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VALIDATION OF A MATHEMATICAL MODEL OF THE SEA KING MK50 HELICOPTER USING FLIGHT TRIALS DATA

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ABSTRACT

Validation of a mathematical model of a Sea King Mk50 helicopter, by comparing model predictions with flight data, is described. Comparisons of both performance and flight dynamic characteristics show that the model provides an adequate representation of flight characteristics over a range of airspeeds. Some specific deficiencies which remain are noted and summarised. The use of System Identification techniques to investigate model limitations and to develop improved representations of dynamic characteristics is discussed. The approach is illustrated by examples from Sea King flight measurements, including an assessment of the effects of inflow, flapping, and engine dynamics on vertical acceleration response to collective inputs at hover.

1. INTRODUCTION

A mathematical model of the Sea King Mk50 helicopter has been developed at the Aeronautical Research Laboratories in order to provide support for operations by the Royal Australian Navy. The model which brings together representations of the aerodynamics/kinematics, control systems, and cable/sonar dynamics, has been fully documented elsewhere (Refs 1,2).

To establish confidence in the ability of the model to predict flight characteristics, a trials program was undertaken in order to provide a comprehensive set of flight test data for comparison with model predictions (Ref.3). Both performance, and stability and control data were obtained, and an extensive database established.

Initial validation has been via a comparison of computed results with flight data, including trimmed flight performance over a range of airspeeds including sideways flight, dynamic responses to disturbances, and other more gradual manoeuvres such as ASW transitions. This validation exercise has resulted in a model which gives a good representation of the Sea King flight behaviour over a wide range of operating conditions. At the same time it has provided a better understanding of limitations in the model and pointed to specific areas where improvements are needed. Particular deficiencies, reflecting possible inadequacies in the model structure, require further investigation. The approach used seeks to isolate phenomena which are apparent in specific dynamic response time histories, and then to apply System Identification techniques to gradually build up adequate representations for the characteristics of interest.

This paper will first outline the main features of the Sea King mathematical model, followed by a comparison of a representative selection of performance and flight dynamic characteristics with flight data. Deficiencies in the model will be summarised, and the use of a System Identification approach to address these will be illustrated, using collective response time histories as an example.

2. MATHEMATICAL MODEL

The Sea King Mk50 Helicopter has a fully articulated main rotor of five blades, and a conventional tail rotor of six blades. Both rotors use blades having a NACA 0012 section. Propulsion is by twin free turbine Rolls-Royce H1400-1 Gnome engines. The mathematical model is a non-linear total force and moment simulation with 7 degrees of freedom, i.e. six rigid body and one rotor rotational mode. A detailed representation of the Sea King automatic flight control system (AFCS) is included.

Features of the model, which is aimed at simulating flight behaviour up to an advance ratio of at least 0.3 (120 knots), are

i. Main and tail rotor blades are assumed stiff in torsion and bending and the rotor is considered quasi-static, in that the disc is assumed to respond instantaneously to fuselage motion,

ii. Rotor aerodynamic forces and moments are obtained using analytical expressions derived from blade element theory radially integrated and summed about the azimuth. Cross coupling terms due to angular rates are included so that the model is not limited to small perturbations,

iii. Reverse flow and blade stall are not accounted for, but an empirical compressibility correction to rotor torque is included,

iv. Momentum theory is used for inflow calculations with linear variation of induced flow in the streamwise direction, depending on wake sweepback angle. A factor of 1.18 is used to account for non-uniformities in the induced flow. A simple first order lag is used to account for transient inflow effects,

v. Pitch-flap and pitch-lag couplings and cyclic control mixing are included in calculations of blade angles,

vi. Aerodynamic forces and moments on the fuselage and tail surfaces are based on expressions used in the Sea King flight simulator, with modifications based on the flight trials,

vii. A simple engine model, incorporating a lead/lag term for engine response and a 1st order lag for fuel flow response, is included to account for large excursions of rotor speed and torque under certain conditions.

The range of validity of this modelling approach can be assessed by comparing model predictions with results from flight trials, as described in the following sections.

3. COMPARISON WITH FLIGHT TRIALS

A large flight trials data bank is currently available for validation, and also for more general flight behaviour studies. The present comparisons are limited to categories which encompass the most likely areas of application in the foreseeable future. These are:

i. Trimmed flight performance for airspeeds ranging over -20 to 120 knots, as well as sideways flight over ±20 knots.

ii. Dynamic response tests, showing the aircraft response to inputs in each of the control channels. Representative examples at hover and 88 knots are presented here.

iii. Other examples, including an engine cut to simulate the loss of one engine, and an automatic transition used in the ASW role.

3.1 Trimmed Flight

Figure 1 presents torque, roll and pitch attitudes, and blade angles in steady trimmed flight. Some scatter in the flight data is attributable to changes in AUW arising from fuel usage (an average AUW of 8727 kg was used for the predictions), and to the effect of wind variations. In particular, a cross wind averaging about 9 knots from starboard was present in the fore-aft flights, becoming a 9 knot head wind in the sideways flight cases. The effect of this on the predicted values is indicated in Fig. 1.

The effect of wind is particularly marked in the torque results near hover (Fig.1a). Good agreement is achieved in both fore-aft and sideways flight if this is accounted for. At higher speeds, discrepancies could also reflect possible errors in compressibility correction or flat plate area, and also retreating blade stall which has not been accounted for. Increasing the flat plate area from 35 ft^2 (3.25 m^2) to 44 ft^2 (4.09m^2), as used in Ref. 4, can be seen to make a significant impact at the higher speeds.

