



SIMPLIFIED INVERSE SIMULATION FOR PRELIMINARY DESIGN PURPOSES

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ABSTRACT

A simplified inverse simulation code developed by AGUSTA PRELIMINARY DESIGN DEPARTMENT is here proposed. The method is able to evaluate, knowing the flight path of the helicopter in the longitudinal plane, the control inputs and the power needed to perform the trajectory. The model here used considers five degrees of freedom (collective and longitudinal cyclic pitch, fuselage attitude, rotor RPM, longitudinal flapping angle), and adopts simplified formulations to evaluate aerodynamic forces and rotor dynamic behaviour

A synthetic description of the mathematical model used is presented; comparisons with flight test data and other methodologies are included too.

1. INTRODUCTION

In modern helicopters the capability to perform flight path constrained manoeuvres is becoming a significant characteristic. Often the flight dynamics requirements heavily impact on the preliminary design of the aircraft.

As an example it can be considered the FLY-AWAY manoeuvre and the NOE flight for a military helicopter and the cat. A take off requirement for civil helicopters.

So the preliminary design department of a helicopter company needs the availability of tools that allow the analysis of these subjects.

Naturally these tools have to match the typical requirements of the first phase of a new helicopter design like: very simple use, short execution time and reduced inputs level necessary for the parametric study typical of this phase.

Here will be presented a synthetic description of the inverse simulation procedure developed by AGUSTA PRELIMINARY DESIGN DEPARTMENT and will be shown comparisons with flight test data in order to validate the methodology.

LIST OF SYMBOLS

- F = forces
- M = moments
- M_C = control moment due to the rotor
- X = longitudinal position in **GROUND AXES**
- Z = vertical position in **GROUND AXES**
- m = helicopter mass
- Ω = main rotor angular speed
- J = moments of inertia
- a = acceleration or lift slope for airfoils
- Θ = pitch attitude
- Θ_0 = collective pitch angle at 75% of radius
- Θ_{90} = longitudinal cyclic pitch
- u, v, w = components in **GROUND AXES** of the speed of the aircraft
- p, q, r = yaw, pitch, roll angular speeds
- τ = climb angle
- α = aerodynamic angle of attack
- L = lift in **WIND AXES**
- D = drag in **WIND AXES**
- T = rotor thrust
- H = rotor inplane force
- ρ = air density
- a1 = longitudinal flapping coefficient
- a0 = coning angle

V_i = induced velocity
 V = total speed
 ϵ = aerodynamic angle of influence
 γ = setting angle for shaft system or aerodynamic surfaces
 $\bar{\delta}$ = averaged value for rotors drag coefficient
 Q = torque
 t = time

SUBSCRIPTS AND OTHER SYMBOLS

SH = SHAFT SYSTEM
NF = NO-FEATHER SYSTEM
d = DISK SYSTEM
B = BODY SYSTEM
G = GROUND SYSTEM
• = d / dt
•• = d^2 / dt^2
x = longitudinal direction
z = vertical direction
htp = horizontal tail plane
fus = fuselage
tot = total value
MR = main rotor
TR = tail rotor

2. SIMPLIFIED MATHEMATICAL MODEL

It has to be pointed out again that the approach adopted in this work is typical of the preliminary design phase.

So, the methodology here presented, incorporates those simplifications that, without reducing too much the accuracy of the final results, are necessary to increase the cost/effectiveness of the method.

2.1 Assumptions

This code has been thought as a starting point for possible future improvements; on these bases a study limited to the longitudinal plane (XZ plane) was chosen. That means: roll and yaw rate and angles always equal to zero and no motions of the CG of the aircraft in the horizontal plane (XY plane) (see fig. 1).

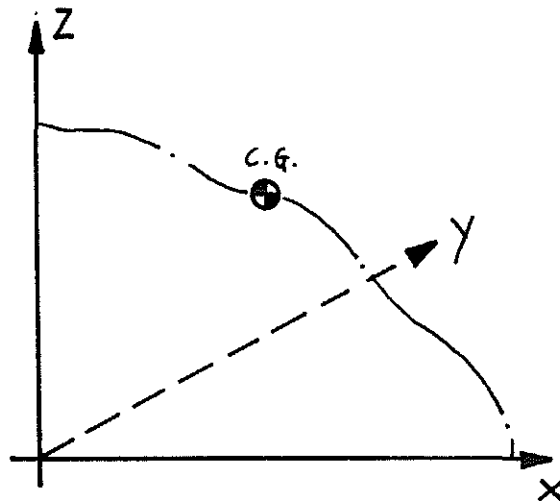


Figure 1.

This could appear as a big limitation, but actually the most part of the manoeuvres of interest for preliminary design purposes are really performed in this plane like TAKE OFF or LANDING manoeuvres, FLY-AWAY, longitudinal and vertical accelerations, QUICK-HOP, linear transitions etc.

The target of the program was, knowing the flight path of the helicopter as a function of time, to evaluate the time histories of the collective and longitudinal cyclic pitch, pitch attitude of the aircraft, longitudinal flapping coefficient and power required.

The code has also the capability to consider changes in available power so the RPM of rotor are considered as a degree of freedom of the model.

An indication of required tail rotor pitch angle is also given as a consequence of having fixed yaw rate and angle to zero.

This can give an understanding of the tail rotor capability to sustain the constrained manoeuvre.

The mathematical model used is a non-linear one for the equation of motions of the aircraft, while the equations describing the dynamic behavior of the rotor are linear and integrated in closed form.

Rigid blade with a constant chord is considered, a constant lift curve slope was assumed; stall, compressibility and reversed flow are ignored for force calculation while those phenomena affect power required.

Infact AG has developed an original mathematical model for the evaluation of the average C_d of a rotor in every flight condition. The program is mainly dedicated to study the articulated rotors typical of Agusta technology, but teetering and hingeless rotors could be also considered using suitable offsets of flapping hinge. Induced velocity is considered constant all over the rotor disk but a complete formulation, good for all flight condition is used for the estimation of this average value. Induced velocity is also corrected to take into account the ground effect; more details will be given in paragraph 2.4.

Fuselage aerodynamic loads are evaluated using empirical expressions obtained from wind tunnel tail off tests. Separate models for horizontal and vertical tail planes are used; influence of main rotor wake on horizontal tail plane is considered too; more details are given in paragraph 2.4 again.

Wind velocities along X and Z axes can be introduced at any time during the manoeuvre.

2.2 Mathematical Model for Flight Path Definition

The inverse simulation algorithm requires as input data the positions, the velocities and the accelerations of the CG of the aircraft as a function of time, and naturally, the boundary conditions at the initial instant ($t=0$).

The program **NFPATH**, being limited to longitudinal plane, requires as inputs only X , \dot{X} , \ddot{X} and Z , \dot{Z} , \ddot{Z} , in **GROUND AXES**.

Really only $X(t)$ and $Z(t)$ are furnished to the program and then by a double derivation procedure $\dot{X}(t)$, $\ddot{X}(t)$, $\dot{Z}(t)$, $\ddot{Z}(t)$ are obtained.

A spline of degree variable from 1 to 5, according to user needs, is fitted through the discrete time points describing X and Z trajectories.

By means of a first derivation process in the control points of the above spline curve the discrete functions describing $\dot{X}(t)$ and $\dot{Z}(t)$, in the same control points, are obtained.

The process is repeated to evaluate the accelerations $\ddot{X}(t)$ and $\ddot{Z}(t)$, fitting another spline (degrees always fixed by the user) through the points describing $\dot{X}(t)$ and $\dot{Z}(t)$ time histories.

At the end of this process $X(t)$, $\dot{X}(t)$, $\ddot{X}(t)$, $Z(t)$, $\dot{Z}(t)$, $\ddot{Z}(t)$, are known at the same time points.

All this procedure is implemented utilizing an IBM standard program called CSMPIII.

A complete trim of the aircraft, performed with a consolidated AGUSTA methodology, of proven validity, provides the set of initial conditions necessary for the integration of the differential equation of motion describing the system.

2.3 Iterative Methodology for the Solution of the Inverse Simulation Problem

As for the direct problem the set of equation that it is possible to write is: in a **GROUND REFERENCE SYSTEM** :

$$\begin{array}{l} 1) \\ 2) \end{array} \left\{ \begin{array}{l} \ddot{X} = F_x / m \\ \ddot{Z} = F_z / m \end{array} \right.$$

Where F_x and F_z are the free forces along X and Z axes. Due to the simplifications introduced into the problem then it is possible to write in **BODY AXES** :

$$\begin{array}{l} 3) \\ 4) \end{array} \left\{ \begin{array}{l} \ddot{\Theta} = M / J_p \\ \dot{\Omega} = (M_e - M_T) / J_{pr} \end{array} \right.$$

where Θ is the pitch attitude angle and M is the free moment acting on the fuselage; Ω is the angular speed of the rotor and M_T is the total torque acting on the drive system of the aircraft ; M_e is the torque delivered by the engines; J_p and J_{pr} are, respectively, the moment of inertia of the aircraft along the pitch axes and the total polar moment of inertia of the rotating parts of helicopter drive system.

