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A NEW APPROACH TO LOW SPEED — LOW HEIGHT TESTING AND FLIGHT MANUAL DATA PRESENTATION

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ABSTRACT

Engine out landing performance is one of the most demanding phases of the entire development testing of a new helicopter. Moreover the presently required H-V diagram provides the helicopter pilot with information which is often ambiguous and of doubtful utility.

This paper discusses how to minimize flight testing hazards and costs and how to improve the presentation of the information in the flight manual. The takeoff and landing path concept is treated as minimum risk zone, complemented by a high risk zone defined more realistically than in the past. For multi-engine helicopters a fly-away height is introduced as upper boundary of the high risk zone. The use of a fly-away mathematical simulation model as an aid to test planning and presentation of information to operators is then discussed.

Calculated data is compared with flight test data for the A109A twin engine helicopter.

1. INTRODUCTION

When during the certification of a new prototype the testing of the engine out autorotation landing performance is forthcoming, quite a number of considerations usually occur to the men involved in this job.

The attention of the flight personnel is obviously concentrated on the risks connected with these tests. As everybody knows, an unusually large number of helicopters have been damaged and crews injured.

On the other hand, those responsible for the planning and coordination of such tests do wonder how to comply with the current FAA regulations without jeopardizing test safety. For istance, where to find a sufficiently large and suitable airfield at the maximum altitude where the helicopter is to be certificated. Again, one wonders also if it is possible to elicit from these tests, data — operational limits in the case of transport helicopters — which is not useless or even misleading for further relay to the operator.

To understand the reasons underlying these considerations a typical H-V diagram in accordance with the regulations, as reported in the flight manual, should be examined, giving some consideration to the way it is determined.

2. DETERMINATION OF THE CURRENTLY REQUIRED H-V DIAGRAM

A typical H-V diagram is shown in Fig. 1. The right-hand side of the diagram is the high speed portion, the much more significant left-hand side is the low speed portion. The prohibited sections are separated by the take off corridor. The more outstanding points of the envelope are the low and high hover points and the so-called curve knee, defined as the highest speed point on the low speed portion.

Let's examine, for instance, how the high hover point is determined. The pilot starts the experiment by simulating an engine failure when hovering at fully safe height above the ground. After familiarizing with the correct entry into autorotation, he then practices a descent in stabilized autorotation at best speed and finally becomes confident with the final transition phase (flare maneuver) permitting landing with small or zero forward and vertical velocities.

The pilot goes once more through this procedure introducing the one second delay time before collective pitch reduction as requested by regulations for the points above the knee. A number of additional tests are then performed at a steadily lower initial height until, in the pilot's opinion, the point has been reached below which the average pilot might not be able to perform a safe landing.

The other salient points of the curve are obtained in the same way until a boundary curve is gradually defined. In other words, the envelope of the limit landing points is displayed as a boundary between a safe flight zone and avoid zones.

3. CRITICAL REMARKS ON THE CURRENT H-V DIAGRAM

3.1 Effects on the operator

According to this type of presentation, one would expect that any landing performed as a result of an actual engine failure occurred in a height and velocity condition belonging to a zone declared as safe will meet with successful results.

As we all know, this is unfortunately not always true, the reasons being essentially connected with the fact that real conditions are sometimes far different from those simulated during testing.

As we have seen, the test pilot gradually determines the H-V envelope after making several autorotational landings. Thus, he is a trained as well as highly experienced pilot. Moreover, the tests he performs are conducted under controlled conditions, i.e. zero wind, a safe and sufficiently long runway, fire suppression and rescue facilities, etc. In addition, he might have given too much credit to the average pilot's skills. Further, the delay time as requested by regulations prior to control actuation — at least one second above the knee, no delay below the knee — is questionable. As a test pilot has put it: "It's quite possible that a pilot is more relaxed during a normal take off rather than when hovering out of ground effect".

In general the risk level connected with the avoid zone is fairly indefinite since no manufacturer will ever go as far as clearly defining the safety margin — in terms of height or velocity — separating the experimented envelope from that subsequently published in the flight manual.

3.2 Effects on the manufacturer

As previously pointed out, in the case of transport helicopters the maximum altitude at which the H-V diagram is determined, with an allowable maximum extrapolation of 2000 ft, represents an operating limitation. In any event, it may not be less than 7000 ft.

Hence, the problem is to find a wide level area of firm and smooth surface at that altitude, accessible to emergency vehicles and not windy. Since an area having all these characteristics is very difficult to find, the alternative is to operate over not fully adequate areas thus jeopardizing the safety level for both the machine and aircrew.