Roll and pitch attitudes are reasonably well predicted by the model, as shown in Figs 1b,c. The 9 knot wind produces a 1 degree increment in roll attitude but little effect on pitch. The good agreement for pitch attitude is due to an empirical wake downwash function, dependent on forward airspeed, used in calculating tailplane forces and moments. In sideways flight, roll is quite well predicted but some discrepancy in pitch is evident at speeds to starboard. This may be attributed to the effectiveness in modelling the downwash effects, but may also reflect the difficulty in trimming a real helicopter in sideways flight.

The tail rotor blade angle (Fig. 1d) shows good agreement in forward flight but in rearward flight the aircraft requires more pitch than predicted, and similarly for right sideways flight. The effect of a cross wind in forward flight also appears to be larger than implied by the measurements. These results suggest that the effects of tail boom side forces are not correctly accounted for in the model.

In Fig. 1e, the main rotor collective pitch angle at 75% radius shows a degree of agreement directly analagous to that for torque, in that deficiencies in torque prediction will show up in collective pitch.

Cyclic blade angles (Figs. 1f,g) correctly indicate trends in the fore-aft case with a discrepancy averaging about 1 degree. In sideways flight, the prediction of longitudinal cyclic pitch is quite good, but lateral cyclic, despite reasonable agreement in flight to starboard, shows a different trend with increasing speed to port. The reason for this is not fully understood but may be due to poor estimates of lateral flapping angle arising from the simplified representation of rotor aerodynamics. The previously-mentioned tail boom side forces may also be a factor.

3.2 Dynamic Response

In comparing measured and predicted dynamic response characteristics it is important to match closely the input disturbances. Thus, model inputs are obtained by adding the measured increments (pilot input) to the model trim values for each run. For normal autostabiliser "on" operations, the blade angles are a combination of pilot and control system inputs. In general, it has been hard to assess the validity of the model with autostabilisers disengaged because of instabilities in both the model and flight behaviour, but some autostabiliser "off" cases are included in Ref. 5. The examples presented here are typical of the results obtained with autostabiliser engaged.

i. Fig. 2 shows measured and predicted responses for a longitudinal cyclic pulse aft input at 88 knots. The primary pitch rate response is reasonably well predicted with the model having a slightly faster rise time. However, the coupled roll response is somewhat over-estimated and leads the measured value by about 0.3 seconds. In forward flight a cyclic pitch change is accompanied by a vertical acceleration response shown in the figure, where a peak to peak variation of about 0.3g is reasonably well modelled.

ii. Fig. 3 shows the response to a port lateral cyclic step, again at 88 knots. The predicted primary roll response is about 30% too high while some small coupled pitch response, negligible in the flight data, is also predicted. A small variation in lateral acceleration is simulated well and in this case there is very little vertical acceleration.

iii. Response to a pedal pulse input at hover is shown in Fig.4. In this case the tail rotor blade angle inputs (i.e. auxiliary servos) are matched, rather than the pedal inputs, because of difficulties encountered in modelling the pedal movements (Ref. 5). The yaw rate and lateral acceleration responses are reasonably well simulated, although the coupled roll response and the engine torque and rpm appear to be 'over-active'.

iv. One example of a response to collective step input at hover is given in Fig. 5. The primary response in vertical acceleration is not well predicted in spite of some allowance in the model for inflow lag. Large torque and engine rpm variations are also present and these lead to a coupling with the ensuing vertical acceleration response. Some roll and yaw rate cross coupling is also apparent. Collective response dynamics will be treated in more detail later in this paper.

3.3 Other Examples

Automatic transition manoeuvres are an essential part of ASW operations, designed to reduce pilot work load. Fig. 6 is an example of a transition down from cruising flight to the hover required for sonar dunking operations. Generally, the trends for both control inputs and aircraft response are predicted well by the model. Some periodic variations of approximately 4 seconds duration in the flight data are believed to be due to main rotor collective blade angle being varied in response to altitude control signals of the AFCS, perhaps due to heavy seas affecting the radio altimeter.

Engine cut tests were performed to simulate the case of the failure of one engine, whereby the engine management system calls on the remaining engine to make up the power loss. Fig. 7 shows the response to a cut in number 2 engine during a 4 degree climb at 82 knots. The predicted torque response of number 1 engine and the rotor rpm response appear to be underdamped by comparison with the flight results. Yaw and roll rate coupling due to tail rotor response is basically similar to flight, but in Fig. 7 the vertical acceleration response in flight appears to show an increase in loading even though power is reduced. This could result from a transient reduction in lag angle and consequent pitch increase from pitch-lag coupling.

3.4 Summary

The present Sea King mathematical model is considered to give an adequate representation, over a range of airspeeds, of the helicopter flight dynamic and performance characteristics. However, some particular deficiencies have been noted in the areas of:

i. Lateral cyclic trim values in sideways flight,

ii. roll cross-coupling with longitudinal cyclic inputs,

iii. torque and rotor rpm dynamics, e.g response to engine cuts,

iv. vertical acceleration response to collective step inputs.

Further work has been undertaken to improve these aspects and initial results relating to (iv) are described in the next section.

