INTEGRATION OF FLIGHT CONTROL AND CARRIER LANDING AID SYSTEM

T. Le Moing
Office National d'Etudes et de Recherches Aérospatiales
92320 Chatillon France

Abstract

Operational avaibility of an aircraft carrier depends largely on the ability of shipborne aircraft and equipments to operate in a large range of weather and sea conditions.

Some shipborne equipments are currently being developed for the French Future Carrier in order to extend its operational limits for aircraft recovery, among them a deck motion tranquillization system, a deck motion predictor system and an all-weather localization system.

The impact of the improvements due to these systems on the approach procedure and flight control for future shipborne aircraft is presented here. A new landing procedure incorporating a prediction of the carrier motion is proposed.

A numerical simulation code has been developed in order to evaluate the improvement of deck landing performances particularly with respect to the accuracy of the prediction of the carrier motion.

1. Introduction

Landing an aircraft on the deck of a carrier is a demanding task. The aircraft must be precisely controlled to a relatively small area of the carrier deck despite not only the wind disturbances caused by the ship airwake, but also the large motion of the touchdown point.

A certain number of guidance informations are generated on board the carrier and provided to the pilot. Concerning the final phase of the approach, these informations are at present mainly provided by the Fresnel Lens Optical Landing System (FLOLS) which requires visual acquisition by the pilot. The pilot is also assisted by the Landing Signal Officer (LSO) who can dictate if necessary control orders from the deck of the carrier.

The present landing procedures are well proven although some deficiencies still remain, especially when the carrier operates under adverse weather and sea conditions. Some equipments are currently being developed for the French Futur Nuclear Carrier to extend the operational limits for aircraft recovery: a deck motion tranquillization system, a deck motion prediction system and an all-weather aircraft localization system. The impact on deck landing procedures of future shipborne aircraft is presented here. As carrier motion can be predicted, improved terminal guidance strategies can be defined. Automatic Carrier Landing Systems (ACLS) can also be developed using all-weather localization systems which provide an accurate determination of the aircraft position relative to the carrier. Fly-by-wire Flight Control Systems (FCS) of future carrier-based fighter aircraft will make possible the implementation of advanced task-tailored control modes which are optimized specifically for the landing phase.

This paper is divided into three parts :

- after a brief review of the state-of-the-art in France of landing aid systems, a preliminary analysis of the constraints related to the aircraft flight path during the terminal phase, leading to the proposition of a new landing procedure which allows recovery in adverse sea conditions,
- a description of a simulation code developed in order to evaluate the new landing procedure,
- presentation and discussion of statistic results on landing performances.

2. Brief review of the state-of-the-art of french systems

An investigation on the landing aid systems which are currently operational or under development on French carriers had been carried out at ONERA [1].

The present landing procedure consists of a guidance strategy in which the aircraft vertical speed and angle of attack (AOA) are kept constant, resulting in a fixed glide slope. Therefore the inclination of the FLOLS system have to be adjusted with respect to the wind magnitude and the carrier speed (Figure 1).

Piloting techniques to keep the aircraft on the ideal flight path require a coordinated action on the thrust and pitch commands which are essentially performed from visual references or control orders dictated by the LSO.

In adverse sea conditions, this procedure can bring the aircraft to cross the deck edge with very low height margins.

The use of a motion prediction with the implementation of an automatic landing mode would extend the operational limits in aircraft recovery.

3. Analysis of a new deck landing procedure

We consider here after only the final phase of the approach (last 10-15 seconds before touchdown). The specific constraints related to the aircraft trajectory are first expressed in a mathematical form. When the deck motion reaches a certain magnitude, the present landing procedure (fixed glige slope) leads to a violation of the above constraints. A new landing procedure making use of the predicted motion of the ship is then proposed.

3.1 Specific deck landing constraints

These constraints can be summarized as follows : the aircraft must cross the stern at a minimum safety height, touchdown the deck at a defined point with a sink rate compatible with the structure limit of the main landing gear, and with a longitudinal speed compatible with the structure limit of the hook and with the capability of the arresting wires to dissipate the accumulated energy.

