N82-13685

A COMPARISON OF LANDING MANEUVER PILOTING TECHNIQUE BASED ON MEASUREMENTS MADE IN AN AIRLINE TRAINING SIMULATOR AND IN ACTUAL FLIGHT

Robert K. Heffley and Ted M. Schulman

Systems Technology, Inc.

SUMMARY

An analysis of pilot behavior, both from an airline training simulator and an actual DC-10, is presented for the landing maneuver. An emphasis is placed on developing a mathematical model in order to identify useful metrics, quantify piloting technique, and define simulator fidelity. On the basis of DC-10 flight measurements recorded for 32 pilots — 13 flight-trained and the remainder simulator-trained — a revised model of the landing flare is hypothesized which accounts for reduction of sink rate and preference for touchdown point along the runway. The flare maneuver and touchdown point adjustment can be described by a pitch attitude command pilot guidance law consisting of altitude and vertical velocity feedbacks. The pilot gains which are identified directly from the flight and simulator data show that the flare is being executed differently in each medium. In flight most of the subject pilots exhibit a significant vertical velocity feedback which is essential for well controlled sink rate reduction at the desired level of response (bandwidth). In the simulator, however, the vertical velocity feedback appears ineffectual and leads to substantially inferior landing performance. The absence of the vertical velocity feedback implies a simulator fidelity problem, and several specific possibilities are discussed. The pilot model of the maneuver provides insight into which aircraft types could be simulated without incurring the apparent fidelity limitation encountered in this case.

INTRODUCTION

This paper is a summary of portions of an analysis of airline landing data which was performed for NASA [illegible] Research Center under Contract NAS2-10817 and reported in Ref. 1. The purpose of the study was to focus on the landing maneuver as it is performed both in flight and in an airline training simulator in order to: (a) measure absolute differences between pilot-vehicle behavior, (b) develop landing maneuver performance metrics, and (c) define how to use such metrics in both simulator and flight.

The data base used in this analysis was collected during a NASA field evaluation of the sole use of simulator training in transitioning airline pilots to a new aircraft type (Ref. 2). The unique aspect of the data acquired is that they involve both actual flight and simulator measurements for a reasonably large number of pilots. Furthermore specific attention was devoted to making the flight and simulator data directly comparable in terms of pilots, aircraft, and environmental conditions.

The procedure used in analyzing the available data was based on manual control theory (Ref. 3 which treats human psychomotor and cognitive behavior as rational, well-tailored actions dependent upon the task, vehicle dynamics, and environment. These actions can be essentially closed loop and compensatory in nature or progressively more open loop and precognitive depending upon the pilot's level of skill or workload demands.

The issue of simulator fidelity has been stated in terms of manual control theory in Ref. 4 and is highly relevant to the analysis. In fact perceptual fidelity is addressed in terms of "essential cueing" as discussed in Ref. 5. As will be seen, there is evidence that the training simulator involved in this study was somehow deficient in inducing the pilot behavior observed in flight. This kind of deficiency should be duly noted in the design and actual use of any simulator where flight task and aircraft conditions are similar to those studied here.

SYMBOLS

h	Height
$\dot{h}_{TD}$	Touchdown sink rate
$\dot{h}_{max}$	Maximum sink rate
k_h	Pilot height loop gain
$k_{\dot{h}}$	Pilot vertical velocity loop gain
k_γ	Pilot flight path angle loop gain = $Uk_{\dot{h}}$
s	Laplace operator
T_{AC}	Effective aircraft flight path lag
U	Airspeed
ζ_{FL}	Effective damping ratio of the landing maneuver
θ_c	Pitch attitude command
ω_{FL}	Effective natural frequency of the landing maneuver
ω_{c_θ}	Pitch loop crossover frequency

FLARE MODEL

The appendix of Ref. 1 reviewed some existing models of the flare maneuver (Refs. 6 through 9), considering their strong and weak points. These ideas were taken into account in constructing a revised flare model which would better explain the recently-acquired landing data as well as encompassing past measurements. One important aspect of this revised model is that there is no added complexity over previous models discussed, in fact there is significant reduction in complexity — so much so that a closed analytic form can be expressed for time histories of altitude, sink rate, normal acceleration, airspeed decay, and touchdown point along the runway. Furthermore it is possible to describe a clear role for the important aircraft properties as well as for the pilot control law properties. This ultimately aids in developing metrics for analyzing the landing maneuver.