Moreover, under the hypothesis made and if a plane of symmetry exists, is very simple to calculate, from the accelerations in GROUND AXES (that are known), the accelerations in BODY AXES with the relationship :

$$5) \begin{Bmatrix} a_{x_B} \\ a_{y_B} \\ a_{z_B} \end{Bmatrix} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \cdot \begin{Bmatrix} a_{x_G} \\ a_{y_G} \\ a_{z_G} \end{Bmatrix} - \begin{Bmatrix} w_0 q \\ 0 \\ 0 \end{Bmatrix}$$

Due to the inverse approach to simulation problem the first set of equations (1-2) are not differential ones, but they can be transformed into two algebraic equations that can be solved to furnish two of the independent unknown of the system. The rotor thrust in DISK AXES and the longitudinal flapping angle respect with SHAFT SYSTEM were selected.

An iterative procedure was then set up to solve the above equations and to evaluate all the other parameter involved in rotor dynamic behavior and, besides, the aerodynamic forces, moments and the rotor torque that are necessary to solve the second set of really differential equations (3-4) to obtain θ and Ω . These two differential equations are solved using the IBM supported program CSMPIII, that is simple to use and particularly thought for these kinds of problems.

At the beginning of each step of integration the following parameters are always known:

$$\begin{aligned} & \theta, \dot{\theta}, \Omega, \dot{\Omega} \\ & x, \dot{x}, \ddot{x} \\ & z, \dot{z}, \ddot{z} \\ & V_{tot} = \sqrt{x^2 + z^2} \\ & \tau = \text{atan}(\dot{z} / \dot{x}) \\ & a_{fus} = \theta - \tau \\ & M_{fus} = f(a_{fus}, V_{tot}) \\ & L_{fus} = f(a_{fus}, V_{tot}) \end{aligned}$$

$$D_{fus} = f(\alpha_{fus}, V_{tot})$$

For $t=0$, as already said, the boundary conditions are determined trimming the aircraft at the desired flight situation (thrust, speed, altitude and temperature).

Inside each step all the other involved variables are evaluated; here will be presented a list of these parameters with their more important functional relationships.

$$T_d = f(\Omega, \rho, \tau, m, D_{fus}, L_{fus}, H_d, L_{htp}, D_{htp}, \Theta, a_{1SH}, V_i, V_{tot}, \ddot{z}, \ddot{x}, \varepsilon_{htp})$$

$$V_i = f(V_{tot}, \alpha_d, \rho, T_d)$$

$$\alpha_d = f(\Theta, \tau, a_{1SH}, \gamma_{SH})$$

$$a_{1SH} = f(m, \ddot{x}, \ddot{z}, D_{fus}, H_d, D_{htp}, L_{htp}, \varepsilon_{htp}, L_{fus}, T_d, \Theta, \tau, \Omega)$$

$$\Theta_0 = f(T_d, V_{tot}, a, V_i, \alpha_d, \Omega)$$

$$H_d = f(\rho, \bar{\delta}, V_{tot}, \alpha_d, \Theta_0, a, V_i, a_{1NF}, \Omega)$$

$$a_{1NF} = f(V_{tot}, \Theta_0, \alpha_d, V_i, \Omega, \dot{\Theta})$$

$$a_0 = f(V_{tot}, \Theta_0, \alpha_d, V_i, \Omega, \text{LOCK number})$$

$$\Theta_{90} = f(a_{1SH}, a_{1NF})$$

$$L_{htp} = f(\Theta, \rho, \gamma_{htp}, \alpha_{fus}, \varepsilon_{htp}, \dot{\Theta}, V_{tot}, \tau)$$

$$D_{htp} = f(\Theta, \rho, \gamma_{htp}, \alpha_{fus}, \varepsilon_{htp}, \dot{\Theta}, V_{tot}, \tau)$$

$$\varepsilon_{htp} = f(V_i, V_{tot}, \alpha_d, \Theta, \tau, \dot{\Theta})$$

$$Q_{MR} = f(\theta, \Omega, \tau, \bar{\delta}, a, \alpha_d, V_i, H_d, T_d, V_{tot}, \rho, \text{MACH number})$$

$$\bar{\delta} = f(\theta, \tau, \Omega, \theta_{90}, \theta_0, \alpha_d, \gamma_{SH}, \text{MACH number})$$

$$Q_{TR} = f(Q_{MR}, \rho, \bar{\delta}_{TR}, V_{iTR}, V_{tot}, \Omega, a_{TR}, T_{TR})$$

$$Q_{tot} = f(Q_{MR}, Q_{TR}) = M_T$$

$$M_C = f(\Omega, a_{1SH})$$

As a first step in this iterative process a starting point for α_d is fixed; then, from the equations of dynamic equilibrium along X and Z axes, as already said, T_d , and a_{1SH} are obtained, being known the other parameters that appear into the equations of T_d and a_{1SH} (all functions of α_d).

After that, a new value for α_d can be calculated from the relation:

$$6) \quad \alpha_d = \theta - \tau + \gamma_{SH} + a_{1SH}$$

with this updated value all the others are recalculated (i.e. $a_{1NF}, H_d, \epsilon_{htp}, L_{htp}, D_{htp}$) until α_d , T_d and a_{1SH} converge on stable values with a margin of error fixed by the user. The user can also choose the degree of relaxation that has to be ascribed to the system.

The flight controls (collective pitch θ_0 , longitudinal cyclic pitch θ_{90} and pedal θ_{0TR}) are obtained from formulas that relate θ_0 to T_d ; θ_{90} to a_{1NF} and a_{1SH} and θ_{0TR} to T_{TR} .

Knowing all the forces and a_{1SH} is possible to obtain the moment acting on the aircraft (i.e. M_{fus}, M_{htp}, M_C , etc.) and with

these, solving the differential equation in $\ddot{\theta}$, to calculate $\dot{\theta}$ and θ that are, then, used in the next step of integration.

Once it is known, as input data, the time history of the power delivered by the engines (power decay for the inoperative engine and increase in the power of remaining engines), and having calculated, at each time step, the power required by the helicopter, equation 4) can be solved giving $\dot{\Omega}$ and, as a consequence, the rotor RPM time history during the manoeuvre. Naturally the updated value of Ω is used for the successive time step.

A simplified engine scheme is used in the present release of NFPATH code, but the flexibility of CSMPIII tool can allow the implementation of very complex engine mathematical models in very short time and simple way.

2.4 Program facilities and options

In this paragraph will be presented a brief explanation about the model used for "ground effect", "horizontal tail plane" and " C_d evaluation for main rotor".

2.4.1 Ground effect

A simple scheme, derived from experience, is used to take into account the "Ground Effect".

The induced velocity is reduced according to a function of the main rotor distance from the terrain.

The program automatically detects the entry of rotor into ground effect and provides the desired correction to induced velocity and, as a consequence, to power required and controls angles.

This, naturally, increase the accuracy of the results in FLY-AWAY manoeuvres and emergency landing cases.

2.4.2 Horizontal tail plane

The evaluation of horizontal tail plane aerodynamic angle of attack takes into account the influence of the main rotor wake.

The model used is rather sophisticated, aerodynamic surface stall is considered and the program is able to evaluate, automatically, the conditions of thrust, speed, climb angle, pitch attitude, and flapping angle at which the wake of the main rotor begins to wet the surface.

This model has been tested using flight test data of different Agusta helicopters always giving good results.

2.4.3 Main rotor C_d calculation

An original model developed by Agusta is used for the evaluation of an average value for the C_d of the main rotor.

The averaged C_d allows the integration in closed form of the equations adopted for torque and H-force, maintaining a good accuracy in the final results.

Stall and compressibility effects are taken into account; besides the algorithm considers also the actual rotor operating conditions, so, calculations are affected by inflow parameter, control angles (θ_0, θ_{90}), flapping velocity, and advance ratio.

The procedure, above described, is included into the iterative process presented in paragraph 2.3.

This method has demonstrated to be very reliable and precise even at very high advance ratios and critical combinations of altitude and temperature.

2.5 The CSMPIII integration procedure

This IBM supported program is a tool dedicated to the numerical solution of any kind of differential equations describing a dynamic system.

This procedure has been chosen thanks to its extreme flexibility for describing systems and for the numerous options available for the user.

For example several integration methods of increasing complexity and precision can be selected, naturally paying an increase in CPU time.

Program allows derivation and integration by mean of simple instructions; tools for interpolation of discrete functions are furnished (program `NFPATH` uses spline facility), and all the parameters involved in the simulation can be varied with time and their time histories can be easily provided by the user.