The hook-to-ramp clearance constraint can be espressed by the following relation (Figure 2) :

$$\gamma r < \gamma clear = -(H_{min} + H_A - H_B) \ / \ L_{AB}$$

where

γ_r : relative flight path angle
L_{AB} : distance from ramp to ideal touchdown point
H_{min} : minimum hook-to-ramp clearance
H_A : stern height at stern crossing instant
H_B : arresting wire height at touchdown instant

The touchdown sink rate constraint can be expressed as follows (Figure 3) :

$$\gamma_r > \gamma_{impact} = \theta_b - (V_{zmax} + V_{zB}) \ / \ (V - WOD)$$

where

θ_b : carrier pitch angle
V_{zmax}: maximum relative vertical speed allowable
V_{zB} : vertical speed of arresting wire at touchdown instant
V : aircraft airspeed
WOD : wind-over-deck

The constraints relative to the arresting wire capability and to the stall limitation are :

$$V_{min} < V < V_{max}$$

3.2 New deck landing procedure

To satisfy the constraints of ramp clearance and touchdown sink rate, the aircraft flight path has theorically to be adjusted and updated with respect to the predicted motion of the carrier at touchdown instant. We define the new landing procedure as follows:

- at the beginning of the approach phase, the present procedure is remained unchanged, i.e. fixed glige slope and fixed airspeed, the glide slope being determined for a given WOD and for a zero mean position of the deck.
- as soon as position and speed of the deck can be predicted with enough accuracy, the glide slope and the aircraft airspeed are then adjusted in order to satisfy the four following constraints:
  - i) the aircraft must cross the ramp above a minimum safety height,
  - ii) the vertical speed at touchdown must be lower than a maximum value compatible with the structure limit of the landing gear,
  - iii) touchdown must occur at the ideal touchdown point,
  - iv) the longitudinal speed and the AOA are limited.

As the aircraft approaches the carrier, the guidance law is continously updated with respect to the improvement of the accuracy of the deck motion prediction (Figure 4).

Figure 5 presents in the plane (V,γ_r)(airspeed, relative flight path angle) the hook-to-ramp clearance constraint i) predicted at stern crossing instant, and the touchdown sink rate constraint ii) predicted at touchdown instant ; these instants depend on range and speed of the aircraft.

The optimal glide slope and optimal approach airspeed are defined by the point which is equidistant to the limits corresponding to the three constraints i), ii) and iv) defined above. This central point is choosen to assume a good robustness with respect to errors : error of prediction of the deck motion, error on the time-to-go, error on the aircraft time response to thrust command...

4. Description of the deck landing simulation code

The new landing procedure consists of a terminal guidance strategy in which the aircraft airspeed and flight path angle are updated with respect to the predicted motion of the carrier at the touchdown instant.

The procedure is applied when the time-to-go is within a time interval where the deck motion can be predicted with enough accuracy. As the shorter the time-to-go the better the prediction, we can be temped to choose this time interval as small as possible but we must make sure that the aircraft has enough manoeuvrability to perform the ultimate flight path corrections. A simulation software has been developed to evaluate this trade-off. The software consists of modules modeling carrier and aircraft dynamics, environment (sea level, ship airwake), landing aid systems (aircraft localization and deck motion prediction) and their interfaces with the aircraft FCS.

Figure 6 presents the block diagram of the simulation.

We can notice that for stability and safety reasons coupling landing aid systems with flight control system does not modify the latter.

Only longitudinal motions ares modeled in the simulation code.

We consider afterwards only the automatic piloting mode as it is suitable for computer simulation.

4.1 Pitch and heave motions model

The model consists of a weave filter and of ship filter.

The purpose of the wave filter, driven by a gaussien white noise, is to generate a stochastic sea surface level at some point along the ship length, with respect to a desired power spectral density. This is used as the disturbance driving for the ship motion filter. Models are written in state space form as follows :

- Wave $\dot{X}_h = A_h X_h + B_h \eta$ X_h : wave state
  $h = C_h X_h$ η : white noise
  h : sea surface height
- Ship $\dot{X}_s = A_s X_s + B_s h$ X_s : ship state
  $Y_s = C_s X_s$ Y_s : ship outputs (pitch and heave)

The wave model is deducted from a 6th-order rational approximation of a Pierson-Moskowitz power spectral density defined with two parameters : pulsation and height of wave.

The 8th-order system for the ship model has been identified with frontal waves and 20 kt of speed.

Prediction of deck motions.

Predictions techniques have been developed by several French organisms especially by ONERA/CERT and afterwards validated by sea tests.

Present studies allows to distinguish two classes of method :

- State-space model :
  The parameters of the model are first identified from simulations results or from sea measurements.

  Prediction is then obtain by integrating the equations of the noise free identified model, from an initial state estimated by a Kalman filter.

  At present, the model structure is assumed perfectly known.

  Effects of the most significant parameter, i.e. the wave pulsation, will be analysed.

- Autoregressive method (AR) :
  In the present study, two 50th-order systems have been retained for the pitch and heave prediction models.
  Coefficients of models have been identified once and for all with data stored during 1000s.

  Parametric analysis will be performed by adjusting artificially the prediction time interval (Figure 7).

Atmospheric disturbance modeling.