Among other things, the data obtained at these altitudes would be meaningful only for those rare operational areas having characteristics similar to the testing ones. Much too often, however, instead of a runway or a decent grass strip, pilots find in the best cases steep slopes or rough ground strewn with stones.

3.3 What operators should know

When performing special operations, for instance cargo sling or hoist operations, pilots are forced to fly in high risk conditions. In these cases, and even more under normal operational conditions, they need not know exactly the H-V envelope as defined so far.

Furthermore when flying at a very low speed near the ground, a pilot is often unable to know exactly his actual speed and height above the ground, as the on-board airspeed indicator and altimeter are often inaccurate in these conditions.

The information the pilot actually wants to know is:

(a) take off and landing profiles;

(b) high hover height at which the pilot can perform a landing or fly away after engine failure in the case of multi-engine helicopters (or at which a safe autorotational landing can be performed in the event of single-engine helicopters);

(c) low hover height at which the pilot can land with a vertical speed compatible with the landing gear structural limits.

Besides this essential information, it may be useful to provide the pilot with some general information on the high risk zones.

4. PROPOSED PRESENTATION OF THE H-V DIAGRAM

On the above depicted grounds, we believe that it would be more profitable for both the operators and the manufacturers to reverse the concept of data presentation in the flight manual. In other words, instead of defining the avoid zones it is better to determine and present the take off profile as a primary information.

Moreover, both from the viewpoint of flight test safety and that of the operational significance it is advisable to modify the concept associated with the high hover point, namely, to consider it as safe fly-away height (for multi-engine helicopters only).

Let's examine on Fig. 2 the proposal for a possible presentation of the H-V diagram in the case, increasingly frequent nowadays, of a Category A transport helicopter. Such a diagram shall be applicable for the allowable take off and landing gross weight versus altitude and air temperature (WAT diagram). Besides the take off path, Fig. 2 shows a "high risk" zone comprised, as far as velocity goes, between zero velocity and a given velocity (V_0) selected by the manufacturer with the following criteria:

(a) It should be positively determinable by the pilot by means of the standard airspeed indicator;

(b) it should be at least 5 kts below the prescribed helicopter velocity (V_1) at the Critical Decision Point (CDP). This is to allow for a given margin of maneuver error.

Let's now examine the ground heights defining the shaded area. The lower height (H_1) should be higher by 3 to 5 ft than the height of the starting hovering point of the take off path. Similarly, at V_0 velocity, the height (H_2) should be from 5 to 10 ft more than that of the take off path in that point. The highest point (H_3) should be defined as the height from which, in case of an engine failure in hover, it is possible to initiate a fly-away maneuver bringing the helicopter to a height not lower than the CDP.

As far as the high speed portion of the diagram is concerned, we would propose, rather than accurately define a possible high risk zone, replace it with a note cautioning for flight at high speed and altitude below the CDP.

If the manufacturer deems it convenient, another WAT diagram covering the weights at various altitudes and temperatures where no high risk zones exist may be presented. Obviously, such a diagram would be correlated to the hovering performance, one engine inoperative.

The take off path referred to weight, altitude and temperature of the WAT diagram should be defined also in the case of multi-engine helicopters not meeting Cat. A take off requirements and single-engine helicopters. Obviously, in this case the WAT curves will be dictated by the single engine climb performance at the best rate of climb rather than at the take off safety speed.

Since now there is not CDP height, the note covering the high velocity flight ought to command caution when flying below 100 ft.

An obvious difference from the multi-engine case concerns the higher height H_3. Now the height H_3 is defined as that from which an emergency landing can be safely made in the event of a full power loss in hovering.

5. EFFECTS ON MANUFACTURERS OF THE PROPOSED H-V DIAGRAM

To demonstrate the proposed H-V diagram, the following points should be experimented by manufacturers:

(a) Low hover point H_1.
Its determination does not pose any particular problem as regards either safety or the location of the necessary area at altitude.

(b) Point at height H_2 and speed V_0.
This is perhaps the most critical point to be demonstrated. The relative test should be performed with take off power and with a normal pilot's reaction time. Therefore, rather than determining a marginal point, the test is to check that which was preselected with a given margin.

(c) High hover point H_3.

In case of multi-engine helicopters the demostration can be made, simulating an engine failure in hovering with one second delay time, quite safely at any altitude as no landing is required. In fact, the parameter to be determined is the height loss between the initial and the lowest point of the flying path. Consequently the difficulty of finding smooth and sufficiently long strips at the altitudes required for the helicopter certification is removed. Single engine helicopters still have the problem of landing, but nevertheless the aim, rather than looking for a boundary point, is to determine a height from which landing can be made with a minimum of vertical and forward speed. Thus experimentation risks resulting from the surface condition at high altitude are limited to a minimum extent.