The program has a complete modular structure and so every change in the model or implementation of new or more complex algorithm can be obtained very simply and quickly.

Graphic options are included too and the code provides very clear and useful printouts.

3. METHODOLOGY VALIDATION

The methodology, here proposed, was validated using flight test data obtained from AGUSTA A109 twin engine helicopter.

In order to prove the extreme flexibility and simplicity of use of NFPATH program a indirect comparison with english program HELINV is here proposed using data presented by D. G. Thomson and R. Bradley at XIV EUROPEAN ROTORCRAFT FORUM.

3.1 A109 flight test data

A complete flight test program was developed by AGUSTA for the certification of A109 helicopter behaviour in O.E.I. conditions.

During these tests some photos were taken, with a special camera, from which is possible to read the vertical and horizontal trajectories of the aircraft as functions of time, respect with GROUND.

Four cases, that differ one from each other because of helicopter weight, altitude, external temperature and position of the CG of the aircraft, are here simulated. We will call them CASE A - B - C - D; the principal parameters that differentiate the cases are here summarized:

CASE	WEIGHT (Kg)	ALTITUDE (Fts)	TEMPER. (°)	CG POSITION (mm)
A	2500	6070	-2	3403.0
B	2620	6100	0	3452.0
C	2705	515	13	3470.0
D	2590	600	14	3471.0

Figures 2-3-4-5 show copies of the photos that have permitted to recreate helicopter's motion (we are sorry for the bad quality of these pictures but it was not possible to do better).

During flights, parameters, like power, roll and pitch attitudes, main and tail rotor collective pitch, longitudinal and lateral cyclic pitch, CG vertical load factor in **BODY AXES** were recorded as functions of time and so they are directly comparable with the outputs of **NFPATH** program.

These four flights have been chosen because the changes in the roll and yaw angles were contained into $\pm 5^\circ$ during the entire manoeuvre and this fact well approximates the assumptions made in **NFPATH** code theory.

Figures 6-7-8-9 compare flight test data with inverse simulation results, respectively, for the four cases A-B-C-D.

In general it can be said that a very good agreement is obtained for pitch attitude angle. Maximum and minimum values are always well estimated; some oscillations can be observed into the model behaviour that are not present in the actual aircraft. This phenomenon could be explained taking into account the "OSCILLATORY NATURE OF THE INVERSE SIMULATION" underlined by Thomson and Bradley^[2].

The same kind of oscillations is shown by longitudinal cyclic pitch diagrams. Generally the agreement with experimental data is not so good for this parameter; the mathematical model shows a too quick response to cyclic pitch inputs; this phenomenon affects, particularly, the initial part of the manoeuvres and, as a consequence, the entire time history of this control.

A rather good estimation, on the contrary, is reached for main rotor collective pitch. Initial values of this flight control are always very well estimated, the trend with the time is, generally, correct; a little overestimation of θ_0 can be noticed when the aircraft enters ground effect. This fact suggests that ground effect model is, probably, too simple.

The accelerations of the aircraft are rather well evaluated as demonstrated by diagrams of vertical CG load factor obtained, for the model, using equations 5). Big discrepancies at the final time from measured and calculated load factors are due to the impact of the aircraft with the ground that cannot be considered using **NFPATH** code.

Figure 10 shows the time histories of measured power that is, naturally, limited at engine **CONTINGENCY RATING** and the power required to perform the manoeuvre calculated with **NFPATH** program.

A good agreement is always obtained, but some discrepancies, found when the aircraft enters ground effect, demonstrate, one time more, that the ground effect estimation must be improved.

Due to difficulties to establish available power time histories congruent with required power estimations, all the presented inverse simulations were performed maintaining constant main rotor RPM.

To give an idea of the variable RPM option impact CASE C was also run giving to NFPATH code the time history of available power measured in flight.

Time history of resulting main rotor RPM are plotted in figure 11 compared with the measured one. Rotor angular speed changes does not significantly affect the other parameters presented in figure 8.

3.2 Theoretical comparison with "HELINV" code and WESTLAND LYNX flight test data

Two very interesting papers describing english inverse simulation methodology "HELINV" were presented by Thomson and Bradley at the XIII (1987) and XIV (1988) EUROPEAN ROTORCRAFT FORUM.

In the document presented at the last FORUM is possible to find a comparison between flight test data of a WESTLAND LYNX helicopter flying a 300 Ft QUICK-HOP manoeuvre and the same path simulated using HELINV program.

HELINV methodology was, then, used to theoretically foresee the behavior of LYNX aircraft performing a LONGITUDINAL LINEAR TRANSLATION manoeuvre.

Program NFPATH was thought to be very simple and flexible to use and to show these characteristics a model of LYNX was prepared using geometrical data found into JANE's book and a little of experience. The model required only 1 hour to be set-up.

Then the same manoeuvres simulated with HELINV code were performed using AGUSTA's methodology.

Figure 12 shows the comparison between LYNX flight test data for QUICK-HOP manoeuvre and NFPATH calculations.

Due probably to conventions of sign used by Thomson and Bradley and not described into their paper, collective pitch diagram, that certainly shows the variations from the initial value of this parameter, had to be changed in sign to be comparable to the one obtained from NFPATH code. Apart from this problem a very good agreement is obtained in collective pitch, pitch attitude and pitch angular velocity.

Longitudinal cyclic pitch shows, another time, oscillatory behaviour, but maximum and minimum values are rather well estimated.

Figure 13 shows the complete theoretical comparison of HELINV and NFPATH methodologies using LONGITUDINAL LINEAR TRANSLATION manoeuvre.

All data are referred to zero initial value and so changes from trim status are here plotted.

A very good agreement is obtained, again, for collective pitch and pitch attitude. Longitudinal cyclic control is, one time more, the parameter in which major differences can be found.

Probably the oscillations into Θ_{90} diagram (for NFPATH code) are a consequence of pitch attitude variations present at the first instants of the manoeuvre and well visible into the graph. These oscillations could be caused by different procedures, used by the two codes, for the interpolation of the trajectory.

4. CONCLUSIONS

Program NFPATH, although more tests are necessary, has demonstrated to be a good tool for preliminary design purposes.

The particular procedure implemented permits the use of very large integration steps (even 0.25 sec.) reducing very much computational time.

The use of CSMPIII language will allow an easy implementation of more complex models describing, for example, engines behaviour.

The modular form of the whole code permits improvements of the algorithm with little effort.

Some updatings of ground effect estimation and rotor dynamic are probably requested and will be studied as soon as possible.

As future further development the implementation of the theory here presented into a procedure able to optimize helicopter trajectory with the aim to allow the best exploitation of the available energy could be thought and realized.