The atmospheric disturbances consist essentially of the ship airwake or burble. At present, without experimental results, the disturbance model included in the MIL-E-8785C is used [2].

4.2 Aircraft model and integrated landing system

For control and guidance studies concerning specific flight phases as it is the case here, it is not often necessary to simulate an aircraft model with its complete aerodynamics, engines, sensors and FCS. At a feasibility study level, it is enough to simulate a "model of behaviour". The aircraft is assumed augmented by appropriate feedback control laws, so that its dynamics are close to the real aircraft. One fictitious aircraft model is used in the present study.

Aircraft localization system.

The Deck Approach and Landing Laser System (DALLAS), used at present on French carriers, has been retained for the simulation codes. It consists of a laser telemeter and deviation sensor intended for tracking a reflector mounted on the nose landing gear (Figure 8).

Equipment modeling, established from technical specifications, includes the following error components:

- sensor data processing errors,
- aiming errors,
- ship motion estimation errors.

Approach and landing guidance.

Guidance objectives during landing approach are airspeed control and hook position control about a desired light path. The desired values are constant in the conventional landing procedure, and depend on the predicted motion of the carrier in the new landing procedure.

The guidance law has been formulated with a state model of aircraft dynamics, linearized about a constant flight path value :

$$\begin{cases} \Delta\dot{X} = A\ \Delta X + B\Delta U \\ \Delta Z = C\ \Delta X \end{cases}$$

with X : state vector
U : input vector
Z : output vector (objectives)

The components of X, U and Z are :

$X = (V, \gamma, \alpha, q, Zh)$
$Z = (V, Zh)$
$U = (dp, dt)$

with V : airspeed
Zh : hook altitude
γ : flight path angle
α : angle of attack
q : pitch rate
dp : pitch command
dt : thrust command

The symbol $\Delta(.)$ represents the difference between the real value and the constant nominal value.

The objective is to make ΔZ tend to a desired value ΔZd corresponding to the ideal approach trajectory.

The linear quadratic method has been used with a two-level controller to derive the optimal control ΔU (Figure 9).

The first level, named feedforward controller, is used to generate a control law ΔUm which make ΔZm to tend to ΔZd according a desired response. Dynamics are defined by the gain matrices Km1 and Km2 of the control law of the form :

$$\Delta Um = Km_1\ (\Delta Xm - \Delta Xd) + Km_2 \int_0^t (\Delta Zm - \Delta Zd)\ dt$$

The second level is a feedback controller which processes output of first level as input orders. A proportional integral control law is used to make regulation error tend to zero in steady state:

$$\Delta Uc = Kc_1\ (\Delta X - \Delta Xm) + Kc_2 \int_0^t (\Delta Z - \Delta Zm)\ dt$$

5. Results of numerical simulation

Statistical evaluation of landing performances were performed through Monte-Carlo simulation. Various simulations were considered for influence analyses of several parameters such as sea conditions, wind forces and accuracy of carrier motion prediction. For each case study, statistical results were computed through 100 numerical simulations, using random samples on the following parameters :

- initial state of the aircraft and the carrier motion,
- wave height,
- carrier airwake,
- measurement errors,

Let us notice that the turbulence such as proposed by MIL-STD model was not taken into consideration in the simulation.

A typical behaviour of the aircraft, using the new landing procedure is first presented for illustration.

5.1 Typical landing with the new procedure

Time histories of a simulation obtained with a sea surface height which corresponds to the operational limits for aircraft recovery and a wind speed over deck of 30 kts are presented in Figure 10 :

Figure 10a shows the desired flight path angle γ_r (full line) and the flight path angle γ_{clear} and γ_{impact} (mixed line) related respectively to constraints of hook-to-ramp clearance and sink rate at touchdown. Figure 10b shows the carrier motion (full line) and its predicted motion (dotted line). Prediction of the stern height was computed at the predicted aircraft crossing time above the vertical plane of the stern. Prediction of the arresting wires height was computed at the predicted instant of touchdown.

Predicted parameters were updated at every one second interval.

Figure 10c shows the difference between the hook altitude and those related to the desired flight path angle.

Figure 10e shows the hook trajectory relative to the actual state of the arresting wires at touchdown (full line), the desired flight path angle (γ_r) issuing from predicted wires (mixed line) and flight path angles γ_{clear} and γ_{impact} from actual wires (dotted line).

Thanks to the carrier motion prediction, the aircraft flew above the allowable minimum altitude of hook-to-ramp clearance, and the normal speed to the deck at touchdown remains within authorized limits.

For this typical simulation case, the usual landing procedure, that means with a constant flight-path angle, would not allow a safety carrier landing indeed the constraint related to hook-to-ramp clearance would be violated, as it can be seen by extending the first part of the actual trajectory up to the carrier.