To summarize, the experimental concept outlined above minimizes risks, allowing at the same time for test pilots to avoid unusual and sometimes aerobatic maneuvers.

6. EFFECTS ON OPERATORS OF THE PROPOSED H-V DIAGRAMS

The above proposed presentation of the H-V diagram has the merit of giving the customer information on how to operate, rather than merely indicating the areas to be avoided. Moreover, the information on the high risk zones has the advantage of being affected to the lowest possible extent by the test pilot's skill and by the test controlled conditions.

In conclusion, according to this philosophy the operator is provided with more accurate and less ambiguous information than in the past.

7. PROPOSAL AIMED AT FURTHER REDUCING THE EXPERIMENTATION COSTS AND RISKS

By means of a fly-away mathematical simulation model, validated by experimental tests, as explained in the following sections, the costs and risks can be further reduced.

As previously pointed out, the H-V diagram must be applicable for those weights, altitudes and temperatures which are defined in the WAT diagram. Hence, at equal temperature conditions (e.g. ISA condition) the H-V diagram could be experimentally demonstrated solely under the worst weight/temperature combination of the WAT diagram.

The selection of the worst combination between that prevailing at low altitude (and high weight) and that at high altitude (and low weight) can be made with the above mentioned simulation model.

Another utilization of this mathematical tool is to improve the presentation of the information to the operator permitting the inclusion of the effects of air temperatures other than standard.

8. MATHEMATICAL MODEL AND COMPUTER SIMULATION

8.1 Description of the model

The mathematical model used in maneuvering flight simulation is based on power, work and energy relations, force balance and momentum theory. This approach circumvents the complex analytical method of rotor aerodynamics by introducing semi-empirical equations. Using data from test flights, by statistical manipulation, we obtained the coefficients in the mathematical relationships. In particular we determined by this method the longitudinal flight characteristics of the helicopter, other than rotor power terms. The flow chart of the computer program is shown in Fig. 3. The language used is CSMP III (Continuous System Modeling Program) by IBM.

The model adopted allows a complete simulation of the maneuver starting from a stationary flight initial condition. The input independent variables are the collective and the longitudinal cyclic controls and the power available. Flight dynamics calculations are restricted to the vertical reference plane and the helicopter roll degree of freedom is neglected (Fig. 4). The output dependent variables are flight trajectory, helicopter speed along the trajectory, and rotor RPM. Some intermediate variables are calculated to describe the main and tail rotor aerodynamics, required powers, and helicopter flight dynamics on the longitudinal plane. The mathematical model first and second order differential equations are numerically integrated through the Runge-Kutta method with fixed 5 msec steps. We will skip the basic rotor aerodynamics equations and required power formulas since they have been widely described and commented on in recent literature. However we will highlight some particular algorithms which have been inserted into the model as a complement taking care that they wouldn't reduce the numerical and analytical simplicity of the model itself.

8.2 Helicopter dynamics in pitch

The fly-away maneuver is characterized by fast and large variations in trajectory slope. This, in the initial phase of the maneuver immediately following the power loss, is due to the reduction of thrust; afterwards the pilot himself, acting on the longitudinal cyclic control, will impose a diving attitude on the helicopter in order to accelerate at the expense of a height loss. In the final phase of the maneuver the helicopter is brought to a level flight attitude consistent with power available. Flight test data suggest a dynamic interdependence between trajectory slope and pitch attitude. This is well described by the following law:

$$\frac{[\Theta]}{[\gamma]} = \frac{(\gamma + \beta\tau)s + \beta}{\tau s^2 + (1 + \beta\tau)s + \beta}$$

where:

$[\Theta]$:	Laplace transform of pitch attitude
$[\psi]$:	Laplace transform of trajectory slope
s :	Laplace operator
β, γ, τ :	empirical constants

The difference between Θ and γ can't be neglected because it considerably affects disk angle of attack and thus rotor aerodynamics.

8.3 Available power

Since we wish to model not only the true in flight emergency conditions, where power loss is pratically instantaneous, but also flight tests where the above occurrence is simulated by manually reducing power, the failed engine transient contribution to available power cannot be neglected. The time decay law of torque is generally of the exponential type with a time constant of the order of one second.

Fuel control system dynamics is to be considered an important element of the overall fly-away dynamics. With rotor RPM variations limited to a few percent, a linearized model for FCS of the remaining engine can be adopted, which will not unduly burden the computing procedure.

8.4 Numerical aspects

The most obvious difficulty in the computing procedure lies with the "simultaneous" solution of the rotor aerodynamic equations. The basic relationships are shown in Step 3 of the program flow chart (Fig. 3). This set of equations cannot be separated and solved in sequence. The CSMP language makes it possible to break up the mathematical loop without excessive computing time usage.