4. SYSTEM IDENTIFICATION

The deficiencies summarised in the previous section arise from inadequacies in the mathematical model, either due to incorrect parameter values or to shortcomings in the model structure. Because of the complex nature of rotorcraft aerodynamics and flight dynamics, the approach used here is to isolate and concentrate on particular aspects, thereby gradually building up an adequate model structure in which there is a reasonable degree of confidence. Parameter estimation techniques are a useful tool both for developing a suitable model structure and for identifying the model parameters. Recent examples of this approach are given in References 6 to 8. The example below illustrates results obtained with Sea King flight data using a maximum likelihood estimation program in the time domain.

The collective response prediction for vertical acceleration shown in Fig. 5 is typical of results obtained in hover for step or pulse inputs, and indicates an inadequate model structure. To investigate further the causes of the deficiency in the prediction of vertical acceleration, a systematic study was conducted to assess the effects of dynamic inflow, blade flapping, and rotor rpm variations. The most comprehensive model, including each of these effects, has the form:

$$\begin{bmatrix} 1 & z_{\ddot\beta} & 0 & 0 & 0 \\ \beta_{\dot w} & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot w \\ \ddot\beta \\ \dot\beta \\ \dot\nu \\ \dot\Omega \end{bmatrix} = \begin{bmatrix} z_w & z_{\dot\beta} & z_\beta & z_\nu & z_\Omega \\ \beta_{\dot z} & \beta_{\dot\beta} & \beta_\beta & \beta_\nu & \beta_\Omega \\ 0 & 1 & 0 & 0 & 0 \\ \nu_{\dot z} & \nu_{\dot\beta} & \nu_\beta & \nu_\nu & \nu_\Omega \\ 0 & 0 & \Omega_\beta & 0 & \Omega_\Omega \end{bmatrix} \begin{bmatrix} w \\ \dot\beta \\ \beta \\ \nu \\ \Omega \end{bmatrix} + \begin{bmatrix} z_{\theta_C} & 0 \\ \beta_{\theta_C} & 0 \\ 0 & 0 \\ \nu_{\theta_C} & 0 \\ \Omega_{\theta_C} & \Omega_Q \end{bmatrix} \begin{bmatrix} \theta_C \\ Q_{Eng} \end{bmatrix} \tag{1}$$

where the elements of the state vector, w, β, ν, and Ω, represent vertical velocity, flapping angle, inflow, and rotor rpm respectively, while the input vector includes both collective pitch θ_C, and torque, Q. The off diagonal terms in the left hand matrix of (1) account for additional accelerations in an articulated system. *A priori values for most of the* matrix elements in (1) can be obtained from the physical principles used in deriving the equations. The values used are shown in Table 1. Some of these differ from one another only by a constant multiple, and this constraint was maintained in the subsequent identification, in order to avoid correlations among the parameters. The constrained parameters in each group are indicated by asterisks.

The effects of progressively including dynamic inflow, flapping, and rotor rpm is illustrated in Fig. 8. Each case represents the best possible fit for that model, obtained using the parameter estimation program. It is clear that each of the effects considered above needs to be included in the model to achieve a good match with the flight data. In Fig. 8a, dynamic inflow alone cannot match the peak accelerations, nor can it reproduce the dip immediately following the peak. The addition of flapping dynamics improves both aspects, although the dip is poorly represented, and periodic variations apparent in the measurements beyond about 1.5 seconds are not simulated. The latter can only be reproduced when engine dynamics are included (Fig.8b). Two other examples of response to collective inputs are shown in Fig. 9. The first case, Fig. 9a, is the same step up response shown in Fig. 5, while Fig. 9b is an example of response to a collective pulse. Both cases show a good match between measurement and prediction of vertical acceleration. Note that no attempt has been made here to match the rpm record, and there is some room for improvement in the rpm model, for example by inclusion of terms proportional to inflow and vertical velocity.

The extracted parameter values for all three cases are shown in Table 1, together with the computed Cramer-Rao bounds (in brackets), which can be used as indicators of their relative accuracy, and hence scatter. In general, a reasonably consistent set of parameters has been obtained for the three cases considered, with the identified values usually quite close to the a priori values. The exceptions are the inflow derivatives, which differ from the a priori estimates by a factor of two or three. The last column of Table 1 shows results obtained by combining the information from all three records in the estimation algorithm. The time history matches remain excellent, while the parameter values now reflect the best information available in each record.

5. CONCLUSIONS

A mathematical model of a Sea King Mk 50 helicopter has been validated by comparing model predictions against flight measurements. A representative selection of performance and flight dynamic data has been presented in this paper. These include trim performance from -20 to 120 knots fore/aft and ±20 knots sideways speeds, dynamic response to control inputs at hover and 88 knots, an engine cut manoeuvre, and an automatic transition to hover.

The model is considered to give an adequate representation of Sea King flight characteristics over a range of airspeeds. Nevertheless some particular deficiencies have been identified and summarised. These are due partly to limitations in the model structure used to represent the Sea King dynamics.

System Identification techniques can be used to gain a better understanding of these limitations and progressively to develop more adequate representations. This approach has been illustrated here with an example relating to vertical acceleration response to collective inputs. It has been shown that representation of inflow, flapping and engine dynamics are all important factors in matching prediction with measurement.