5.2 Influence of sea conditions

Low, medium and high sea surface height values were used for simulation purpose.

Figure 11 presents root-mean-square (RMS) errors of landing performances with respect to the instant Tc, where the new guidance strategy is applied. This instant is defined as the predicted time to touchdown on the flight deck. Full line curves are related to a perfect prediction case, whereas dotted line curves are related to results obtained with an auto-regressive prediction model.

Let us notice that the results related to the conventional landing procedure, that means with constant flight path angle, are represented in the Figure 11 with Tc equal zero. Root-mean-square errors of the presented parameters (normal speed, horizontal dispersion at touchdown, hook-to-ramp clearance) decrease as Tc increases and remain constant with high values of Tc. This Figure 11 shows that the new landing procedure is all the more efficient as the amplitude of carrier motion increases.

5.3 Influence of wind conditions

Influence of wind conditions was performed by using an ideal motion prediction in order to better evaluate the impact of separate parameters. Figure 12 presents distribution functions related to landing performances obtained with sea conditions of § 5.1 and four wind conditions. The increase of mean wind speed induces a greater flight path angle and an increase of RMS errors on landing performances.

Nevertheless, minimum hook-to-ramp clearance and the maximum speed at touchdown remain approximately constant.

5.4 Influence of motion prediction accuracy

Both the two prediction algorithms described previously were evaluated with sea surface height and wind speed over deck of § 5.1.

Figure 13 presents root-mean-square errors of landing performances parameters in terms of a parameter k which represents the uncertainty error of the motion prediction model.

Auto-regressive model

With this model, results with k=0 are related to a perfect prediction model. Decrease of landing performances remains weak when parameter k is below 0.8.

Beyond this value k=0.8, the root-mean-square of hook-to-ramp clearance increases more sharply.

State-space model

With this model parameter k is related error in the wave pulsation (k=1 corresponds to zero-error model). RMS errors in landing performances increase in the ratio of one to two when parameter k changes within 0.5 and 2.0.

6. Conclusion

The present landing procedures on carrier have been well experimented although improvements could be obtained by taking into consideration new techniques such as prediction of the carrier motion, etc... Thus, in adverse sea conditions the present landing sequence -using a constant flight path angle- may lead to a ramp crossing with very low margins.

Study related to prediction of the carrier longitudinal motion allow a development of a new landing sequence which could improve operational use for carrier aircraft.

This new landing procedure consists in computing, in real time, a new guidance strategy where flight-path angle is changed according to the prediction motion of the carrier at the crossing time above the stern and the touchdown, such that the constraints on hook-to-ramp clearance, sink rate and position at touchdown remain within the allowable limits. This desired value is updated periodically in terms of the prediction accuracy which increases as the aircraft approaches the carrier.

The performance evaluation, which is achieved in the present study through a complete numerical simulation with an final automatic landing sequence, confirms the interest of the prososed new landing procedure. Nevertheless, let us remind that the results were obtained through models whose accuracy and validity domain remain to be demonstrated :

- theorical model of carrier motion,
- airwake model behind the carrier, from the U.S. MIL-Specifications,
- no turbulence models.

Parametric simulation results show an improvement of landing performances which are all the more efficient as the carrier motion become larger. Those results show also that this improvement is compatible within the accuracy which could be achieved with the actual motion prediction techniques for the French carrier.

Although further studies remain necessary in order to better evaluate and to validate the improvement of landing performances presented in this paper, this new landing procedure could be considered, as a future guidance concept which could integrate flight control systems and landing aid systems.

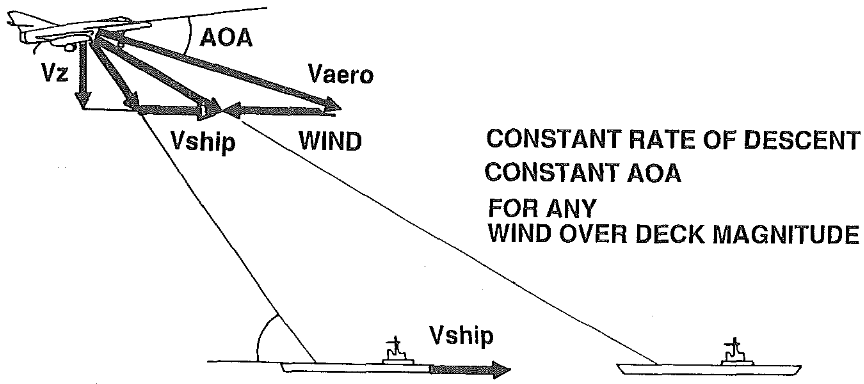
References

(1) "B.Dang Vu, T.Le Moing, "Intégration of flight and carrier landing aid systems for shipboard operations" Symposium AGARD-FMP on Aircraft/Ship Operations,May 20-23,1991.

