored in the design of automatic flight control systems as noted in a number of studies [5,6,7]. Thus it is important that the source of this discrepancy be quantified. Physically, it appears that the difference is primarily associated with the uncoupled lag mode dynamics. A unique high order linearized analytical model has been developed at Princeton [12]. With literal coefficients it becomes possible to trace various physical aspects of these complex problems. Calculations made with this high order linear model show that the lag motion is relatively weakly coupled to the body motion dynamically [13]. In fact, the primary reason that the lag motion is of importance in this problem is because of its role in attenuating a part of the inplane aerodynamic force produced by cyclic pitch [5]. Studies of various aspects of the lag motion dynamics have been conducted [13,14]. As shown in [14] the cyclic lag excitation is primarily directly due to the cyclic control input, and the resulting body motion produced by cyclic has almost no contribution to the lag response. Thus, the calculated cyclic lag velocity response due to cyclic pitch is almost the same for a fully coupled rotor/body system calculation, and a shaft fixed calculation as shown in Figure 1 [14]. Note that the shaft fixed calculation includes flap motion as well as lag. Consequently the difference between theory and experiment must be primarily associated with the flap lag dynamics. Also, without pitch lag coupling, the dynamic coupling between the flap and lag motion is weak. That is, lag motion has little effect on flapping,and cyclic lag motion is primarily produced by cyclic control inputs. The flapping produced by the control inputs also produces cyclic lag through coriolus and aerodynamic terms but the coupling is largely one way. Thus the lag frequency is largely determined by the lag equation alone. The reduction of the physics for articulated rotors based on the nature of the interaction makes the discrepancy between theory and experiment more surprising since we are dealing presumably with a relatively simple one degree of freedom system.

Figure 2 shows a frequency response for the UH-60, comparing the difference between various theories and experiment. The notch due to the lag motion dynamics occurs in the 15-20 rad/sec frequency band. This figure is taken from [8], which examines among other things the effect of various dynamic inflow models on the response.Examination of this figure, as well as others in this paper, indicates little effect of the various dynamic inflow models on the theoretical frequency at which this notch occurs, also supporting the argument given above that this discrepancy is primarily associated with the lag degree of freedom, and its proper description. To emphasize the nature of this disagreement, Figure 3 presents other results. Some of the data from Figure 2 is shown on an expanded scale, compared with other theory [11]. Another data set is shown, for a CH-53, along with comparison to theory [9], very similar to that for the UH-60 [11]. The only explanation offered in the literature is found in [9] where a fictitious, powerful lag spring is added. Recall that this notch is located at the regressing lag frequency, consequently increasing the lag stiffness, which increases the lag frequency in the rotating frame will lower the regressing lag frequency. This spring does not exist in the aircraft.

Consider further the CH-53 comparison between theory and experiment related to the lag degree of freedom [9,10]. The characteristics of the mechanical lag damper of this aircraft have been measured experimentally in two ways, through bench tests, and directly in flight test. The experimental results from these two different experiments agree very well and also show that the damper characteristic is reasonably linear for the amplitudes of interest here, and that the spring effect of the damper is quite small and gives a negligible contribution to the lag frequency, as shown in detail in [10]. Thus the lag damper characteristics may be considered known.

Consider now the rigid blade lag dynamics as predicted by the blade geometric and inertial properties and the experimental lag damper characteristics. The calculated rigid lag dynamics in the rotating frame are shown in Figure 4. The very high level of damping produced by the damper can be noted. This model gives a lag natural frequency of about .32 per rev., where the notch in the flight test data corresponds to a rotating lag frequency of about .42 per rev. Thus a very powerful spring of unknown origin would be required to explain this discrepancy [9]. Consider the effect of the damper. It clearly applies a powerful moment to the root of the blade, indicating that it would be desirable to consider the effects of blade flexibility. An approach, using assumed modes was formulated. The flexible blade is modelled by hinged plus cantilever modes so that the root boundary condition provided by the damper is satisfied. This approach was first examined in the non rotating case, by comparison to the exact solution for a uniform beam. In the rotating case a well converged solution is obtained using two cantilever and two hinged modes. Figure 5 shows the effect of adding damping using the lag model with flexible modes. The lowest mode increases in frequency with increasing damping, i.e., the trend shown in Figure 4 obtained from the rigid model is reversed. Using the experimental value of lag damping, the natural frequency of this lowest mode is about .42 per rev., very close to the value that gives very good for agreement with experiment in the fixed frame.

Roll Rate Response (Hover)

The UH-60 time response to a lateral control input has been compared to different theories in [8, 12, and 19], with the roll rate response showing quite reasonable agreement with experiment. Although, in [8], it was found that modifying the form of the dynamic inflow theory of [22] gave better agreement with test data, while in [12] very good agreement is shown using the theory of [22]. In [19], the theory of [22] is used, and the first peak in the response is predicted quite well. These results are shown in Figures 6, 7, and 8. Figures 6 and 8 illustrates very clearly the influence of dynamic inflow on the response. Also comparison of the 12 state (quasi-static model) with the 27 state model shows the second order nature of the response. The case referred to as Howlett has no harmonic inflow components. The "rigid wake" model gives the strongest effect of the inflow, which corresponds to the largest value of the roll damping, and consequently the smallest peak roll rate. See also Figure 9 for the effect of the inflow model on the frequency response.