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Coefficient	a priori Value	Collective Step Up	Collective Step Down	Collective Pulse	Combined Flights
z_w	-0.88	-0.86 (.02)	-0.90 (0.1)	-0.77 (.01)	-0.80 (.01)
$z_{\ddot{\beta}}$	-0.912^F	-0.912	-0.912	-0.912	-0.912
$z_{\dot{\beta}}$	18.2^*	16.2	15.1	15.2	16.6
z_β	31.9^*	35.5	37.4	37.1	34.7
z_ν	0.88^*	0.78	0.73	0.74	0.80
z_Ω	12.0	6.40 (1.5)	12.5 (2.0)	15.8 (3.1)	6.82 (1.7)
z_{θ_C}	-399	-443 (6.4)	-467 (5.9)	-464 (5.4)	-434 (5.4)
$\beta_{\dot{w}}$	0.050^F	0.050	0.050	0.050	0.050
β_w	1.3^*	1.5	1.1	1.5	1.4
$\beta_{\dot{\beta}}$	-29.8^*	-33.5	-25.1	-43.2	-30.6
β_β	-559	-555 (21)	-539 (22)	-467 (47)	-537 (23)
β_ν	-1.3^*	-1.5	-1.1	-1.5	-1.4
β_Ω	106	40 (12)	38 (8.3)	79 (11)	94 (7.7)
β_{θ_C}	682	768 (52)	576 (50)	784 (142)	701 (58)
ν_w	2.9^*	7.1	8.2	10.3	6.9
$\nu_{\dot{\beta}}$	-56.2^*	-140	-161	-203	-135
ν_β	-104^*	-256	-297	-374	-250
ν_ν	-4.9	-8.4 (0.5)	-9.2 (0.7)	-13.0 (0.9)	-9.7 (0.6)
ν_Ω	-125	-89 (22)	-213 (39)	-353 (82)	-109 (27)
ν_{θ_C}	1296	3222 (247)	3713 (313)	4681 (457)	3120 (255)