9. TEST AND CALCULATED DATA COMPARISON

A flight program was run with the aim of providing data to validate the computer simulation and to extend the method for predicting the height loss consequent to a fly-away maneuver from hovering.

The tests were carried out with the twin engine A109A helicopter at various gross weights and altitudes. The cut off engine power rate of decay and pilot's actuation of longitudinal cyclic and collective pitch were entered into the computer simulation program. Figures 5 and 6 show two examples of comparison between calculated data — solid symbols — and the time-histories of a few flight recorded parameters. Both at high weight/low altitude (Fig. 5) and at low weight/high altitude (Fig. 6) a satisfactory agreement was reached, with the exception of pitch attitude and rotor RPM for the high altitude case, where a slight discrepancy was recorded. From the test flights typical collective pitch maneuvers were determined as a function of power required in hover, of minimum power in forward flight and of helicopter limitations (minimum rotor RPM and maximum one engine operative power). Flight data were then compared with data calculated using standard collective pitch maneuver and assuming no longitudinal cyclic control actuation. Even in these cases a good correlation was observed in particular for the height loss parameter, thus validating the use of a standard collective pitch maneuver.

For the purpose of predicting the fly-away height loss at various weights, altitudes and air temperatures (WAT diagram) the following procedure may be employed:

(a) Perform one engine failure preliminary flight tests at various weights and altitudes.

(b) Define standard collective pitch maneuver as a function of the above stated required powers and optimized through successive correlations between calculated and flight data.

(c) Compute height losses at the various combinations of weights, altitudes and air temperatures of the WAT curves, using the standardized collective pitch maneuver.

10. CONCLUSIONS

Let us review the main points we have covered, the first of which to our knowledge is shared by other people involved in the rotorcraft industry:

(a) Replacement of the present H-V diagram, focused on the avoid zones, with the safe take off and landing path and the high risk zones, conservatively defined.

(b) Introduction of the fly-away height instead of landing height for multi-engine helicopters.

(c) Certification flight tests only for the worst combination of weight and altitude of the WAT diagram as defined by a computer simulation model program, validated by preliminary flight tests.

It is our opinion that with these concepts the certification H-V tests of a new helicopter can be made easier and safer and, most important of all, the manufacturer can provide the operator with meaningful and not misleading information.