Similar comparisons for the AH-64 are shown in [17,18]. The measured flight test response is compared to two theories. Theory B does use the dynamic inflow theory of [22], and it is not completely clear what theory T uses for dynamic inflow, given the discussion on pg. 1239 of [18]. Response comparisons are shown in Figures 10 and 11. Generally these theories underestimate the measured roll response for the AH-64, compared to the UH-60 where the tendency of the theory is to over estimate the response. As a last comparison between theory and experiment the frequency response comparison from [18] is shown. Agreement between experiment and theory are much less clear in this case.

It can be seen that proper modelling of the harmonic components of the dynamic inflow is an important factor in calculating the control response of helicopters. Model rotor experiments have identified dynamic inflow characteristics [23,24] that show very good agreement with theory [22]. The use of flight data for identification has been less successful [7,20]. The results obtained in both of these studies are very different from the theoretical results of [22]. The result obtained in [7] assuming a quasi-static inflow is quite reasonable. However, in the dynamic case the inflow time constant has been selected at a rather unrealistic value in the identification process, resulting in a dynamic inflow model considerably at variance with the theory and experimental results of [22,23,24]. This is also true of the results obtained by parameter identification given in [20]. In interpreting these results in terms of the theory of [22] it is important to note the distinctions between the form of the theory used in parameter identification and the form of the theory in [22]. This is illustrated in Figure 13. Table I compares the theoretical values of the inflow time constant and gain with those found by identification in [7,20].

The most difficult difference to explain is the off axis response, which in all cases considered above, results in a theoretical prediction that is basically in sign to experiment. It is interesting to note that there is a very strong similarity between the off axis response of the AH-64 and the UH-60.

CONCLUSIONS

1. For articulated rotor helicopters with strong lag dampers, blade flexibility must be included to properly model the contribution of the lag motion the helicopter frequency response.

2. Dynamic inflow plays a significant role in the prediction of on axis roll and pitch response of helicopters. Attempts to identify harmonic inflow characteristics from full scale tests have not been very successful.

3. Off axis response characteristics of single rotor helicopters are not understood.

ACKNOWLEDGEMENTS

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TABLE I:

DYNAMIC INFLOW CHARACTERISTICS
THEORY AND IDENTIFICATION

	THEORY (UH-60) [22]	(RIGID)	IDENTIFICATION (AH-64) (Q-S)		
τ_o sec	.07	.14	1.33	0	*
K_I nd	.50	1.0	2.33	.54	-.56
REF	[12,19]	[8]	[20]	[7]	

*Constrained $\frac{\tau_o}{1 + K_I}$ = 1.724 sec.

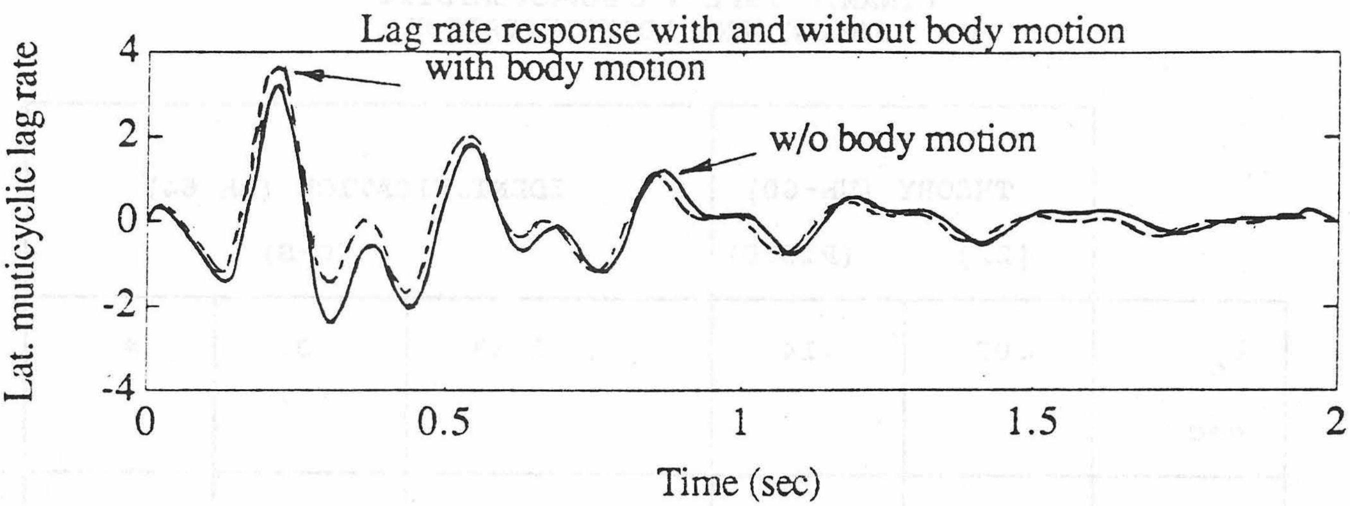

Fig. 1: Lateral Multiblade Lag Rate Response Including and Neglecting Body Motion.