(2) "Military Specifications, Flying Qualities of Piloted Airplanes", MIL-F-8785C, November 1980.

Figure 1

FINAL APPROACH GEOMETRY



GLIDE SLOPE = Vz / (Vaero - WOD)

Figure 2

HOOK TO RAMP CLEARANCE

γ < - (Hmin + HA - HB) / AB

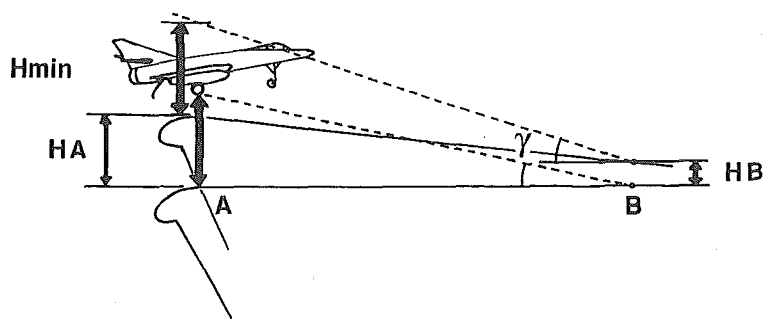


Figure 3

TOUCH DOWN SINK RATE

γ > θ - (Vnmax + Vnb) / (Vaero - WOD)