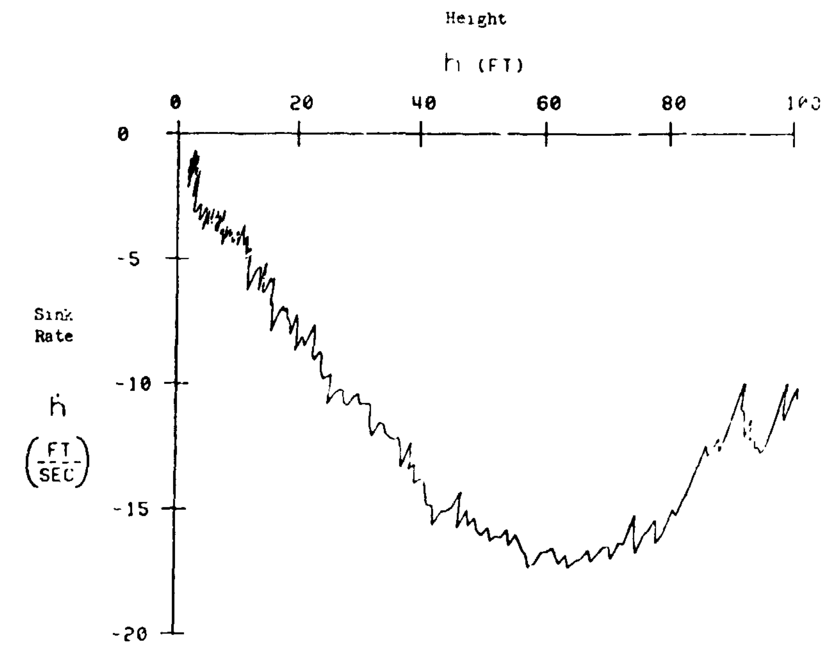

Figure 1. Phase Plane Trajectory of a Typical Landing Maneuver

The theoretical basis for the revised model is the assumption of dominant second-order characteristic response which is strongly suggested by the phase planes constructed from flight data of which Fig. 1 is an example. This leads to the basic characteristic equation:

$$\ddot{h} + 2\zeta_{FL}\omega_{FL}\,\dot{h} + \omega_{FL}^2\,h = 0$$

It is further assumed that this characteristic equation is associated with a pilot-vehicle system having an altitude command loop (outer loop) and that the flare maneuver corresponds to the response from an initial offset with respect to the terminal conditions (i.e., from an initial altitude and sink rate). Thus, analytically, the flare is regarded as an unforced response from a set of initial conditions to a set of desired conditions at touchdown.

In considering the pilot control law implications of a second-order characteristic response, the first step is to examine the aircraft equations of motion with respect to altitude. The complete longitudinal formulation described in Ref. 10 can be simplified to a first-order, single-axis form:

$$\ddot{h} + \frac{1}{T_{AC}}\dot{h} = \frac{U}{T_{AC}}\theta_c$$

Where T_{AC} is the effective first-order lag time constant between a pitch-command, θ_c, and flight path response.

The approach used to infer piloting technique in the landing maneuver was to solve directly for the difference between a fitted differential equation describing closed-loop motion and the effective flight path response of the basic airplane. The difference, assuming negligible atmospheric disturbances, should be the effect of pilot actions and can be interpreted literally as a pilot control law, i.e.,

$$\ddot{h} + 2\zeta_{FL}\omega_{FL}\dot{h} + \omega_{FL}^2 h = 0 \qquad \text{(fitted differential equation of landing maneuver)}$$

minus

$$\ddot{h} + \frac{1}{T_{AC}}\dot{h} = \frac{U}{T_{AC}}\theta_c \qquad \text{(Aircraft flight path equation)}$$

equals

$$\left(2\zeta_{FL}\omega_{FL} - \frac{1}{T_{AC}}\right)\dot{h} + \omega_{FL}^2 h = -\frac{U}{T_{AC}}\theta_c \qquad \text{(inferred pilot control law)}$$

Rearranging the result,

$$\theta_c = -\underbrace{\frac{\omega_{FL}^2 T_{AC}}{U}}_{k_h} h - \underbrace{\frac{2\zeta_{FL}\omega_{FL}T_{AC} - 1}{U}}_{k_{\dot{h}}} \dot{h}$$

Hence the effective control law gains can be related directly to parameters describing the maneuver and the aircraft:

$$k_h = \frac{\omega_{FL}^2 T_{AC}}{U}$$

$$k_{\dot{h}} = \frac{2\zeta_{FL}\omega_{FL}T_{AC} - 1}{U}$$

or basing a control law term on flight path angle, γ, rather than sink rate, $\dot{h}$:

$$k_\gamma = 2\zeta_{FL}\omega_{FL}T_{AC} - 1$$

IDENTIFICATION OF PARAMETERS

The foregoing theoretical development shows that two motion parameters and one aircraft parameter are needed to obtain the effective pilot control law parameters.