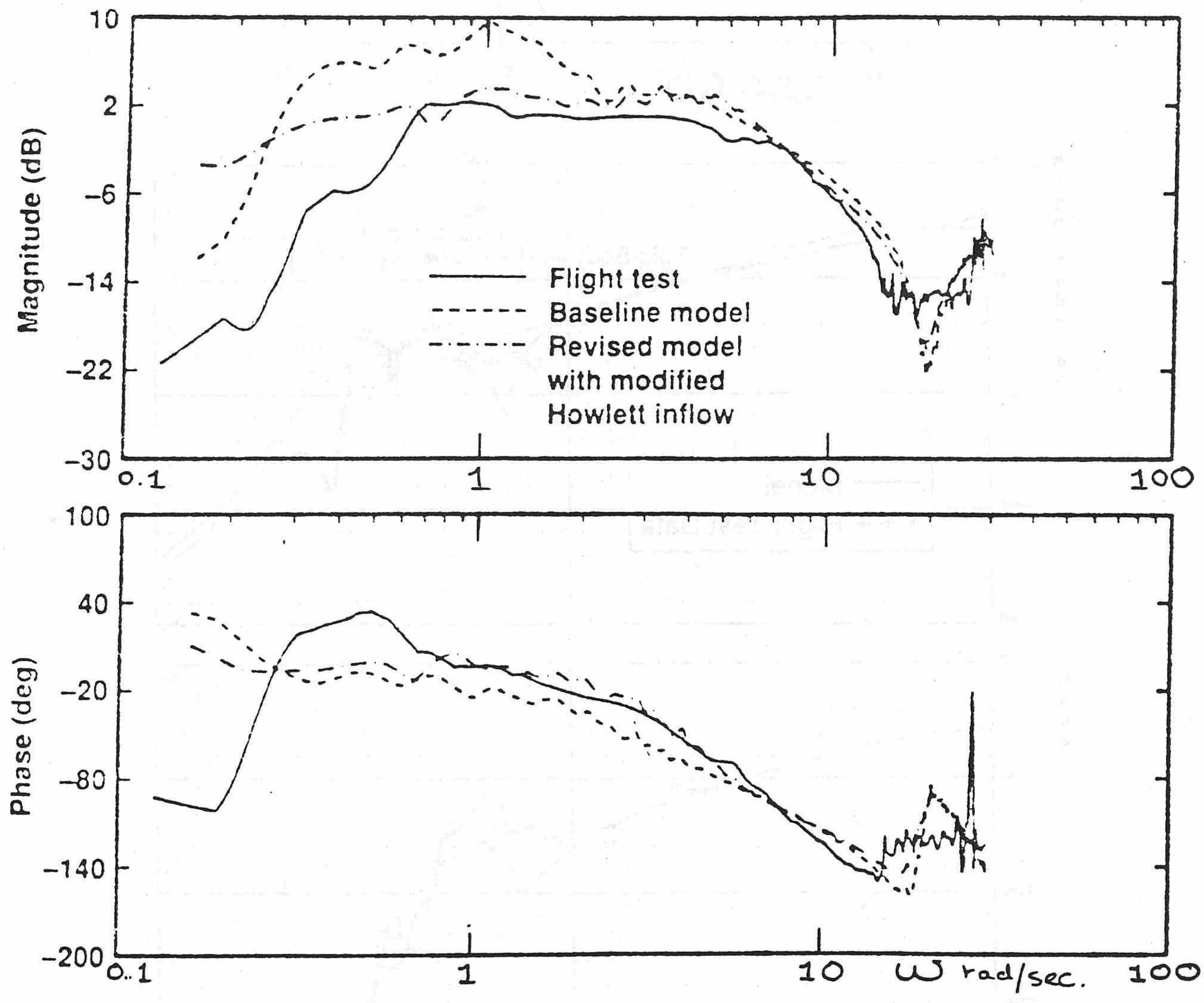

Fig. 2: Roll-Rate Response to Lateral Cyclic UH-60 Aircraft. Flight Test and Theory [8].