Bracketed values are Cramer Rao error bounds

^{F} - Coefficient is fixed

* - Coefficient is varied via a hard constraint

TABLE 1 COLLECTIVE RESPONSE MODEL PARAMETERS

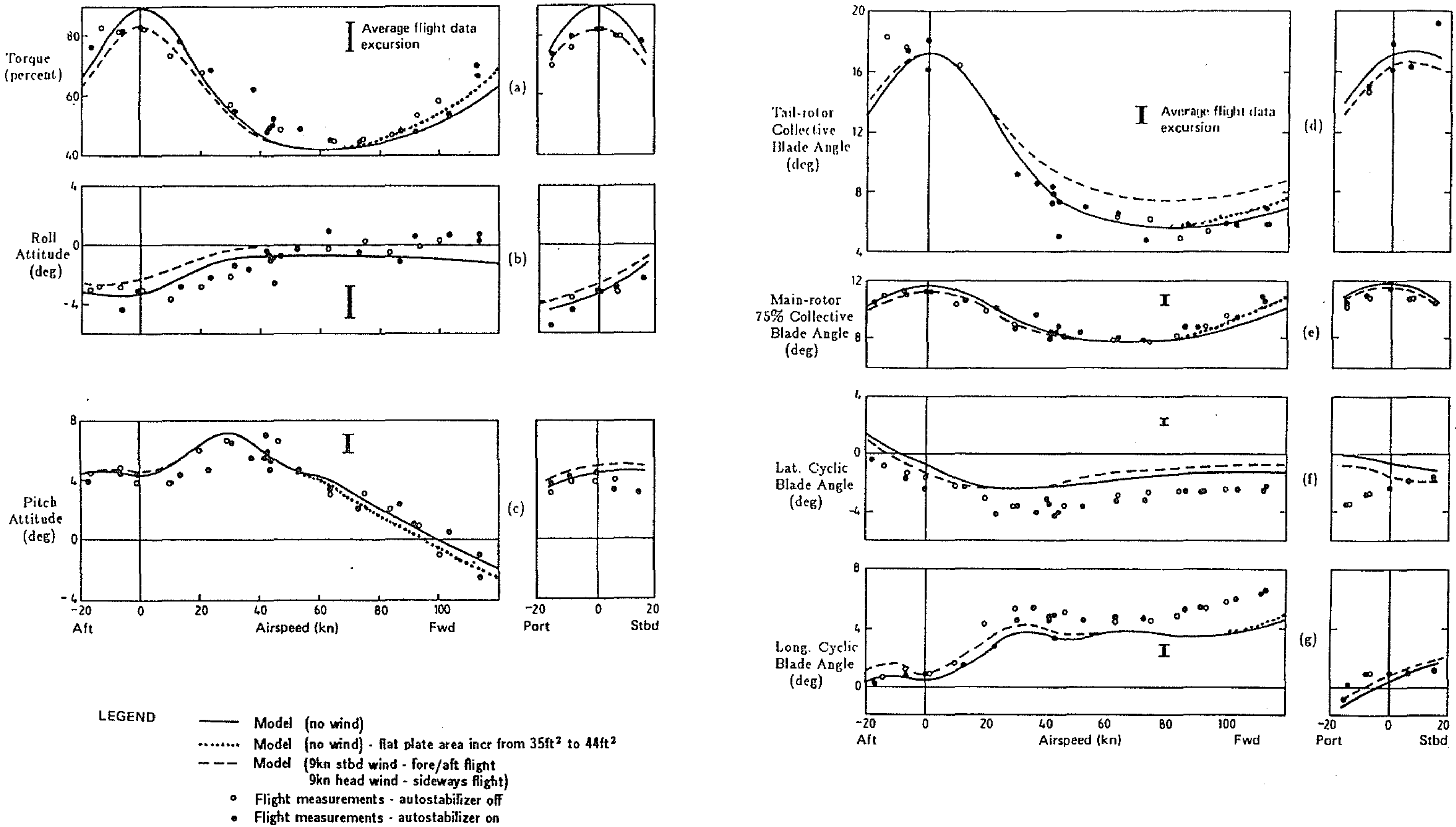

Fig. 1 COMPARISON OF SEAKING MATHEMATICAL MODEL WITH TRIMMED FLIGHT MEASUREMENTS - TORQUE, ATTITUDES, BLADE ANGLES

FLIGHT
M/MODEL

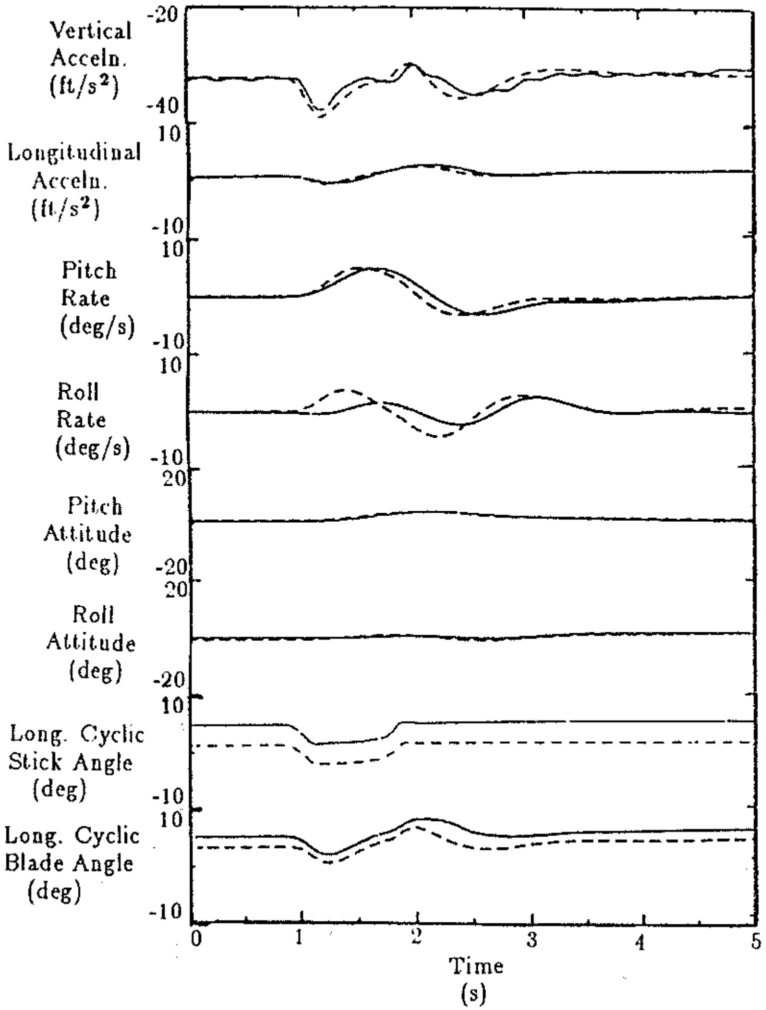

Fig. 2 DYNAMIC RESPONSE —— LONGITUDINAL CYCLIC INPUT (88 knots)

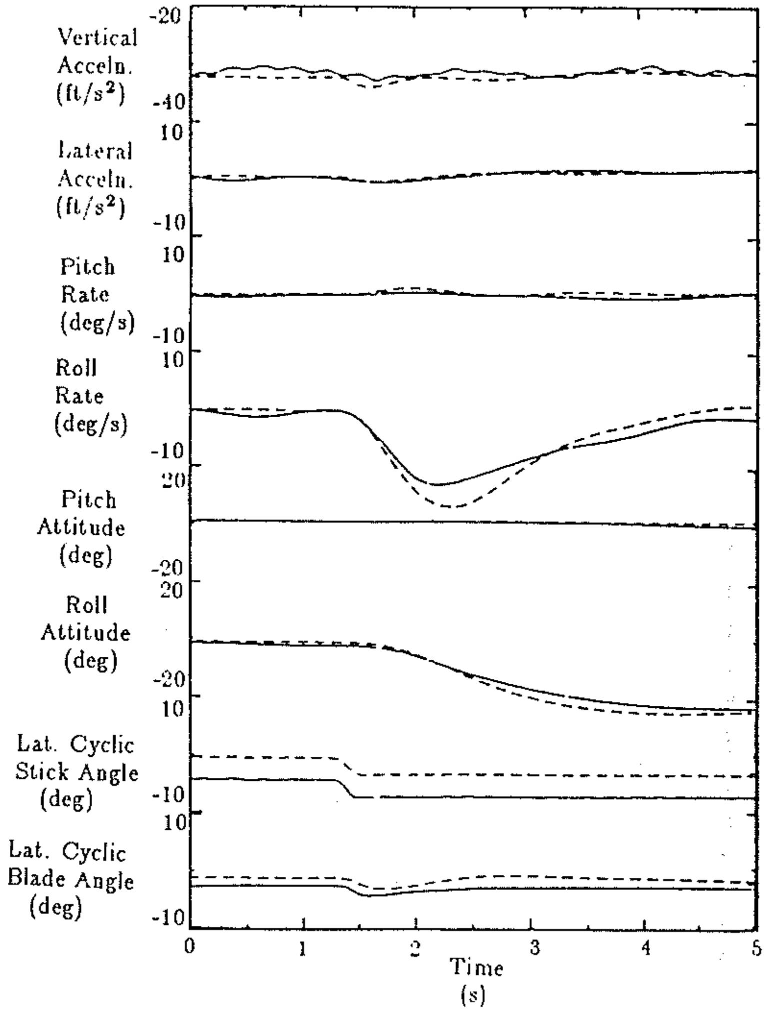

Fig. 3 DYNAMIC RESPONSE —— LATERAL CYCLIC INPUT (88 knots)