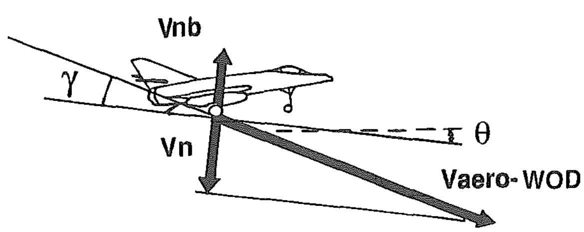


Figure 4

NEW DECK LANDING PROCEDURE

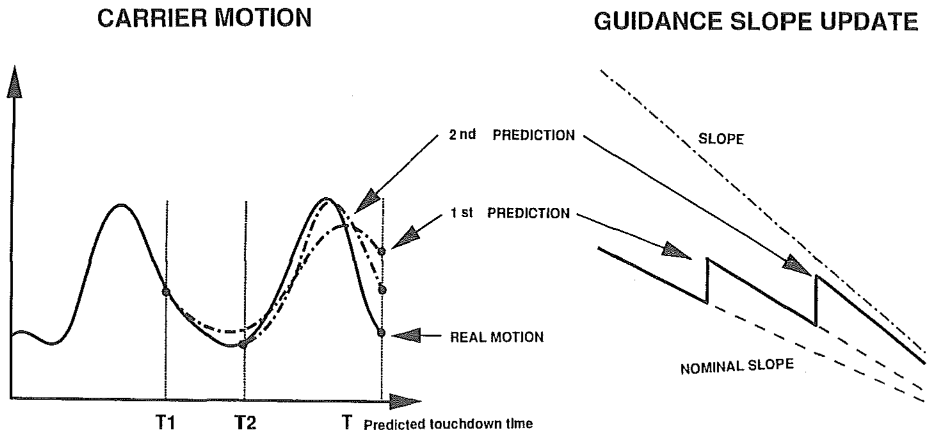


Figure 5

GUIDANCE STRATEGY

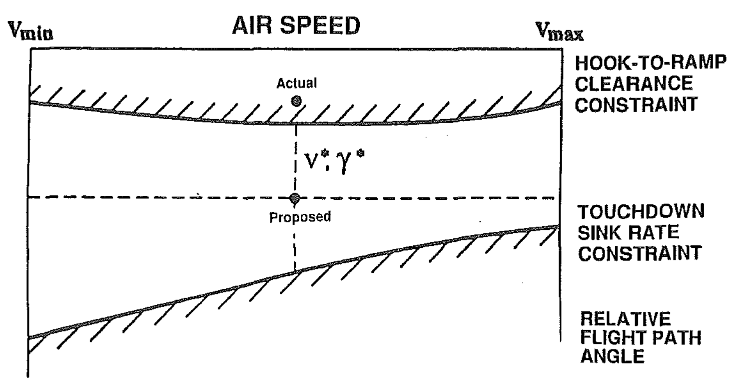


Figure 6

SIMULATION BLOCK DIAGRAM

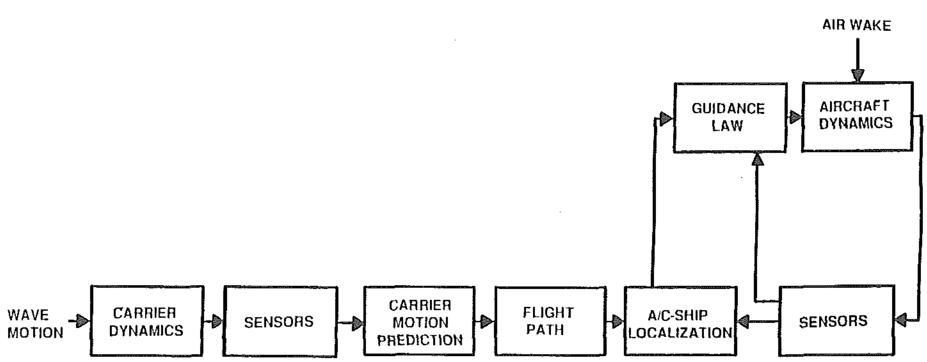


Figure 7

AUTO-REGRESSIVE PREDICTION MODEL

PREDICTION QUALITY MODIFICATION

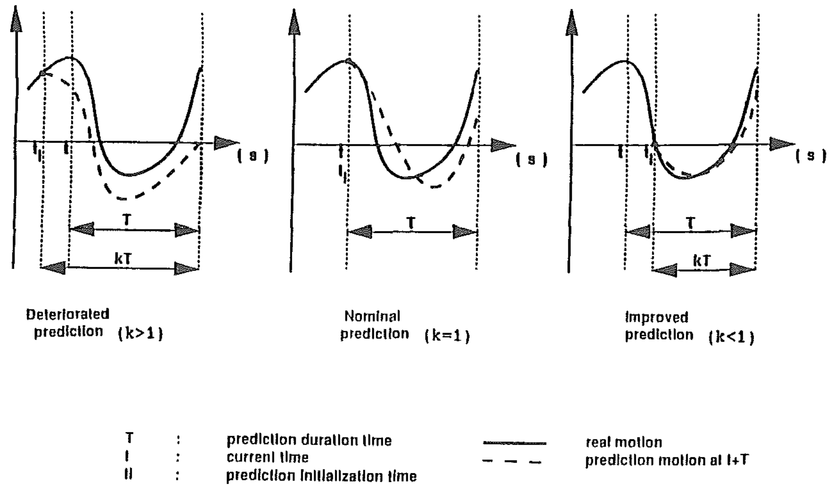


Figure 8

DECK APPROACH AND LANDING LASER SYSTEM (DALLAS)