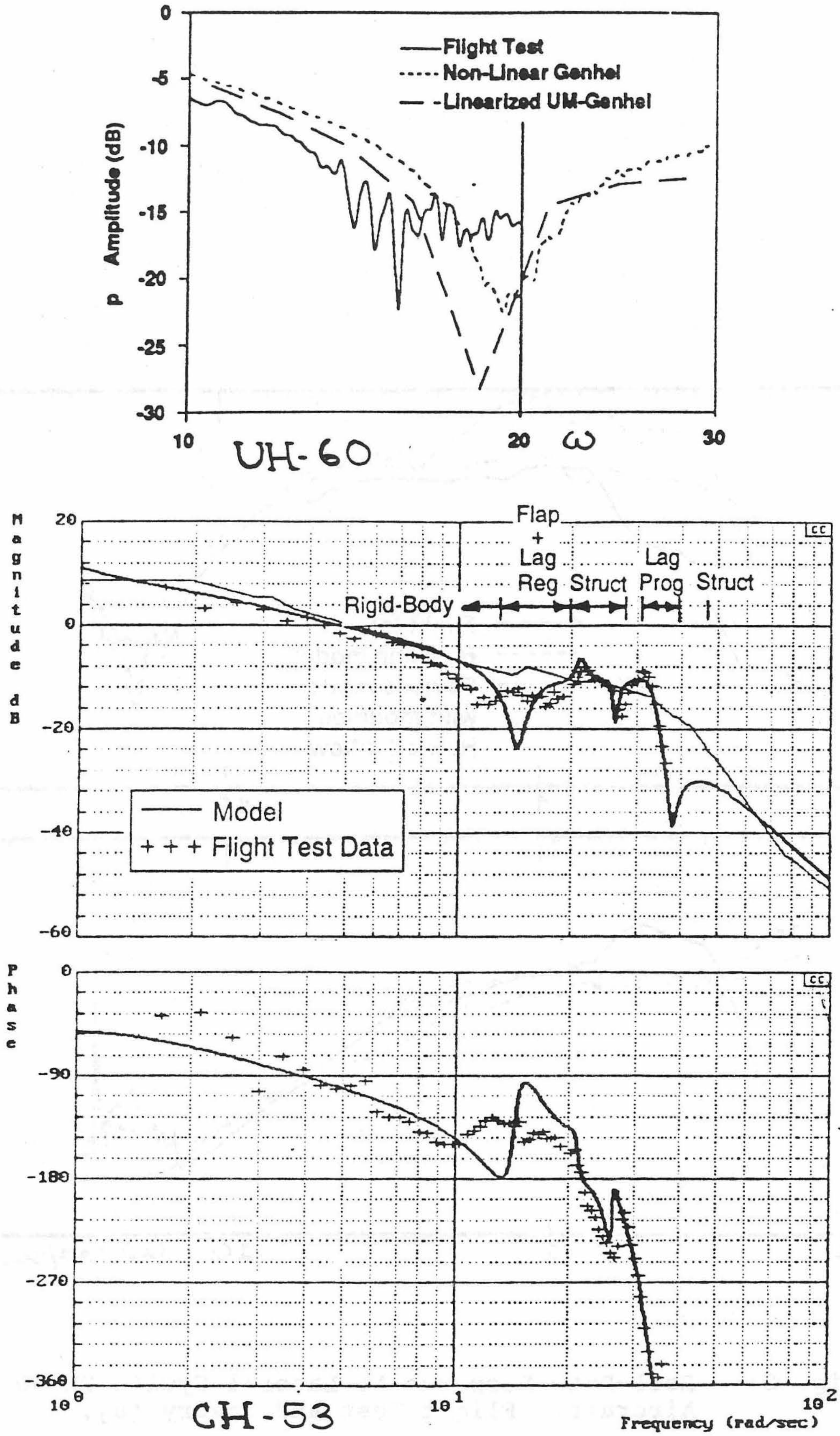

Fig. 3: Comparison of Theory and Experiment [9,11].

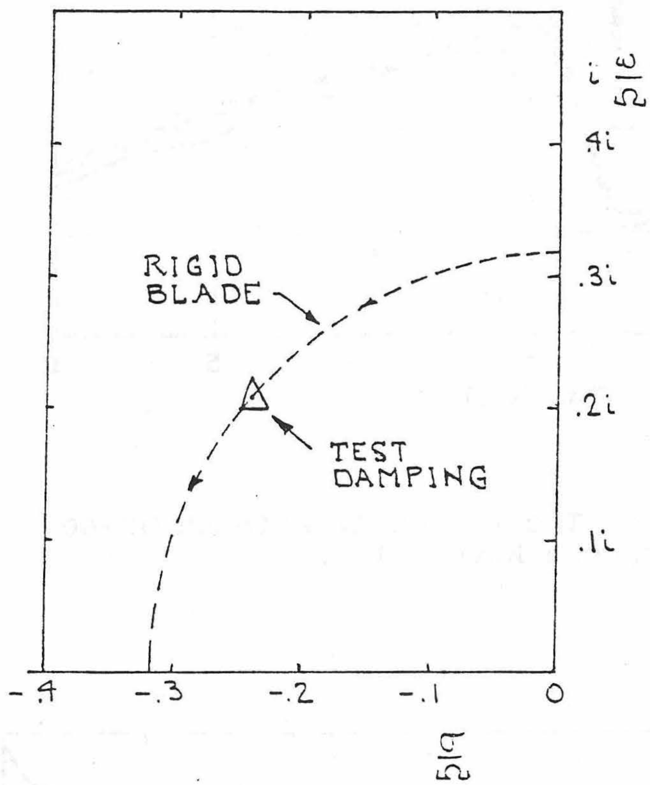

Fig. 4: Root Locus - Effect of Damping on Rigid Blade Model.

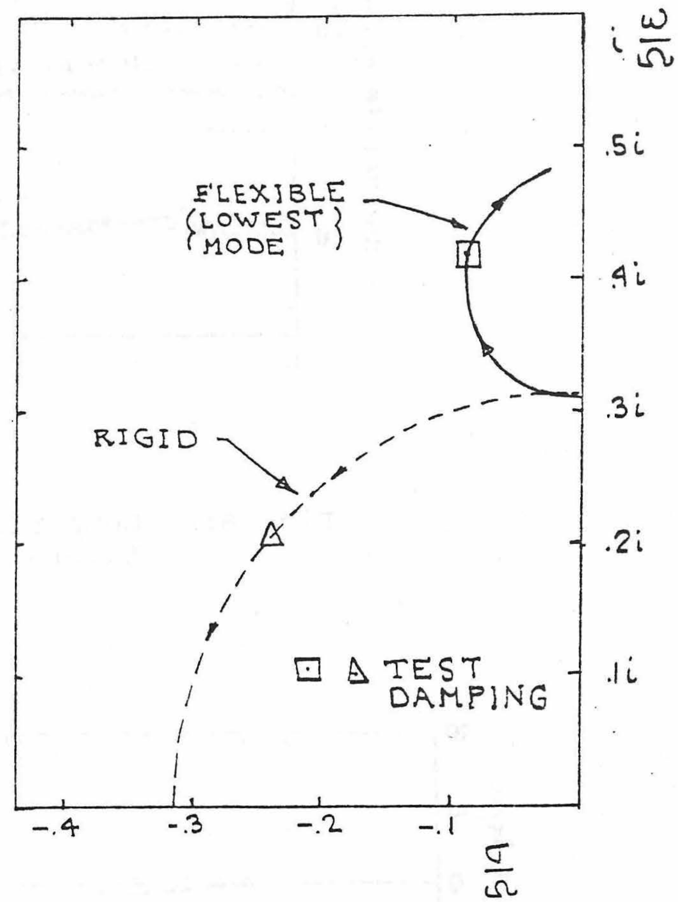

Fig. 5: Locus of Roots Comparison of Effect of Damper on Rigid and Flexible Blade Models.