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FIGURE 2 - CASE A

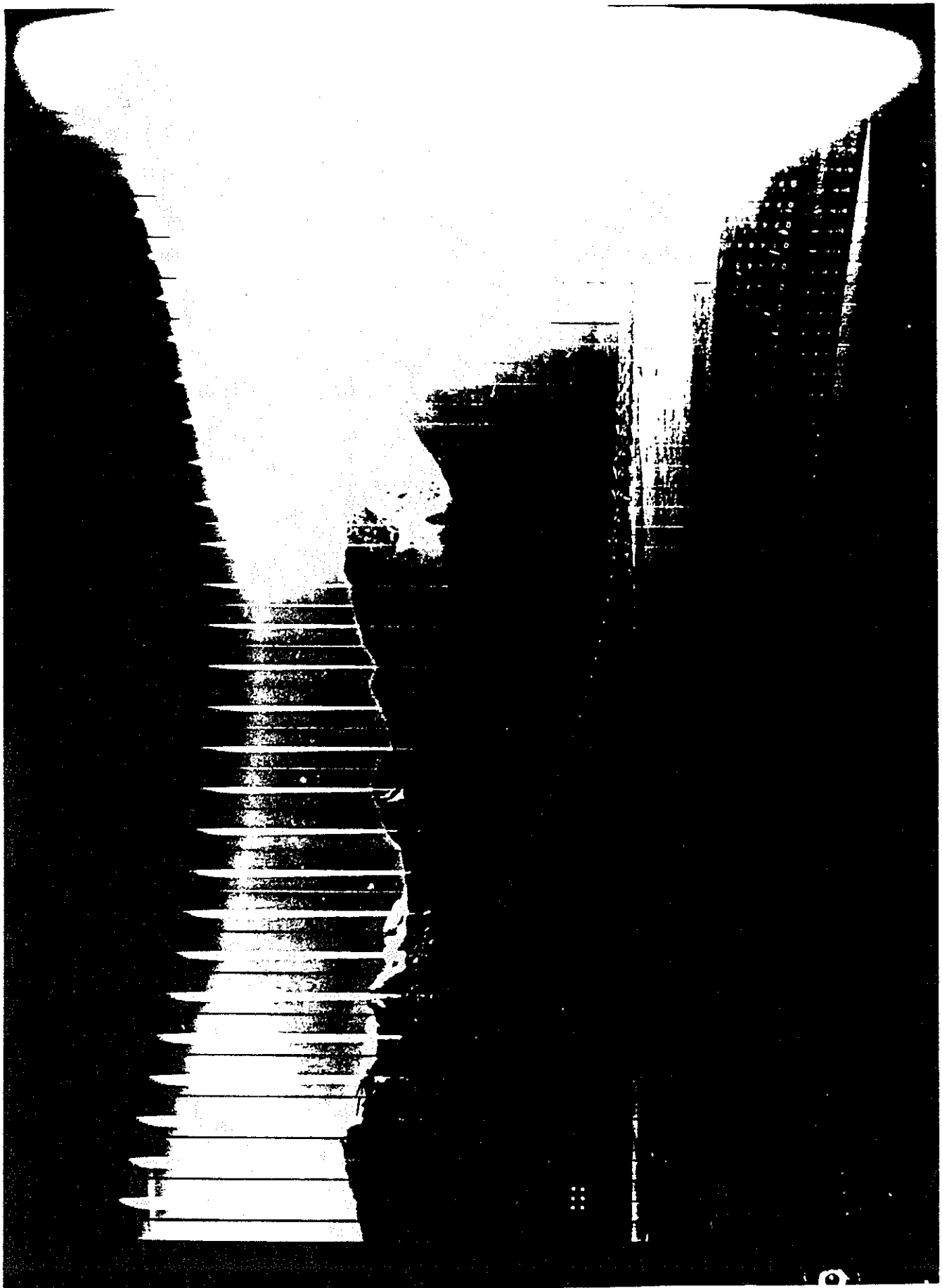


FIGURE 3 - CASE B

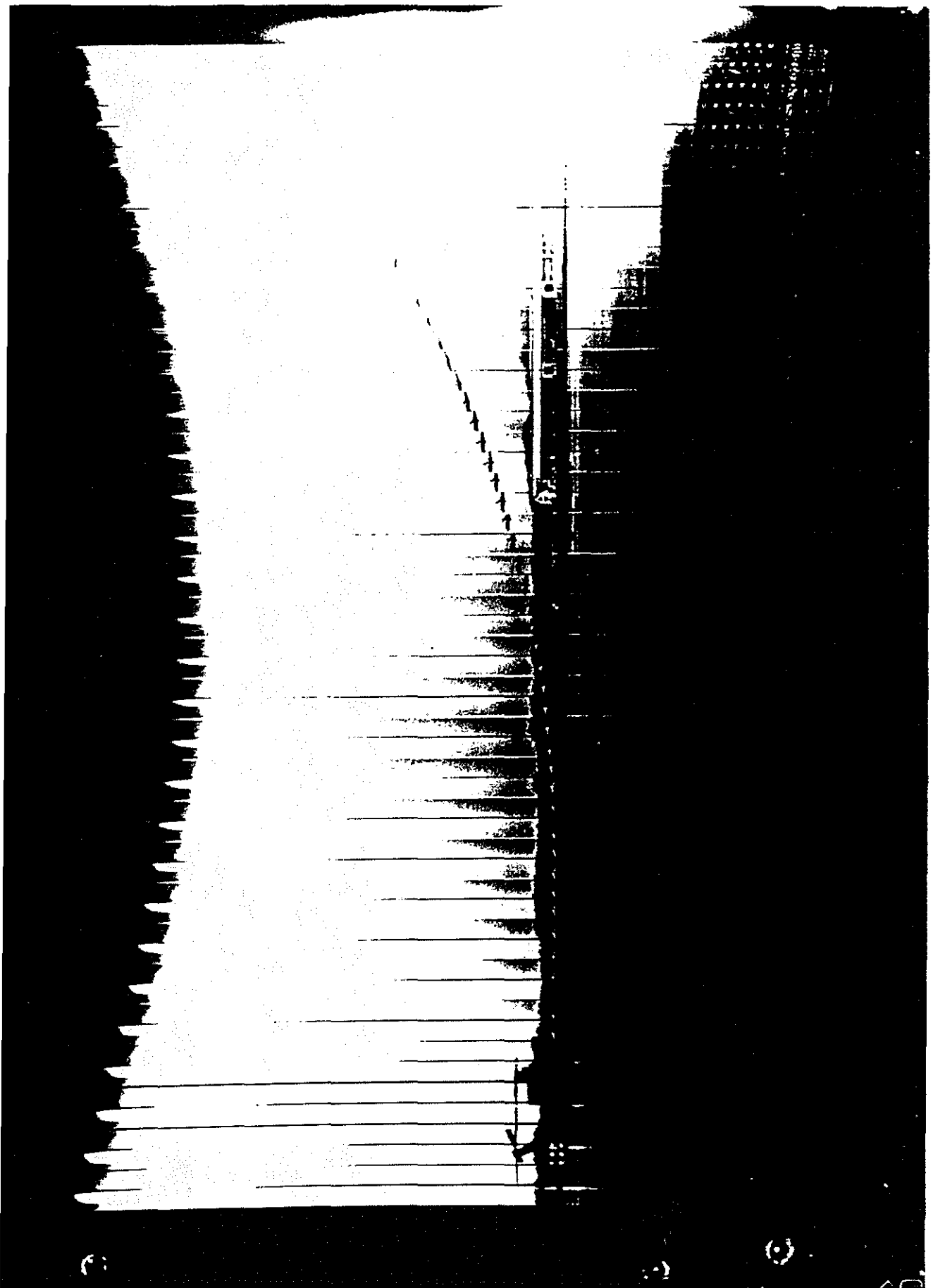