FIGURE 1. TYPICAL HEIGHT—VELOCITY DIAGRAM

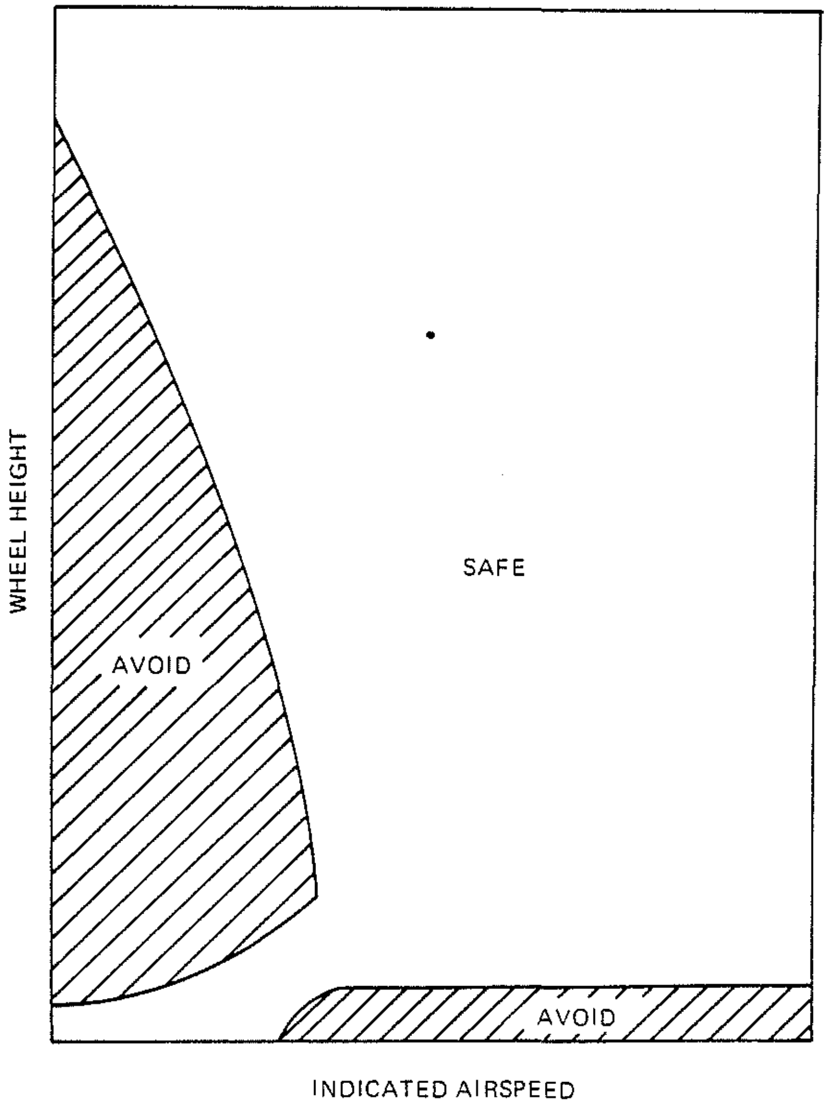


FIGURE 2. PROPOSED HEIGHT–VELOCITY DIAGRAM FOR MULTI–ENGINE CAT. A HELICOPTER.

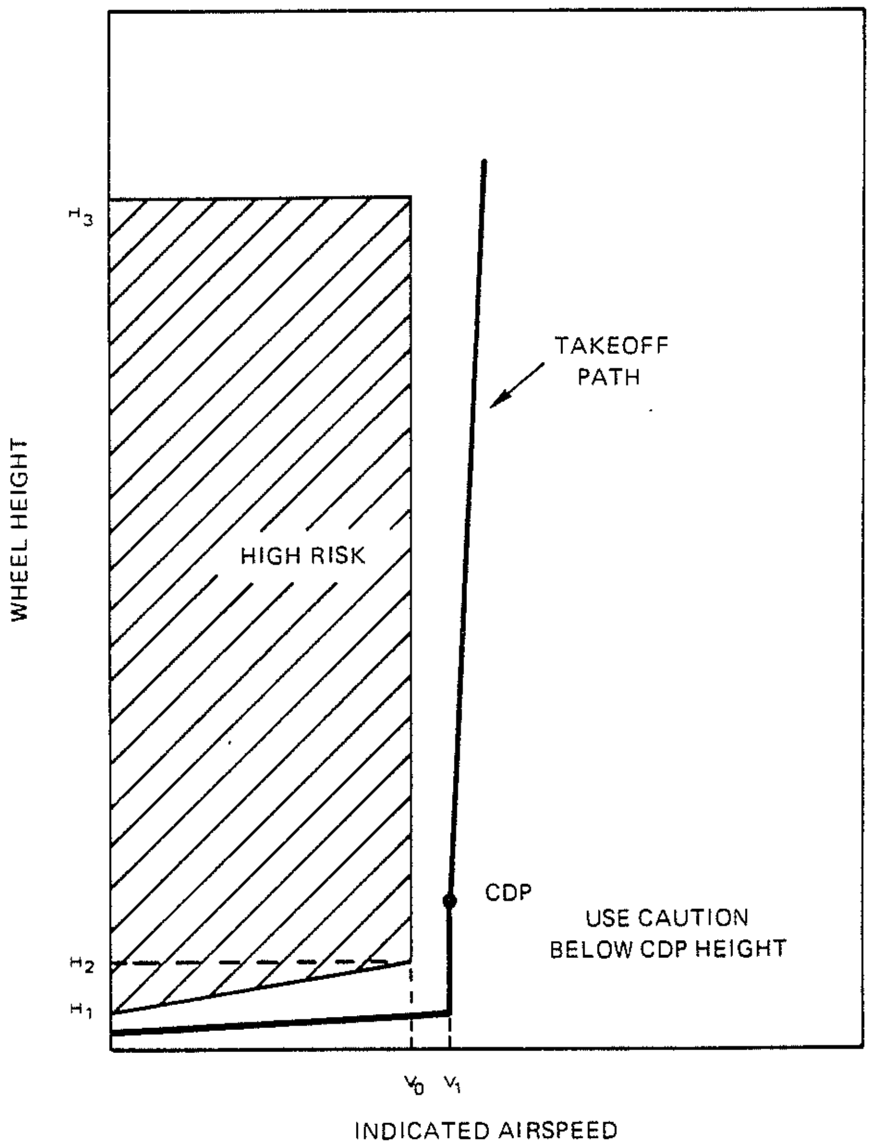


FIGURE 3. COMPUTER PROGRAM FLOW CHART.