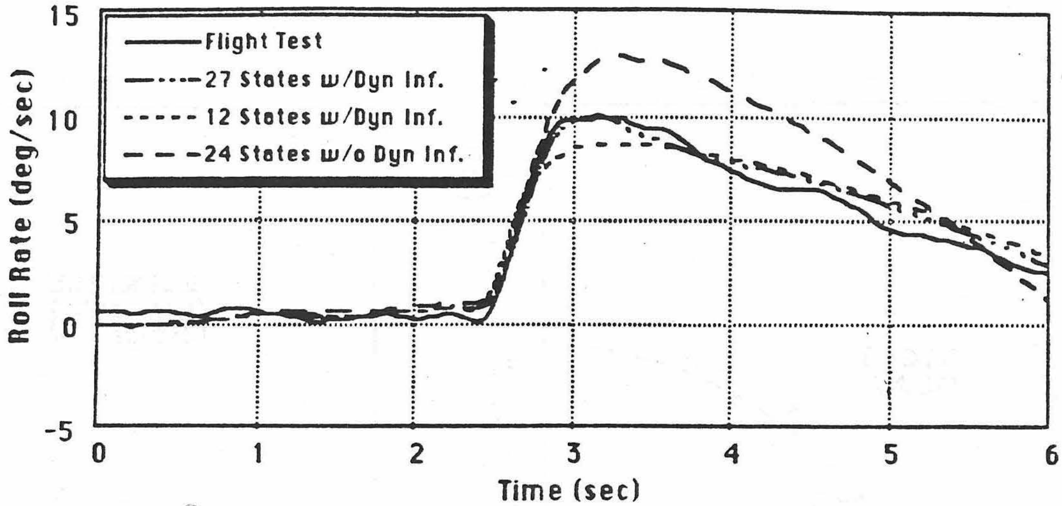

Fig. 6: Comparison of Theory and Experiment UH-60 Lateral Response Hover [12].

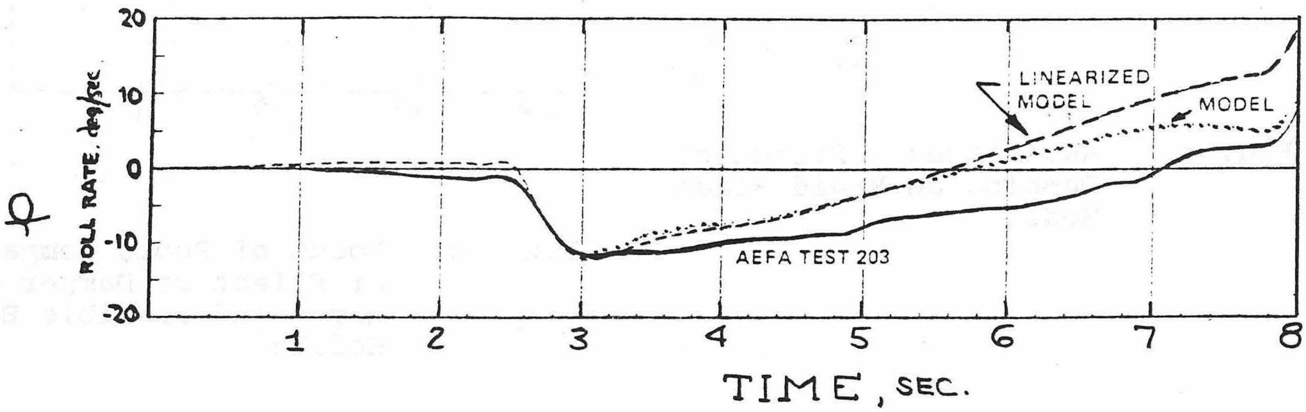

Fig. 7: Comparison of Theory and Experiment UH-60 Lateral Response Hover [19].