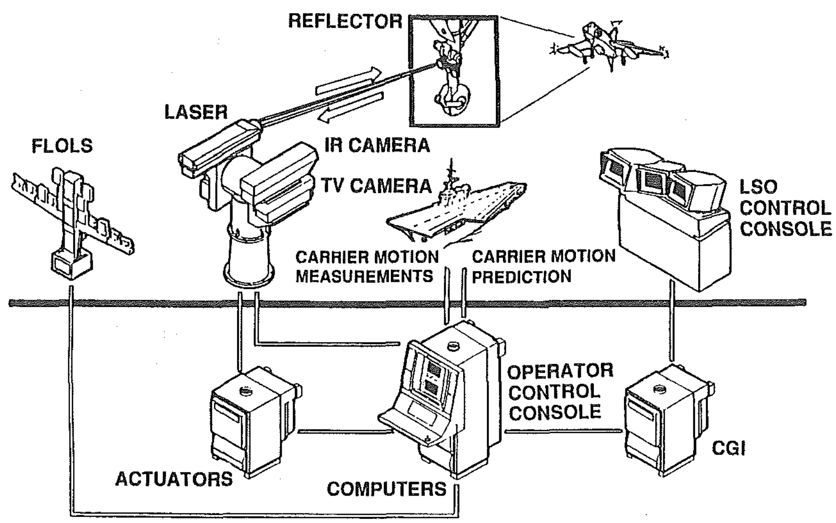


Figure 9

LONGITUDINAL FLIGHT CONTROL SYSTEM

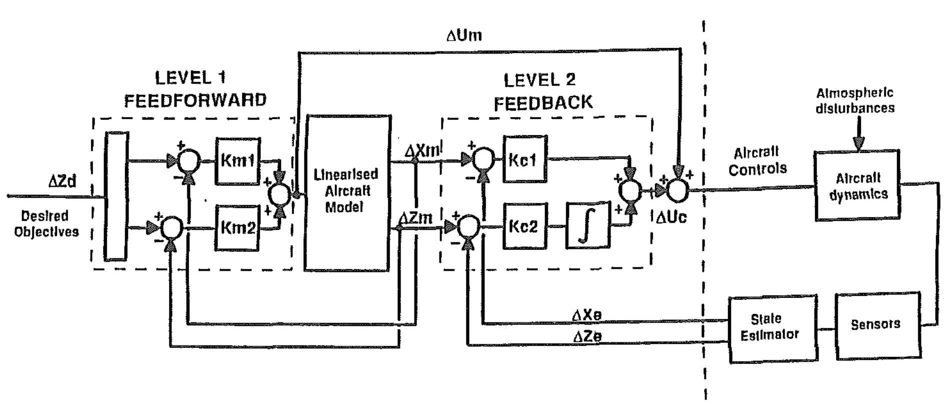


Figure 10 SIMULATION RESULTS

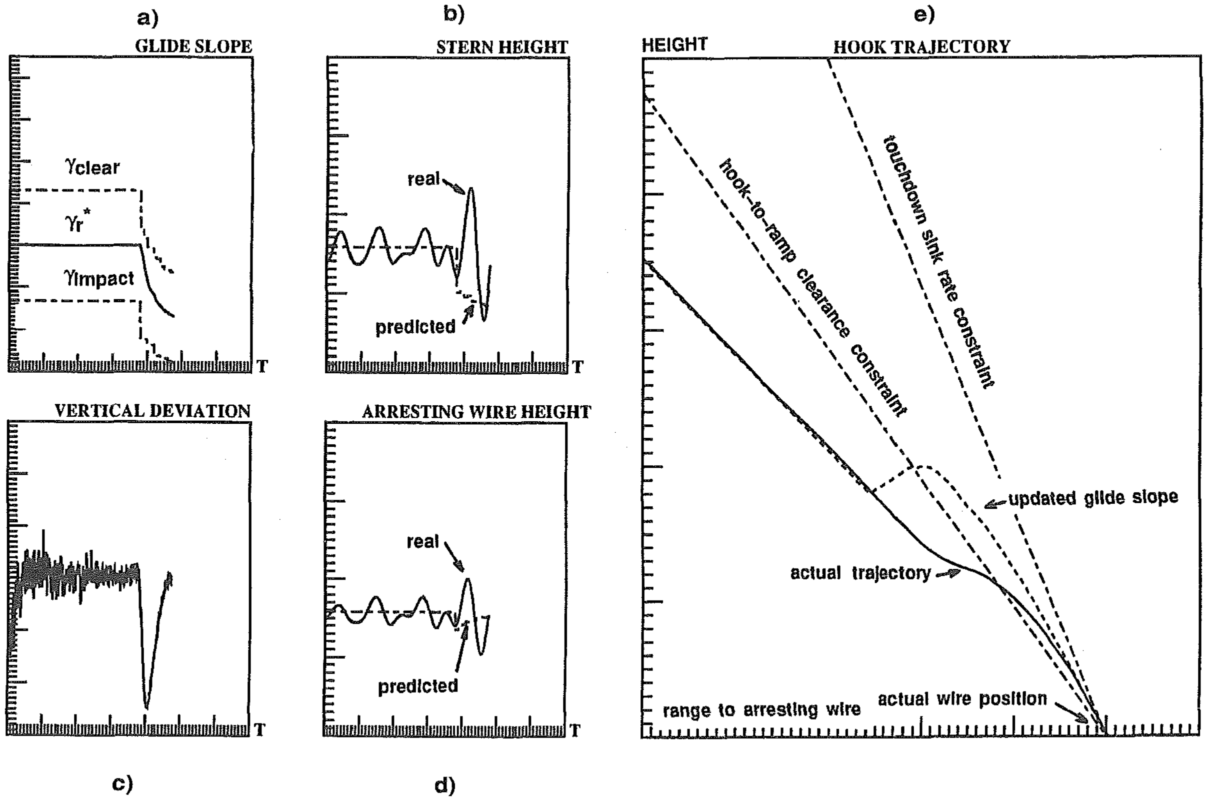


Figure 11 EFFECT OF SEA CONDITIONS

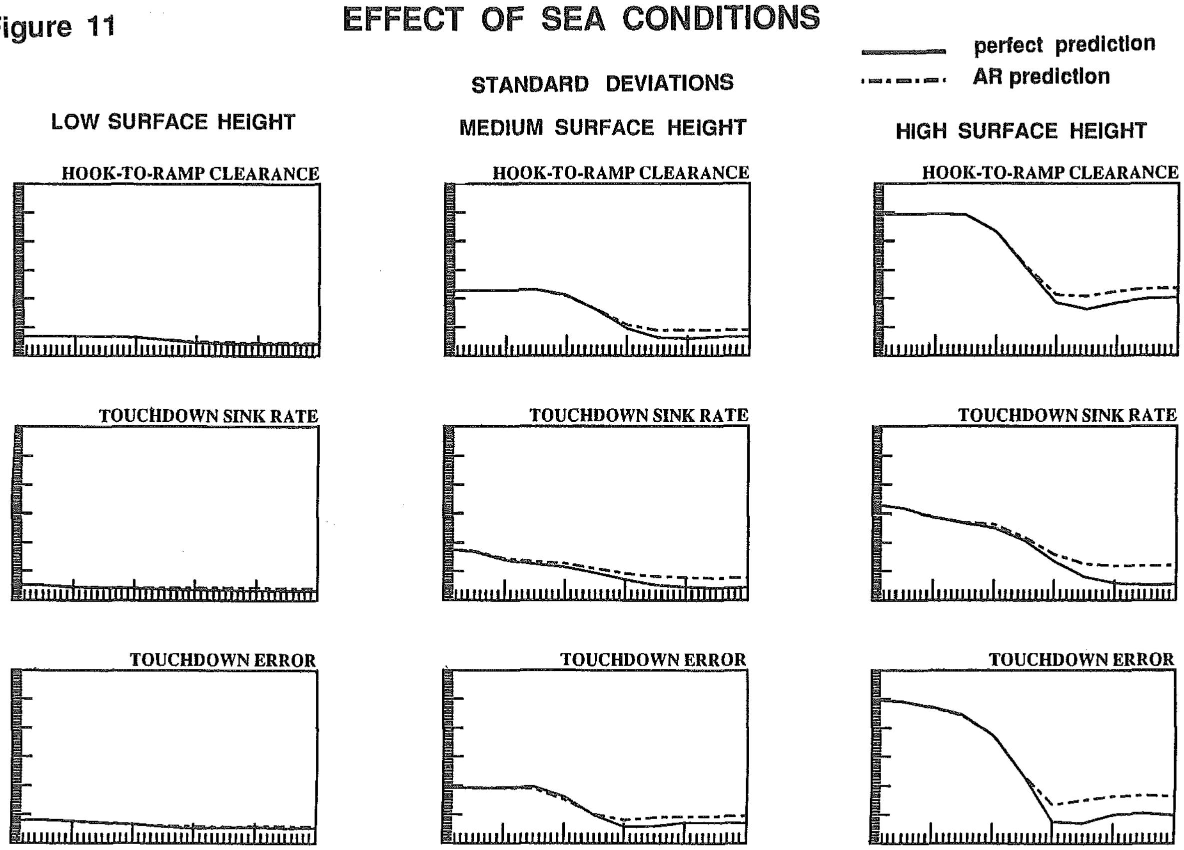