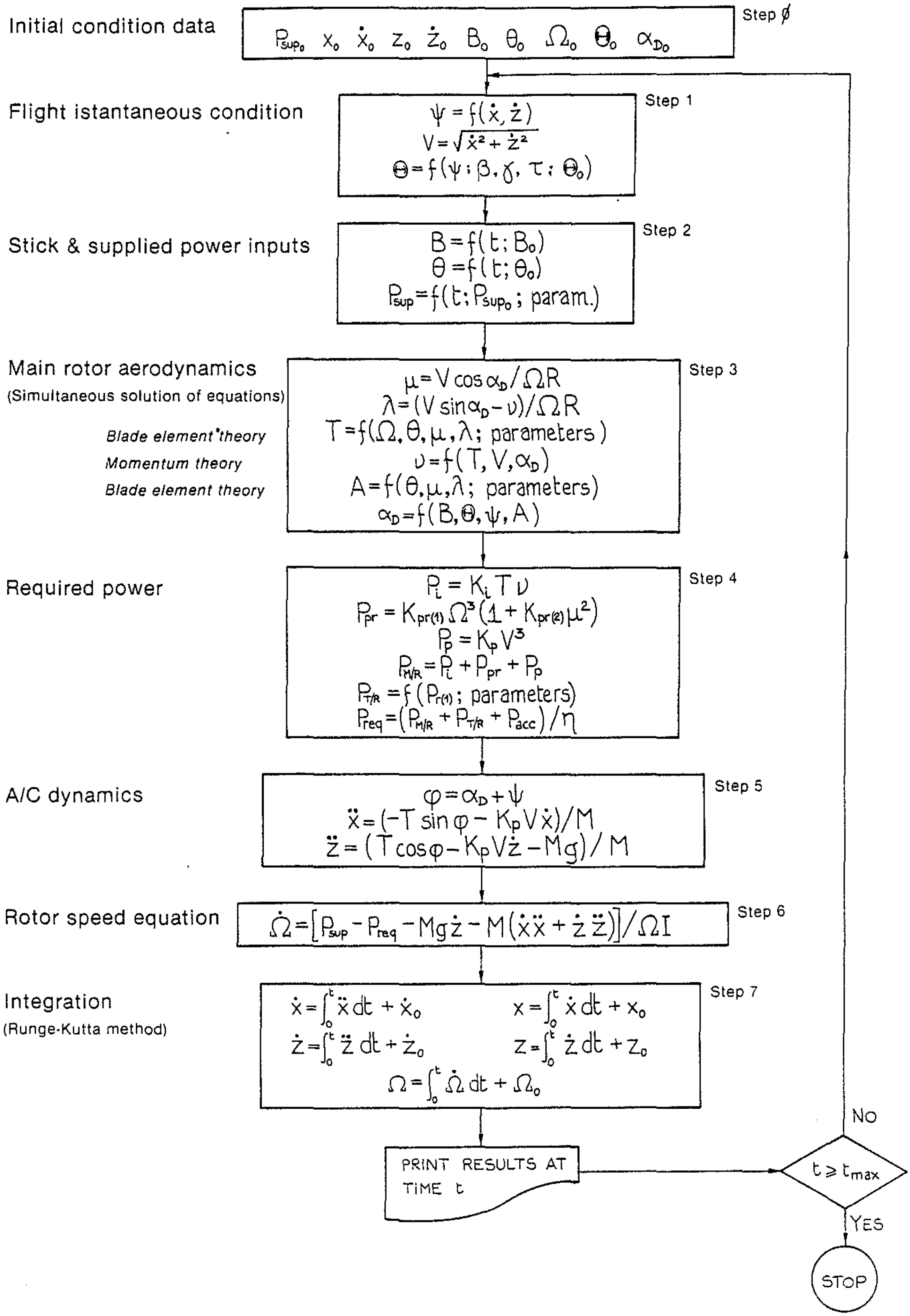
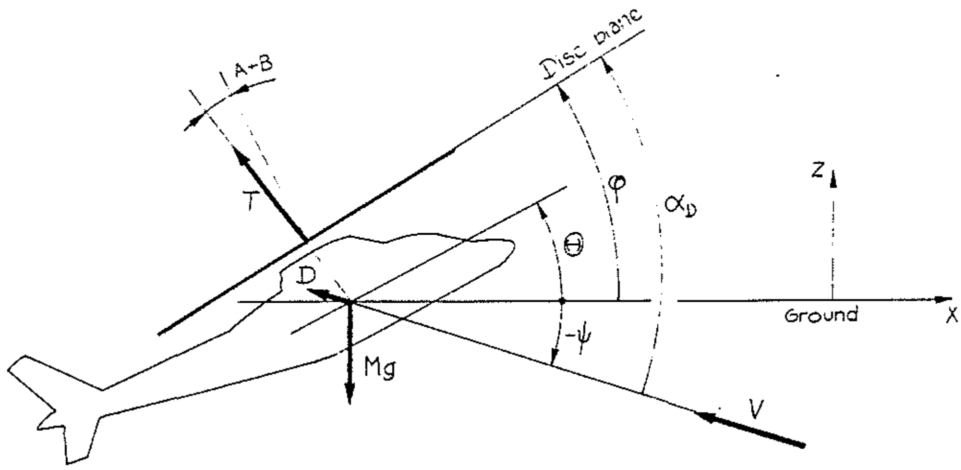