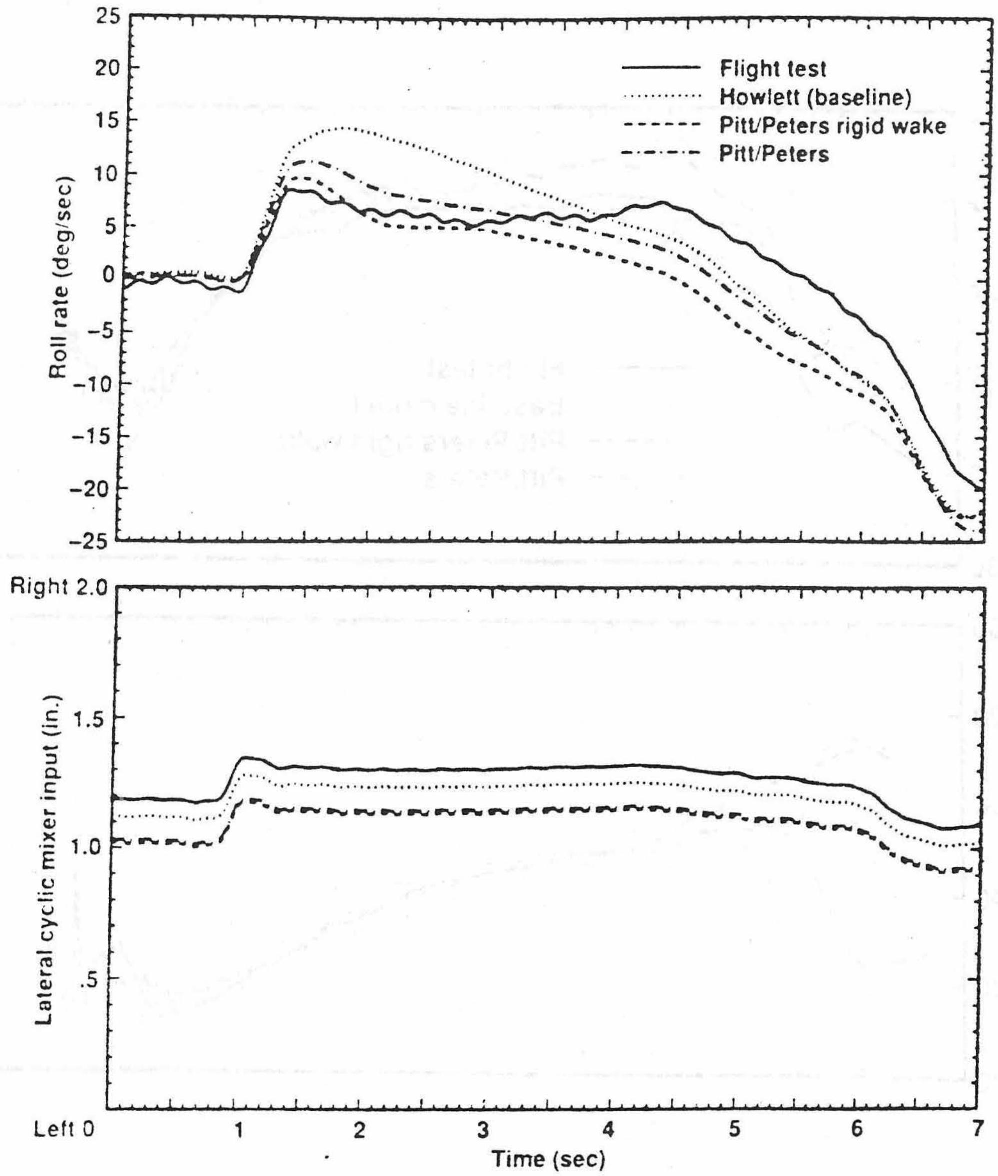

Fig. 8: Comparison of Theory and Experiment UH-60 Lateral Response Hover [8].