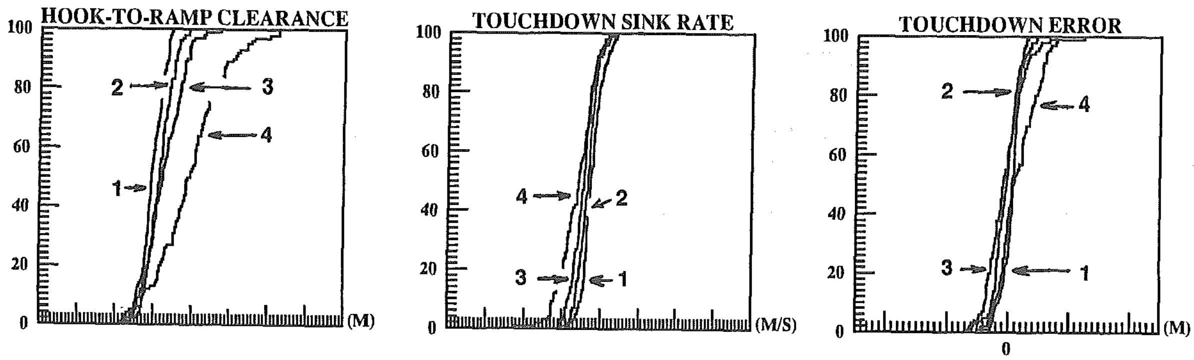


Figure 12

EFFECT OF WIND INTENSITY

DISTRIBUTION FUNCTIONS



WIND INTENSITY : 1 < 2 < 3 < 4

Figure 13

EFFECT OF PREDICTION TECHNIQUE

STANDARD DEVIATIONS

AR PREDICTION METHOD

STATE MODEL PREDICTION

k: prediction interval time scale factor

k: wave pulsation scale factor