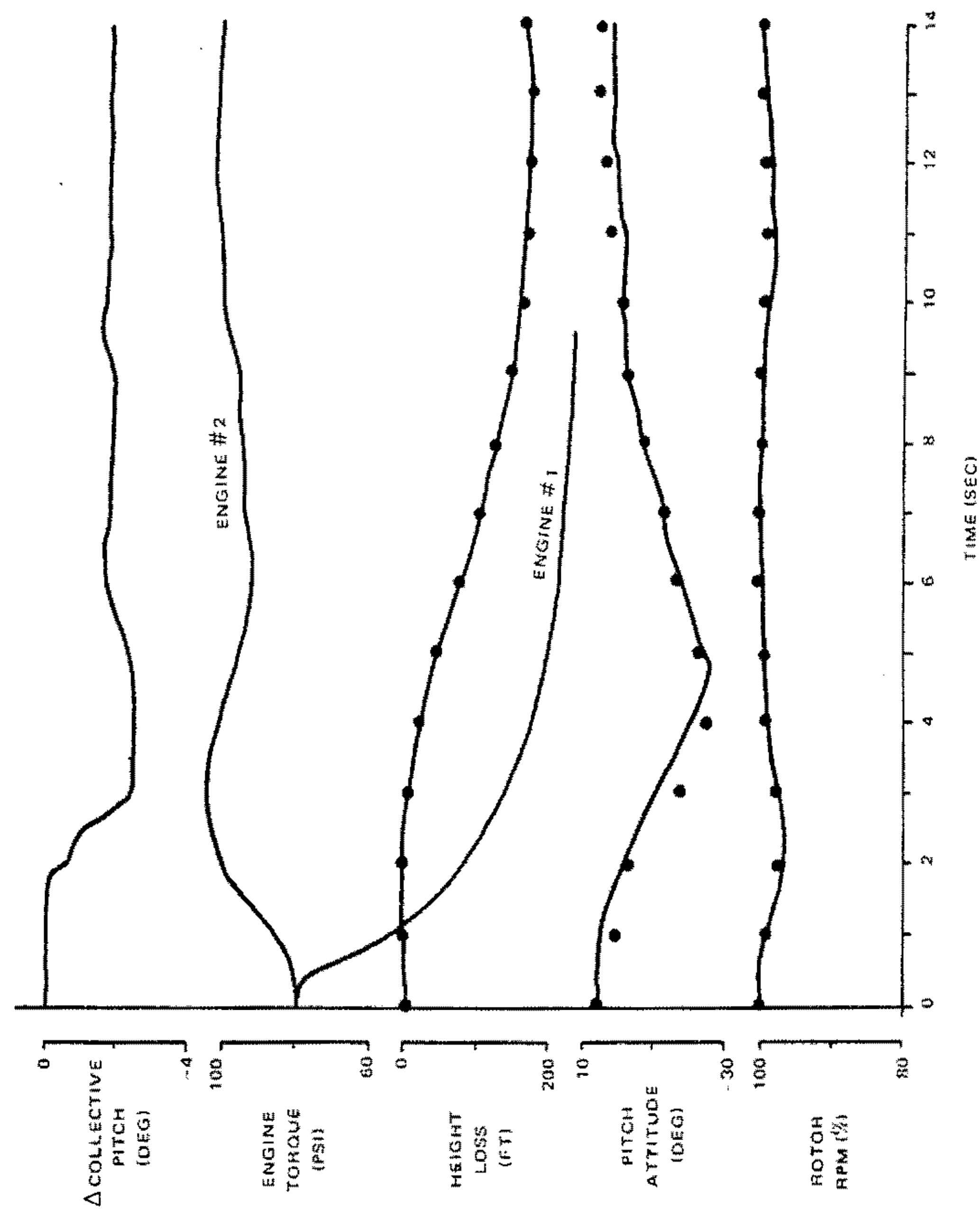
FIGURE 4.