FLIGHT
M/MODEL

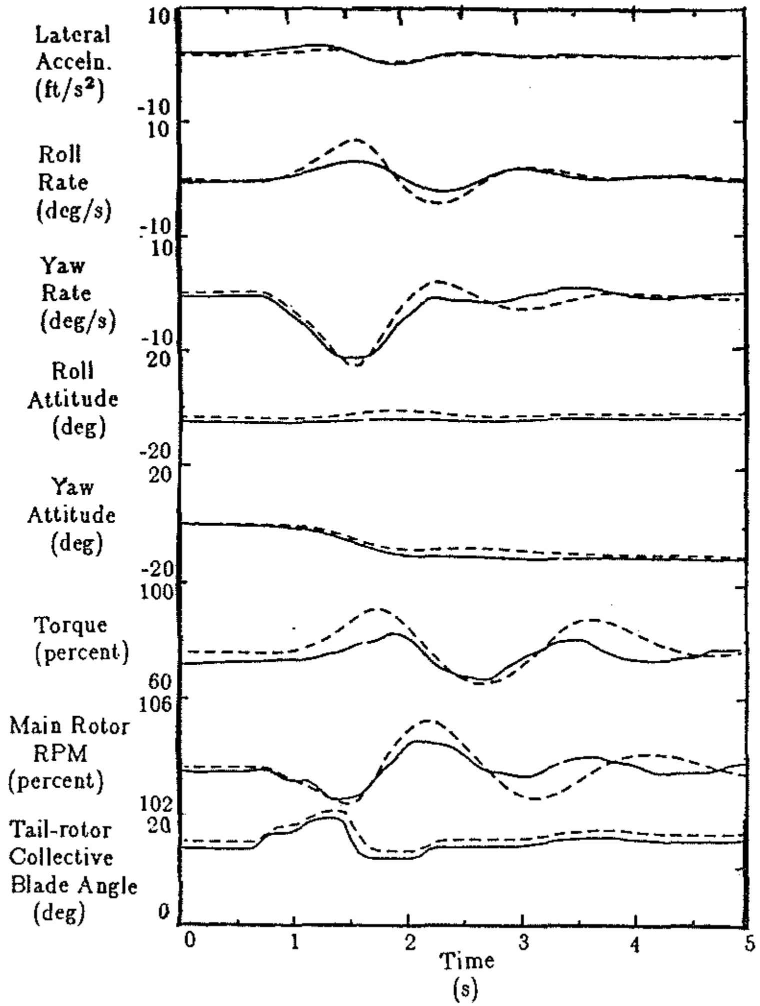

Fig. 4 DYNAMIC RESPONSE —— PEDAL INPUT (Hover)

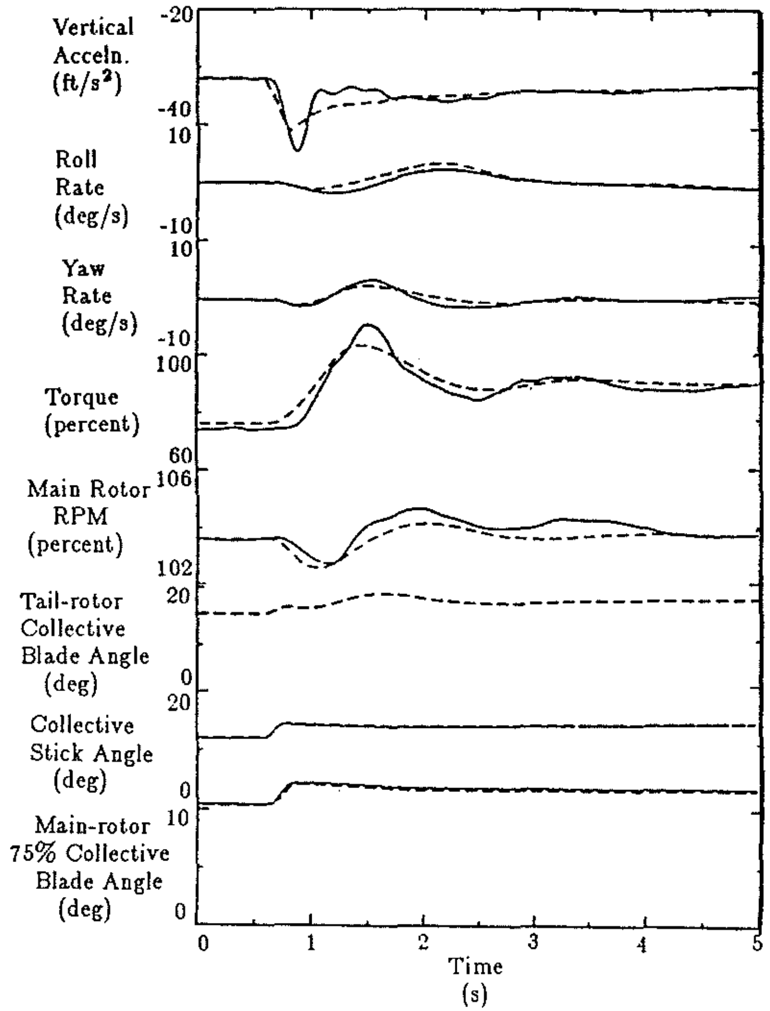

Fig. 5 DYNAMIC RESPONSE —— COLLECTIVE INPUT (Hover)