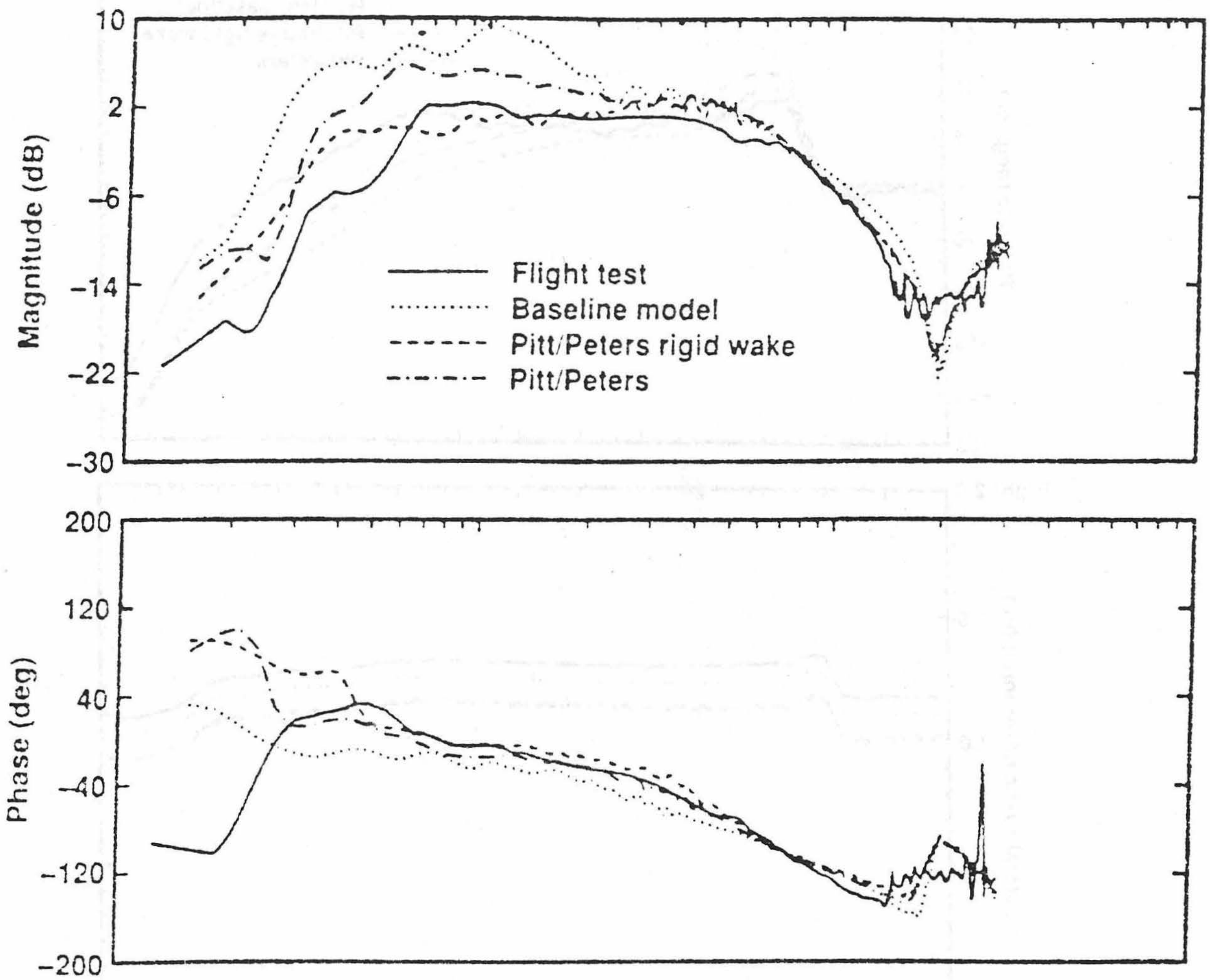

Fig. 9: Roll Rate Frequency Response [8] UH-60. Dynamic Inflow Models from [22].

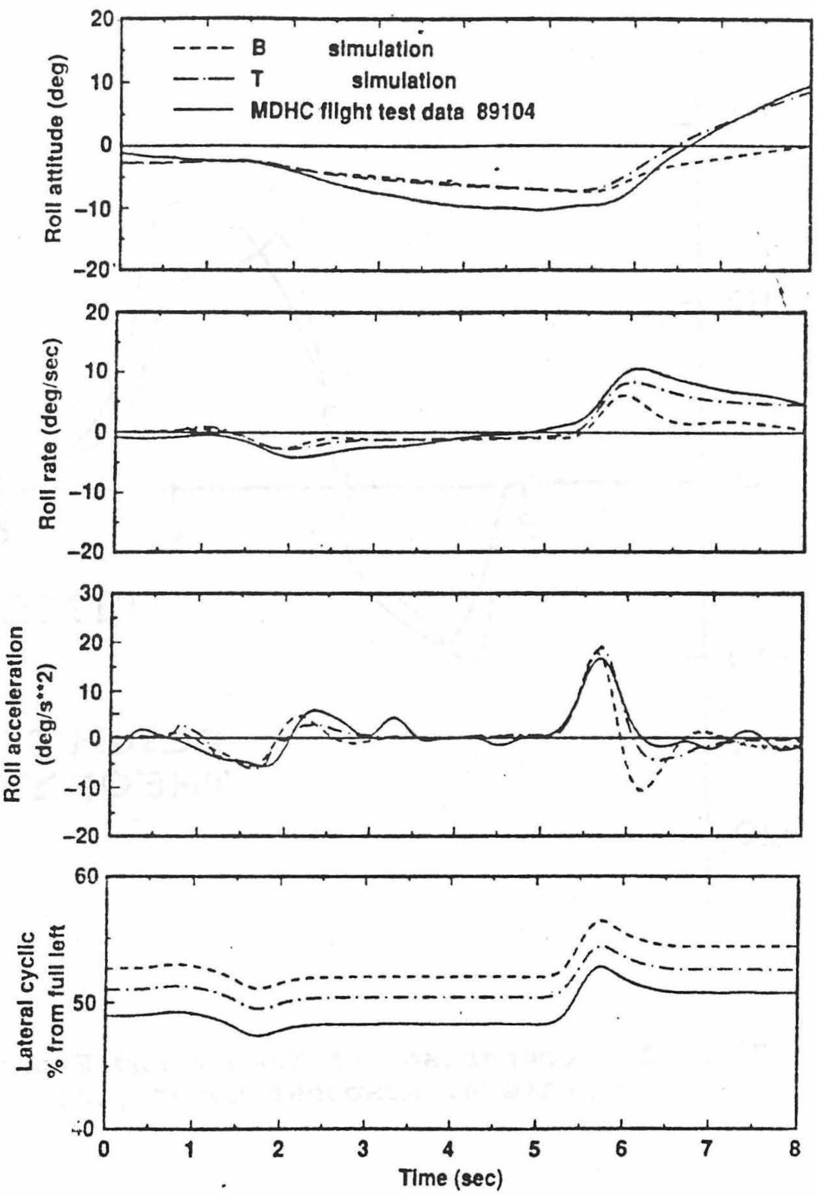

Fig. 10: Comparison of Theory and Experiment AH-64 Lateral Response Hover [17].