FIGURE 4 - CASE C

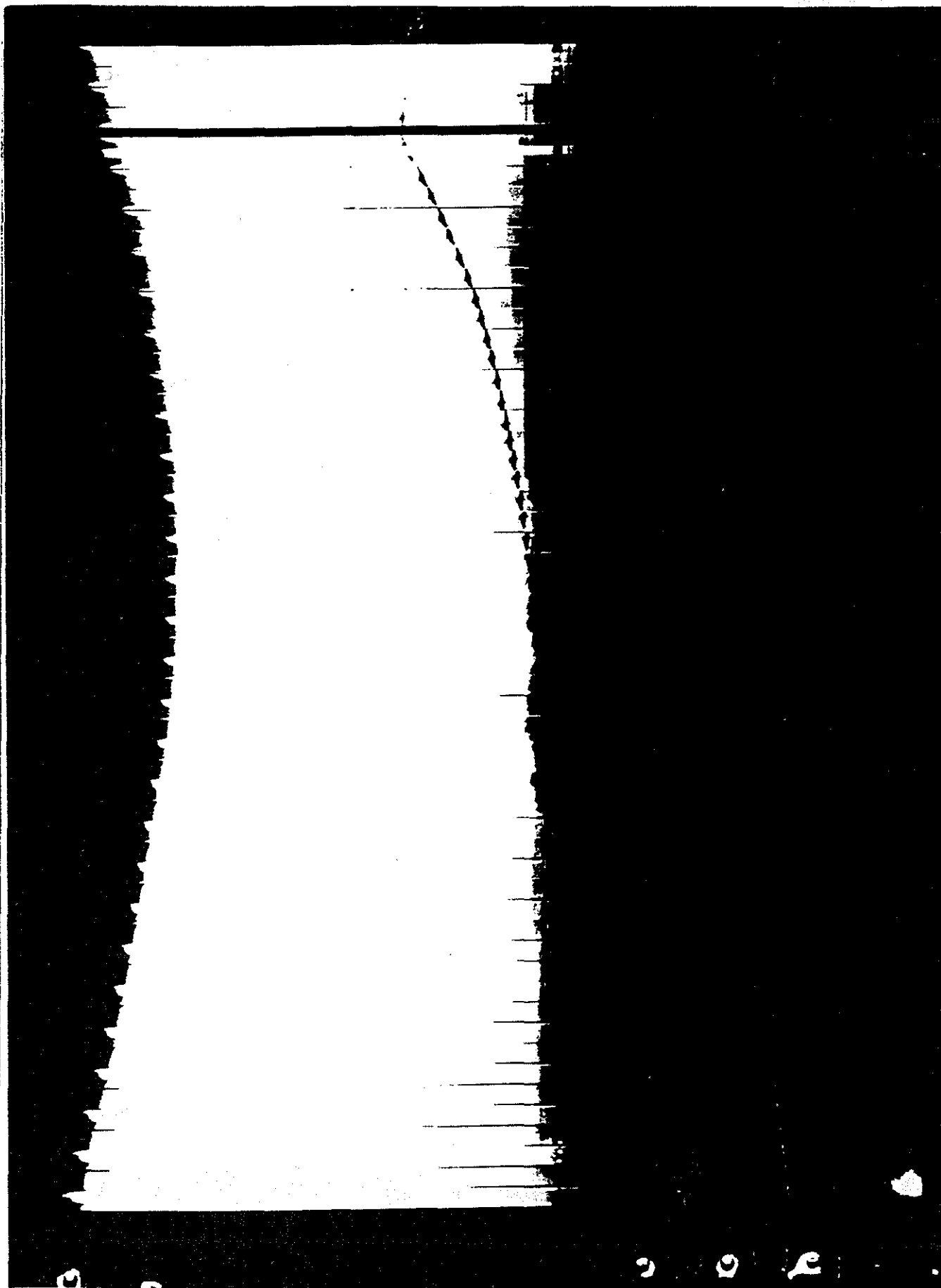


FIGURE 5 - CASE D

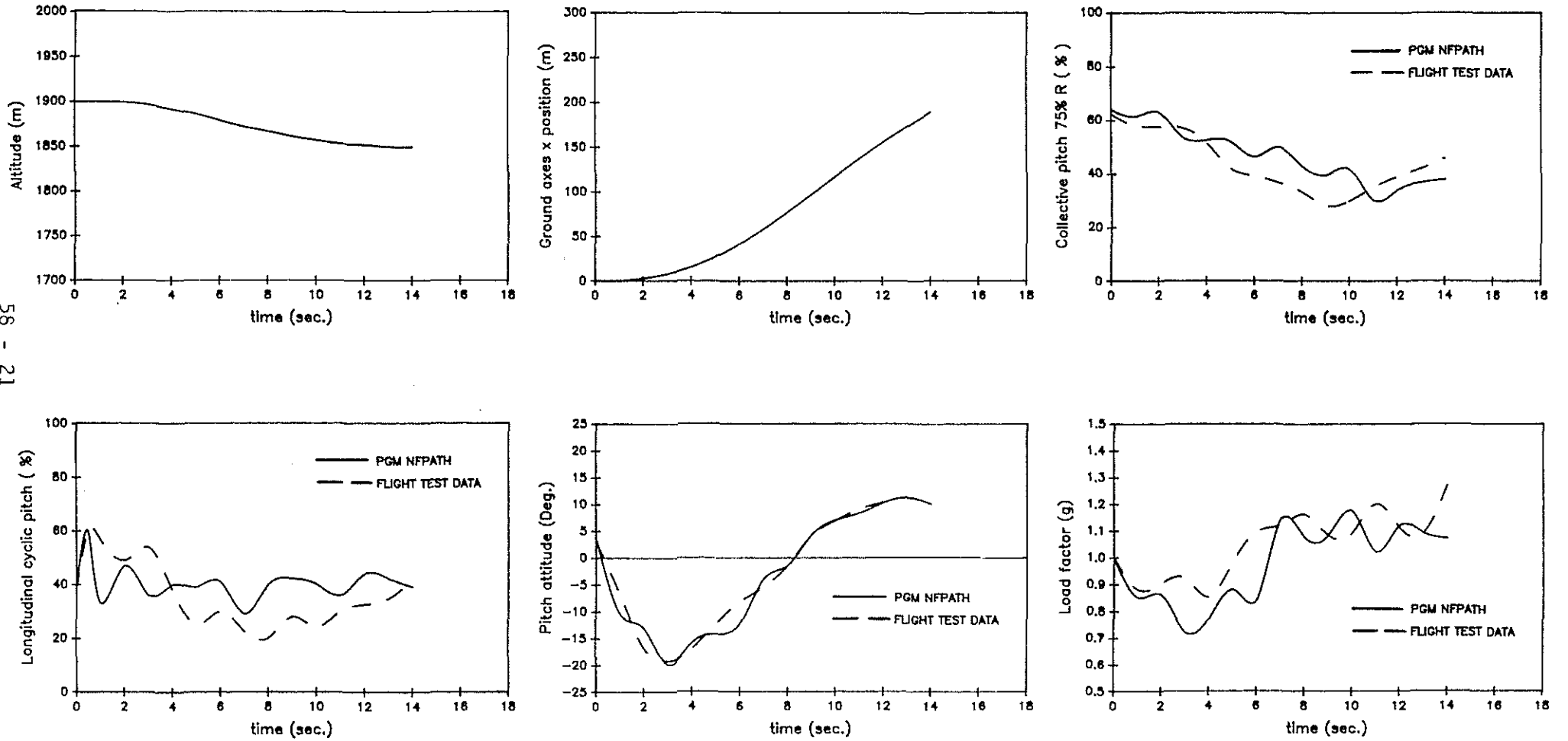


FIGURE 6 - CASE A