NOTATION

A	Tilt back angle
B	Long. cyclic pitch input
D	Drag force
I	Rotational system inertia
g	Gravitational acceleration
$K_{...}$	Empirical factors
M	Mass of helicopter
P_{acc}	Accessory power
P_i	Main rotor induced power
$P_{M/R}$	M/R total req. power
P_p	Parasite power
P_{pr}	M/R profile power
P_{req}	Total required power
$P_{T/R}$	T/R total req. power
P_{sup}	Total available power
R	Main rotor radius
T	Main rotor thrust
t	Elapsed time in simulation
t_{MAX}	Final time in simulation
V	Helicopter velocity
α_D	Disc angle of attack
β, γ, τ	Parameters of pitch attitude equation
η	Efficiency factor
λ	Inflow ratio
μ	Advance ratio
ν	Induced velocity
Θ	Pitch attitude
θ	Collective pitch input
φ	Disc angle in ground reference system
ψ	Flight path angle
Ω	Main rotor rotational speed
X, Z	Horizontal and vertical coordinates in ground reference system

FIGURE 5. TEST AND CALCULATED DATA COMPARISON
A109A – 2600 KG/200 FT



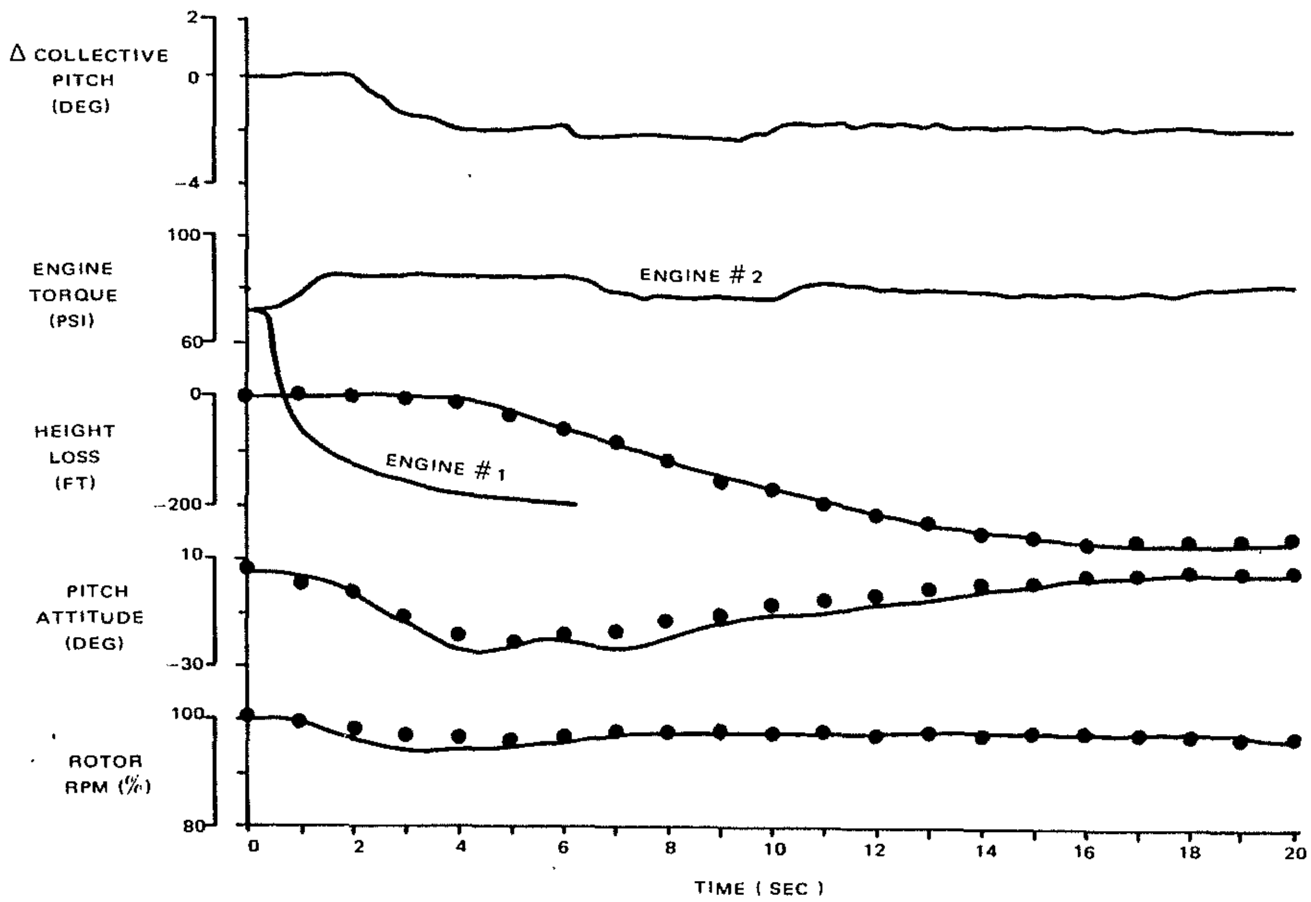


FIGURE 6. TEST AND CALCULATED DATA COMPARISON
A109A – 2180 KG/8000 FT