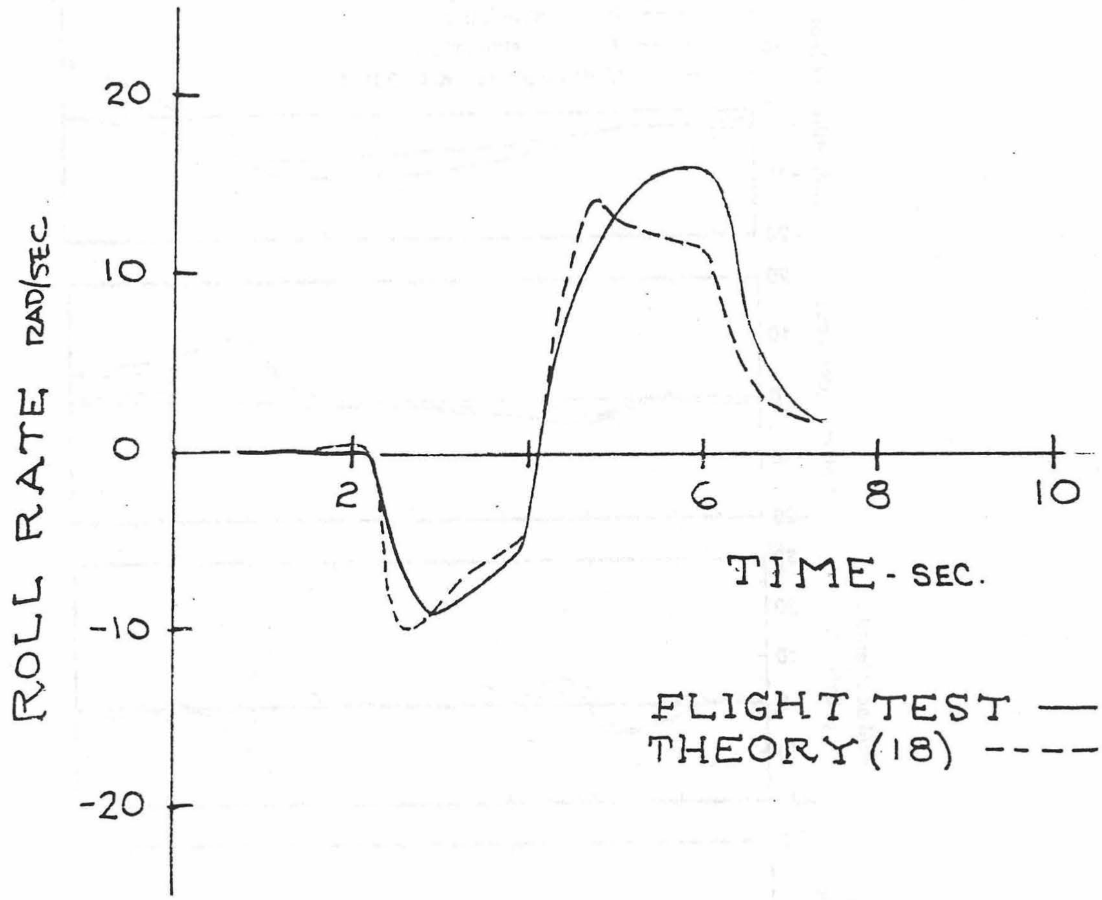

Fig. 11. Comparison of Theory and Experiment AH-64 Lateral Response Hover [18].

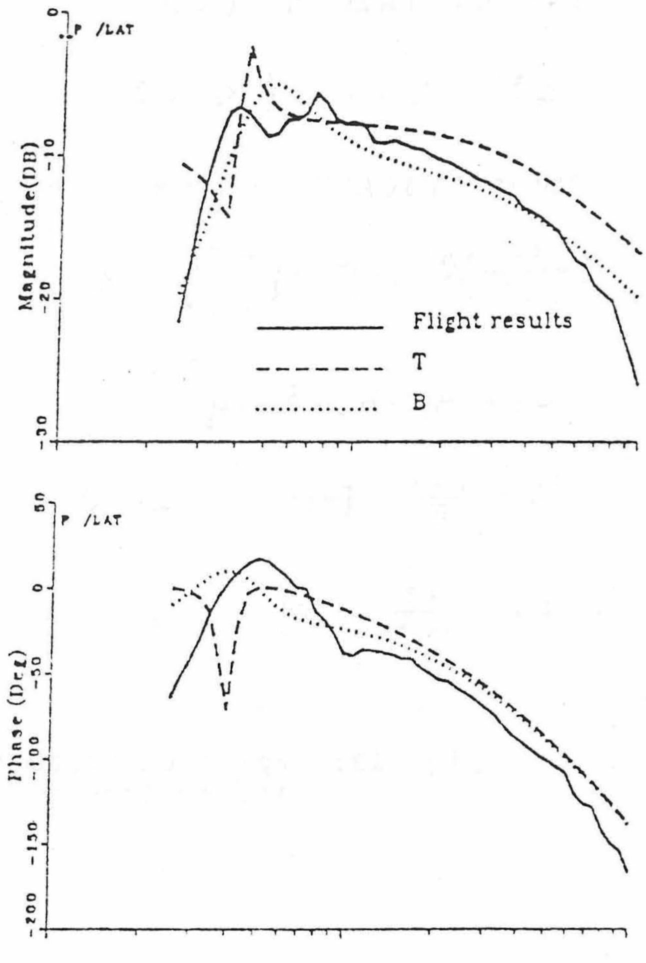

Fig. 12: Roll Rate Frequency Response AH-64 Hover [18].

INFLOW THEORY . (· COS)

$$\bar{\tau}_o \bar{v}_c' + \bar{v}_c = -K_I(\alpha_c + \bar{v}_c)$$

IDENTIFICATION FORM [7,20]

$$\left\{\frac{\bar{\tau}_o}{1+\bar{K}_I}\right\}\bar{v}_c' + \bar{v}_c = \left\{\frac{-K_I}{1+K_I}\right\}(\alpha_c)$$

$$\alpha_c = A_{1s} - b_{1s} - \dot{a}_{1s} - q$$

$$\bar{\tau}_o = \frac{.113}{\bar{v}_o} \quad [22] \qquad \approx 2.0$$

$$K_I = \frac{a\sigma}{16\bar{v}_o} \quad [22] \qquad \approx 0.5$$

Fig. 13: Forms of Dynamic Inflow Theory.