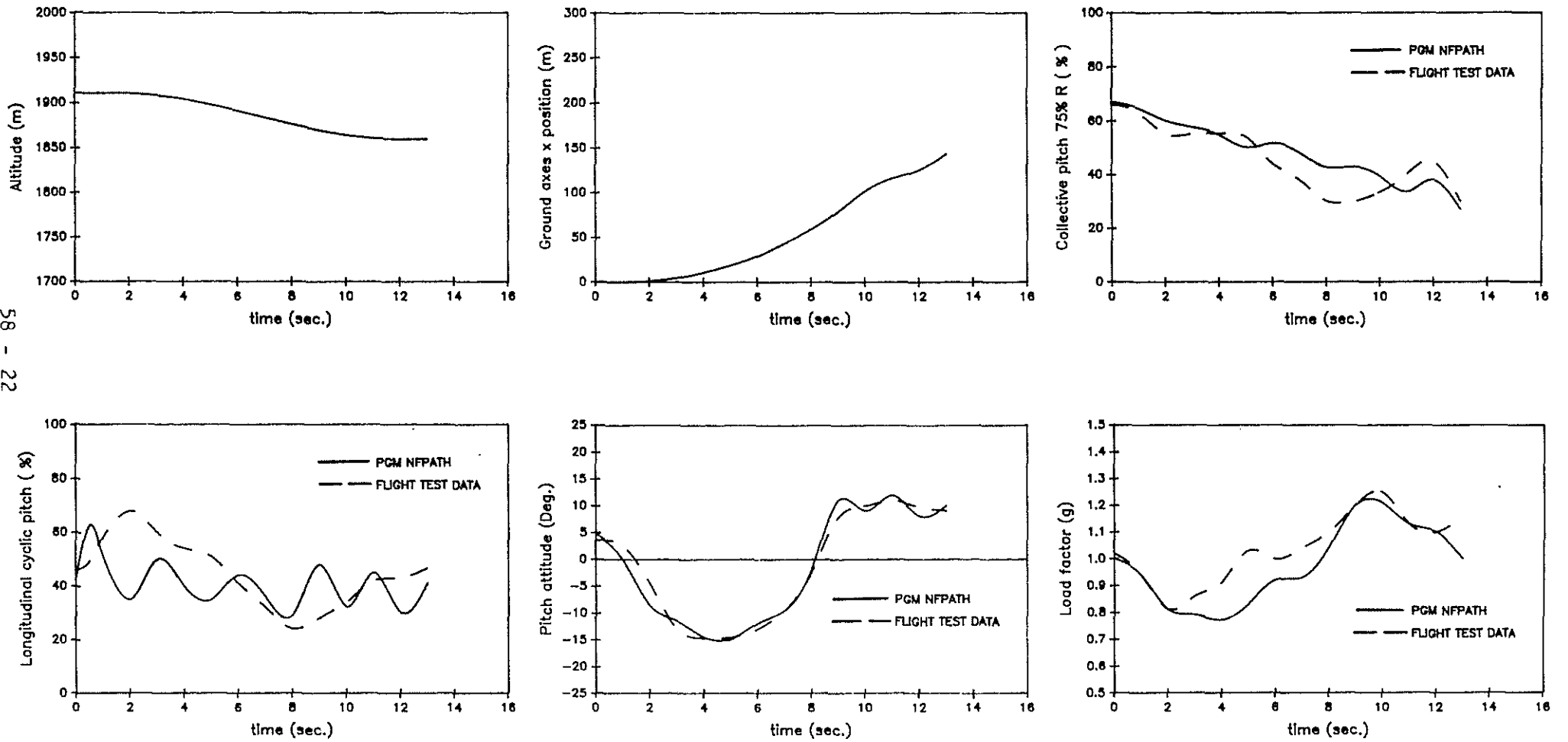


FIGURE 7 - CASE B

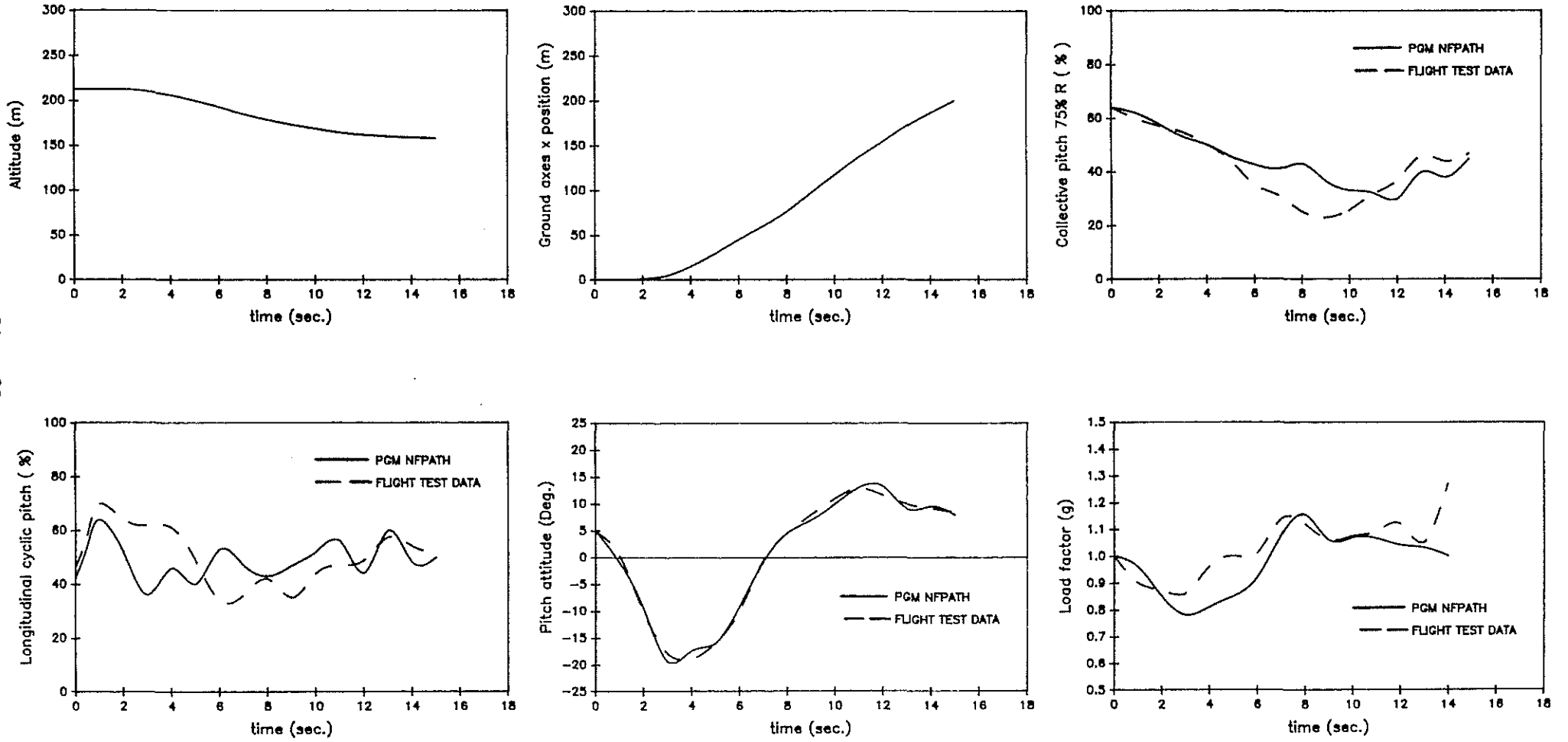


FIGURE 8 - CASE C

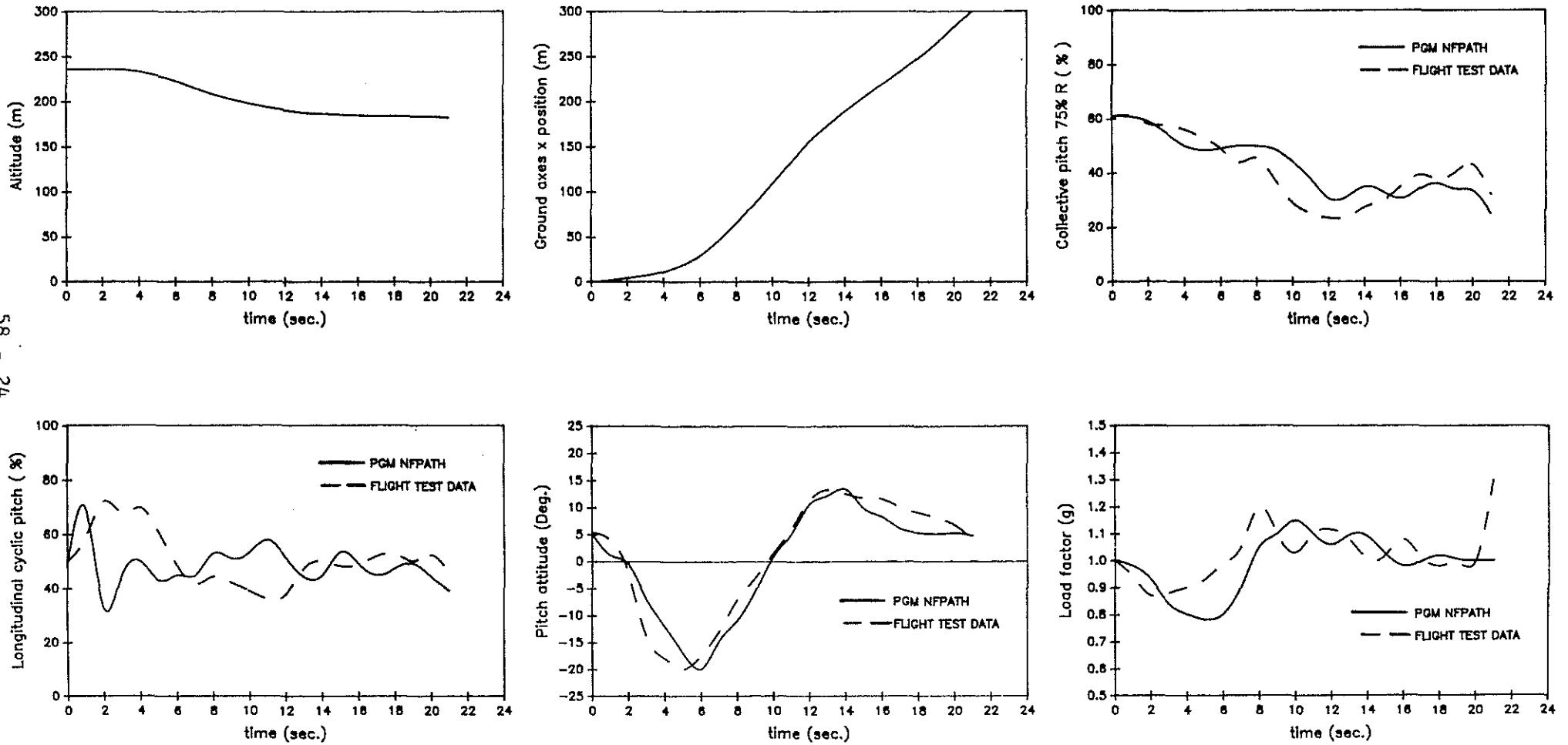


FIGURE 9 - CASE D