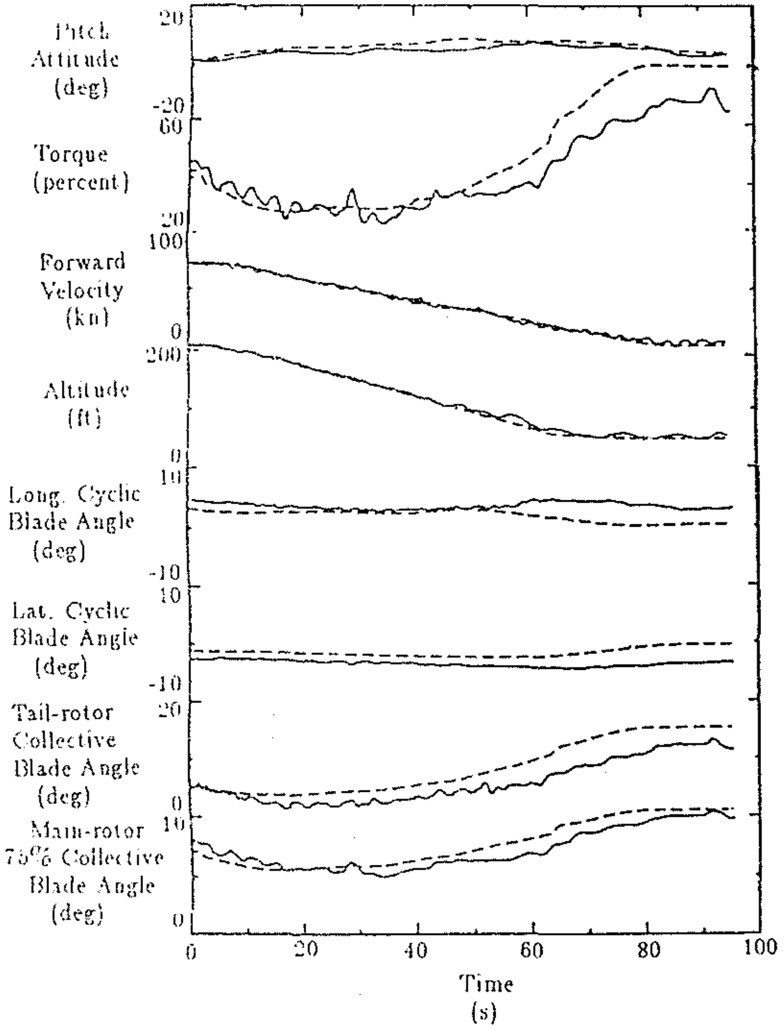

Fig. 6 TRANSITION DOWN

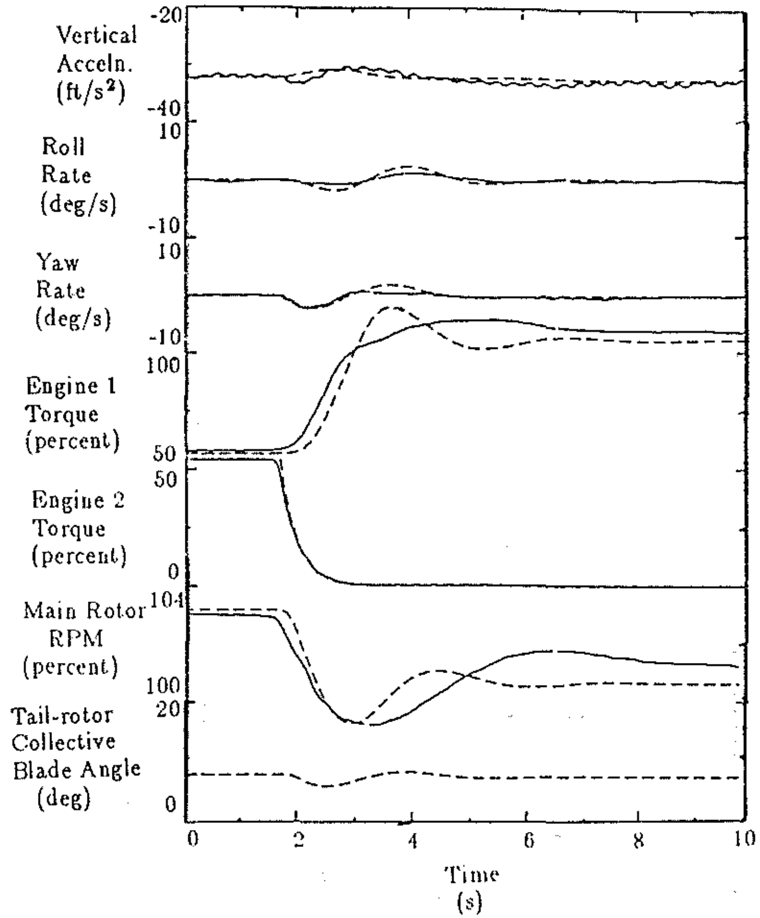

Fig. 7 ENGINE CUT —— SIMULATED FAILURE OF ONE ENGINE (82 knots - 4 degree climb)