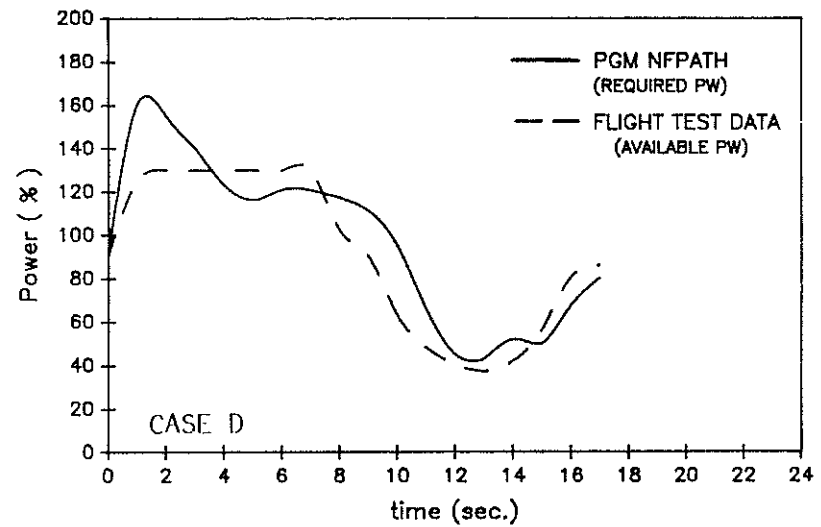
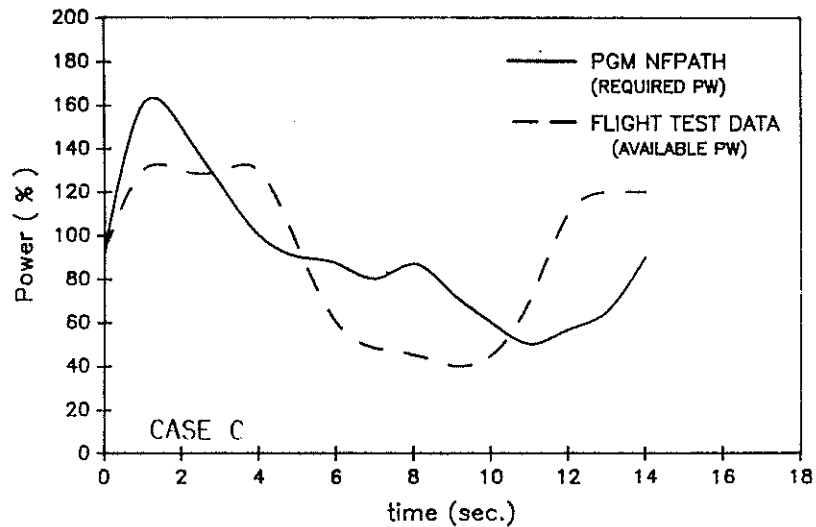
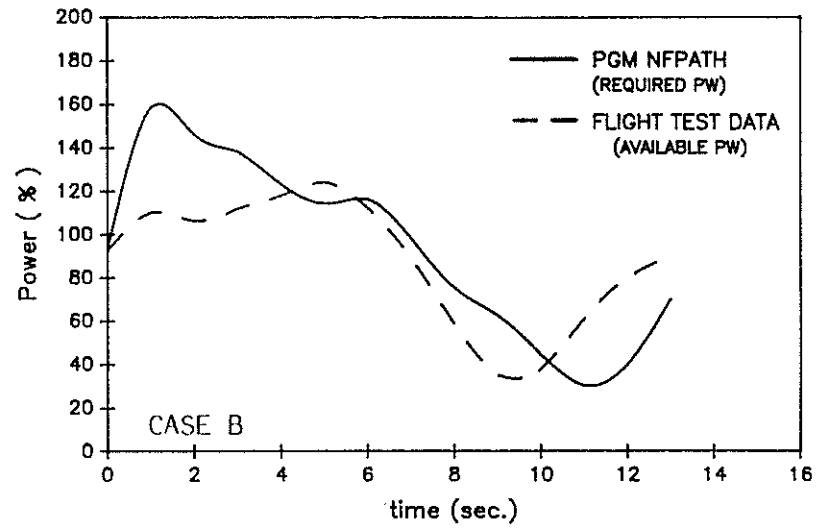
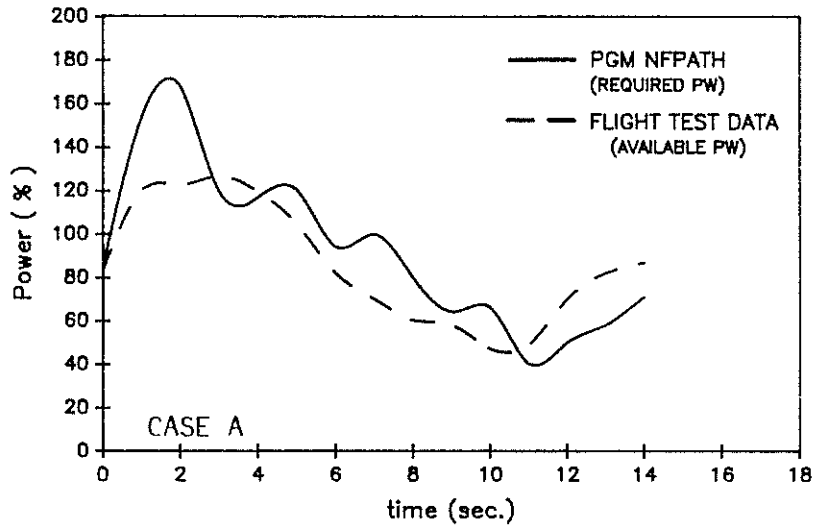