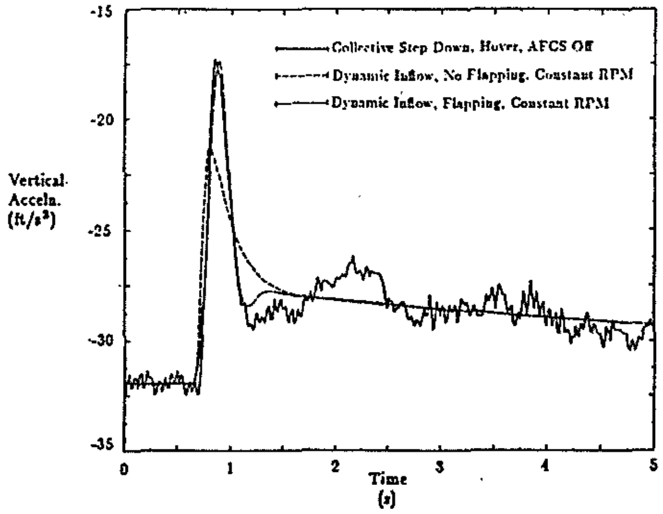

Fig. 8a EFFECTS OF DYNAMIC INFLOW AND FLAPPING ON VERTICAL DYNAMICS

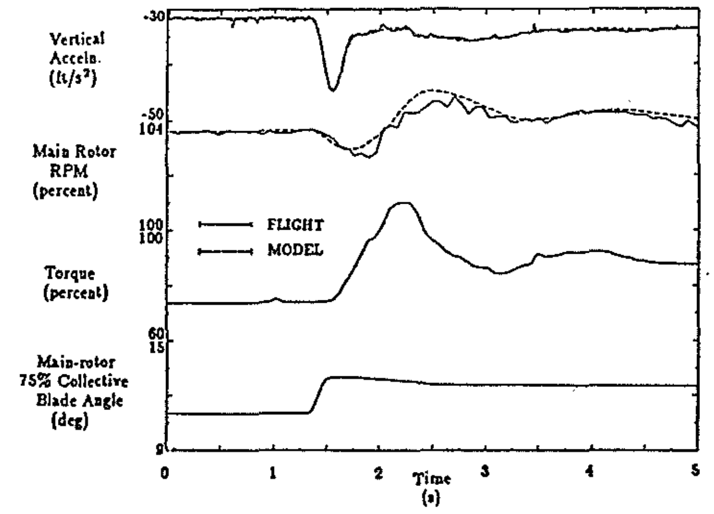

Fig. 9a VERTICAL ACCELERATION RESPONSE TO A COLLECTIVE STEP UP

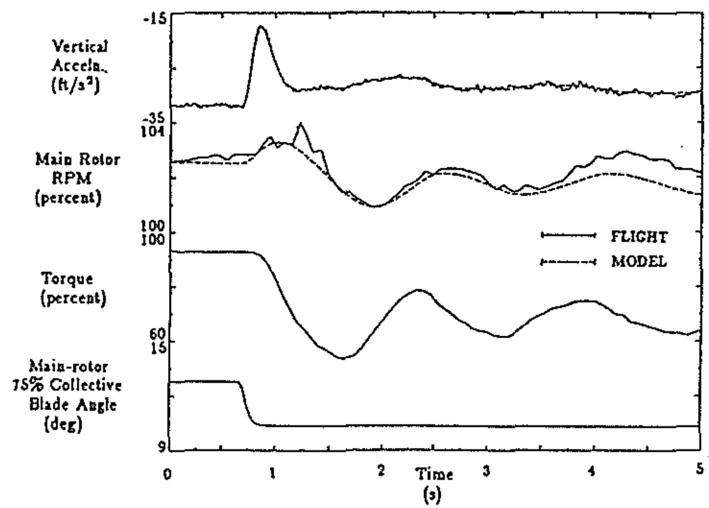

Fig. 8b VERTICAL ACCELERATION RESPONSE TO A COLLECTIVE STEP DOWN

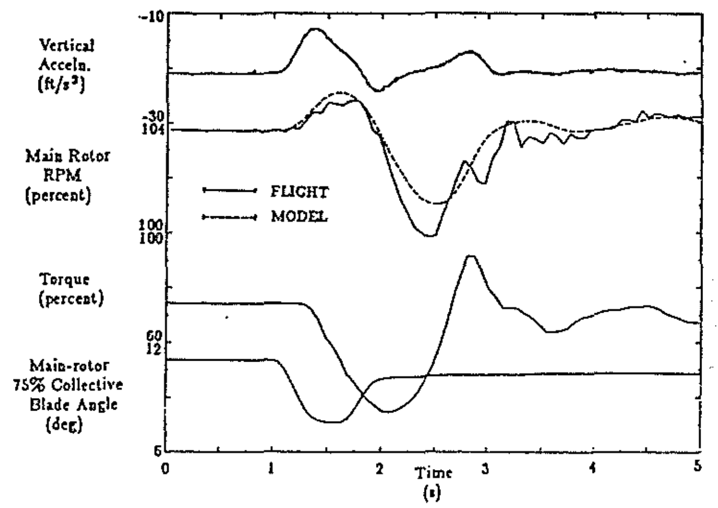

Fig. 9b VERTICAL ACCELERATION RESPONSE TO A COLLECTIVE STEP PULSE