FIGURE 10

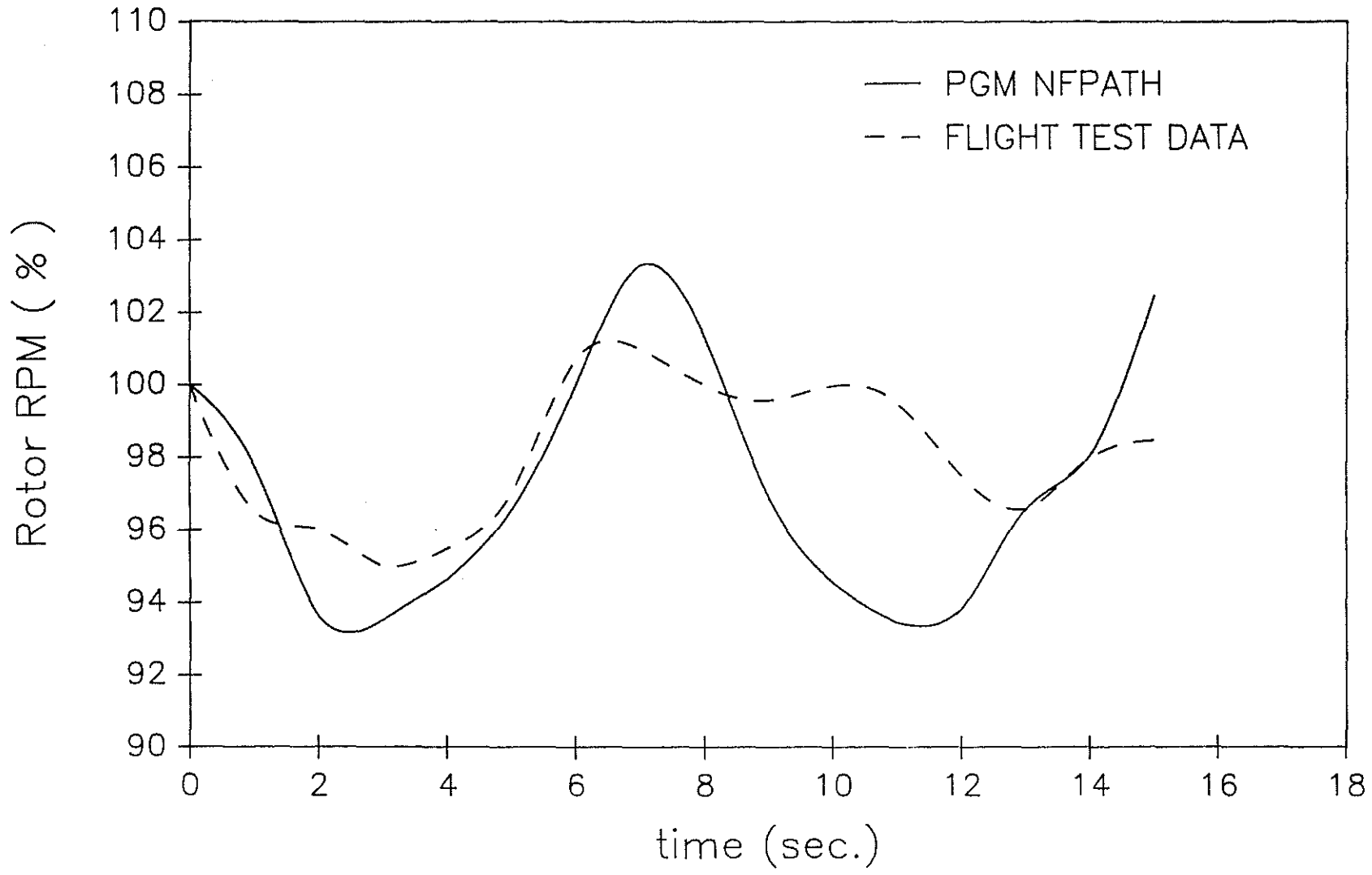


FIGURE 11

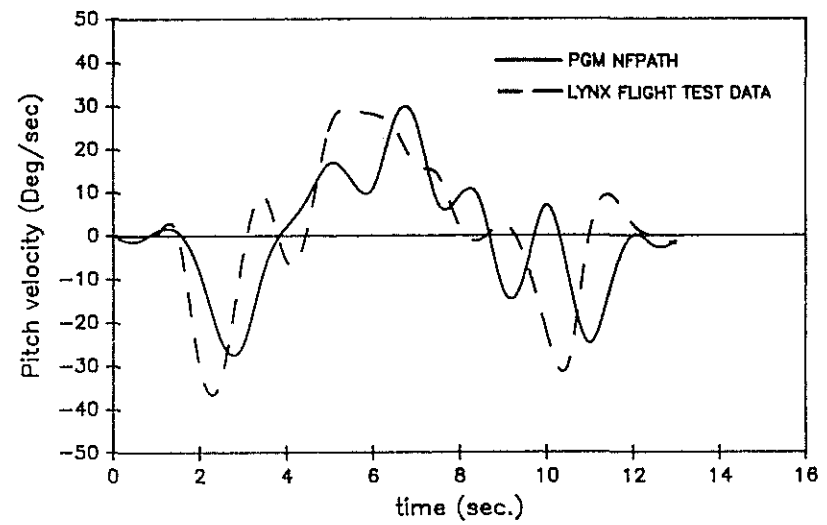
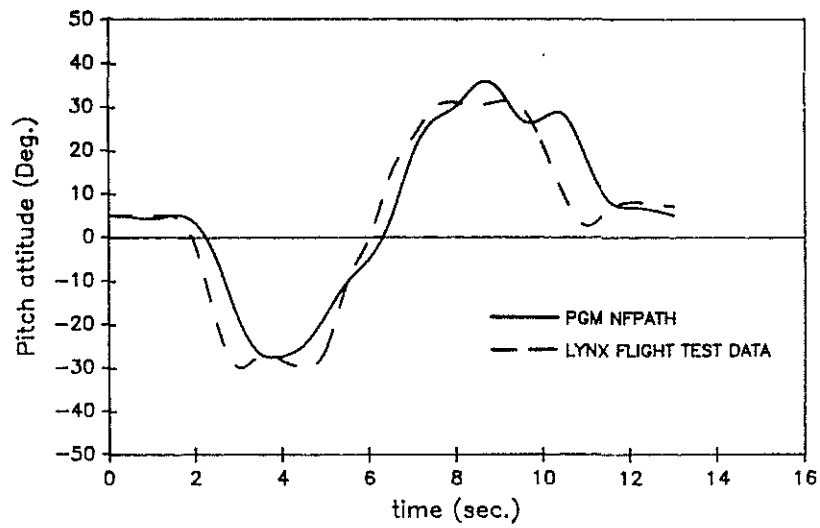
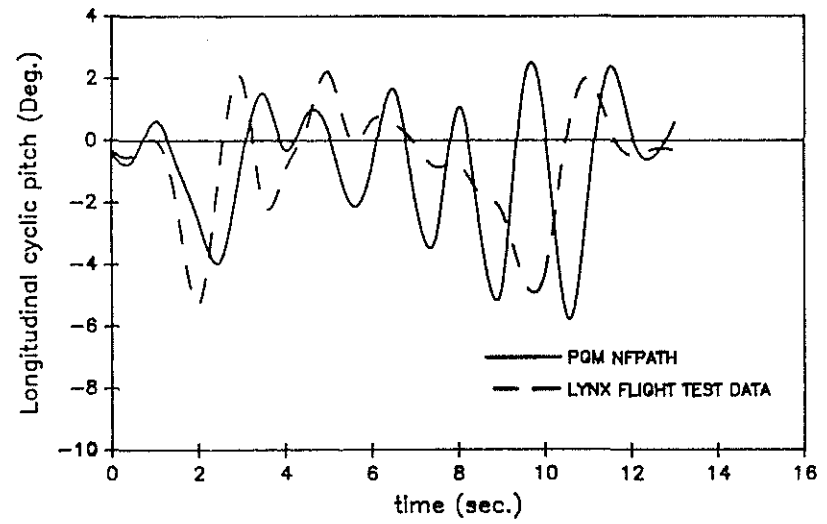
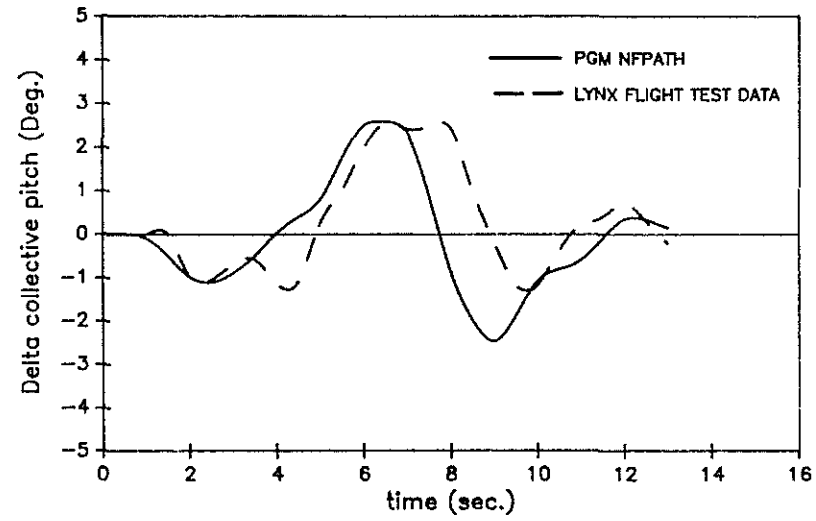


FIGURE 12

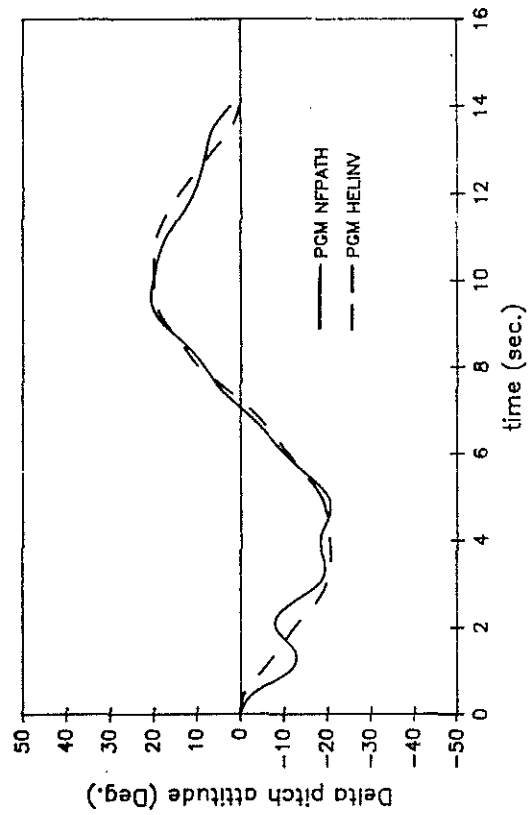
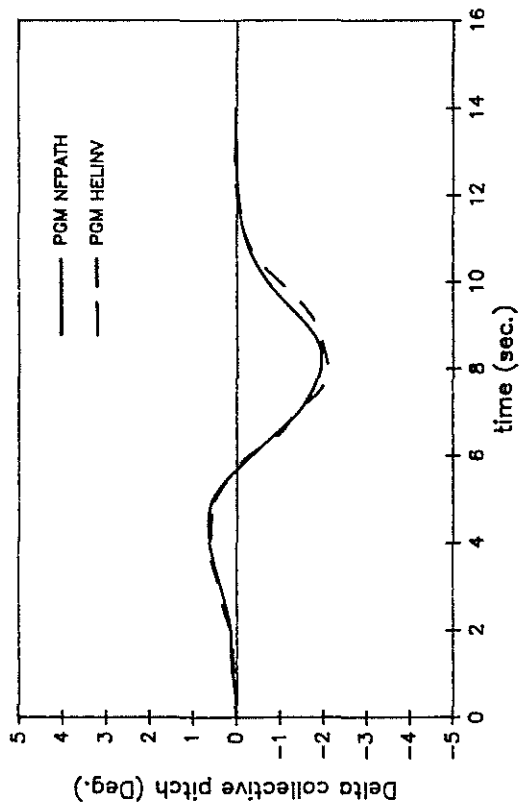
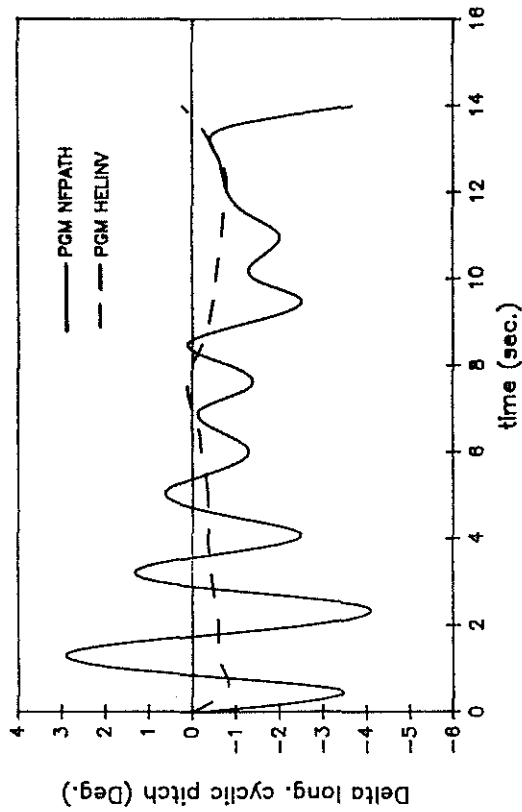


FIGURE 13