The aircraft parameter, T_{AC}, was obtained from an estimate of the flight path response for a pitch attitude command in a DC-10 at an average landing weight and speed. Allowance was made for the contribution of lag in the closed-loop pitch response as well as the lag due to airframe heave damping, T_{θ_2}. An effective first-order pitch response lag of 0.7 sec was assumed based on previously observed transport aircraft pitch attitude closures ranging from 1 to 2 rad/sec crossover frequency, ω_{c_θ}. For the airframe heave damping component, a value of 1.8 sec was estimated for the average T_{θ_2} corresponding to the loading and approach airspeeds flown. A composite flight path response lag, T_{AC}, was obtained by summing the pitch response and heave response lags, i.e.,

$$T_{AC} \triangleq T_{\theta_2} + \frac{1}{\omega_{c_\theta}} \cong 2.5 \text{ sec}$$

This approximation can be shown to be valid for landing maneuvers having an effective damping ratio, ζ_{FL}, in the vicinity of 0.7 — the nominal value found in the flight data.

The landing maneuver was identified directly from phase plane trajectories plotted for the flight and simulator landings. Two separate procedures were developed for obtaining independently the effective flare damping ratio, ζ_{FL}, and the effective natural frequency, ω_{FL}. It was found that a strong relationship existed between ζ_{FL} and the ratio of touchdown sink rate to maximum sink rate (just prior to flare), $\dot{h}_{TD}/\dot{h}_{max}$.

The effective natural frequency of the flare, ω_{FL}, was shown to be a strong function of the shape of the flare trajectory and nearly independent of ζ_{FL}. As a consequence it was possible to identify ω_{FL} using transparent overlays of families of phase plane trajectories.

RESULTS OBTAINED

Nominal Landing Maneuver

The check-ride landings of the flight-trained group of pilots were used to obtain an indication of the nominal landing maneuver for the

DC-10. Figure 2 shows samples of the flight data in terms of landing trajectory phase planes for several pilots. Note that for each of the five pilots there were three landings. Figure 3 shows the identified landing maneuver parameters, ζ_{FL} and ω_{FL}, for these pilots along with a plot of pilot control law parameters. (Note that the height loop gain, k_h, is plotted opposite ω_{FL}^2 and the effective flight path angle gain, k_γ, is plotted opposite $\zeta_{FL}\omega_{FL}$.) Means and standard deviations of nominal landing parameters are summarized in Table 1.

It can be seen that the nominal flare maneuver parameters are grouped in rational locations with respect to the several factors, previously mentioned, which affect the landing; namely, the natural frequency — an indicator of closed-loop bandwidth — is situated midway between the closed-loop airspeed response mode (about 0.1 rad/sec for this aircraft) and the closed-loop pitch response (about 1 to 2 rad/sec). This partitioning of frequency helps to insure that airspeed will not bleed off excessively during the landing maneuver, and that pitch response will not significantly detract from the heave response phase margin. (If pitch loop crossover is set too close to flight path crossover, then a K/s^2-like controlled element is created.) The nominal value of damping ratio centered at about 0.7 helps to insure that a good touchdown sink rate is obtained regardless of the conditions at flare initiation. Too low a damping ratio, say 0.4, would correspond to a hard landing even from a nominal approach sink rate. At the other extreme, a damping ratio greater than, say, 0.9 would correspond to a floating tendency resulting in excessive runway landing distance. The nominal $\zeta_{FL} \cong 0.7$ and $\omega_{FL} \cong 0.4$ rad/sec are therefore entirely appropriate from the standpoint of good closed-loop control considerations.

The nominal piloting technique parameters spanned a range of effective loop gains. Most noteworthy, however, is that some degree of sink-rate or flight-path-angle feedback is apparent except where a very low height gain is employed. For the average k_h of 0.13 deg/ft*, an average k_γ of 0.45 (or $k_{\dot{h}}$ of 0.12 deg/ft/sec) was observed. This in turn implies that cues in addition to height may be used by the pilot. These data, however, did not indicate which of the several visual (or even motion) cues might have been involved.

In addition to the two landing maneuver parameters, ζ_{FL} and ω_{FL}, attention was given to how to characterize initiation of the landing. Flare height has been generally regarded as a likely candidate for a landing parameter, but the data showed no clear tendencies. Instead a wide range of heights for flare initiation were observed. Also most landings involved a "duck-under," i.e., an increase in sink rate, just prior to the

---

* This agrees with the DC-10 flight manual procedure — about 3.5 deg net pitch change over the final 30 to 40 ft.

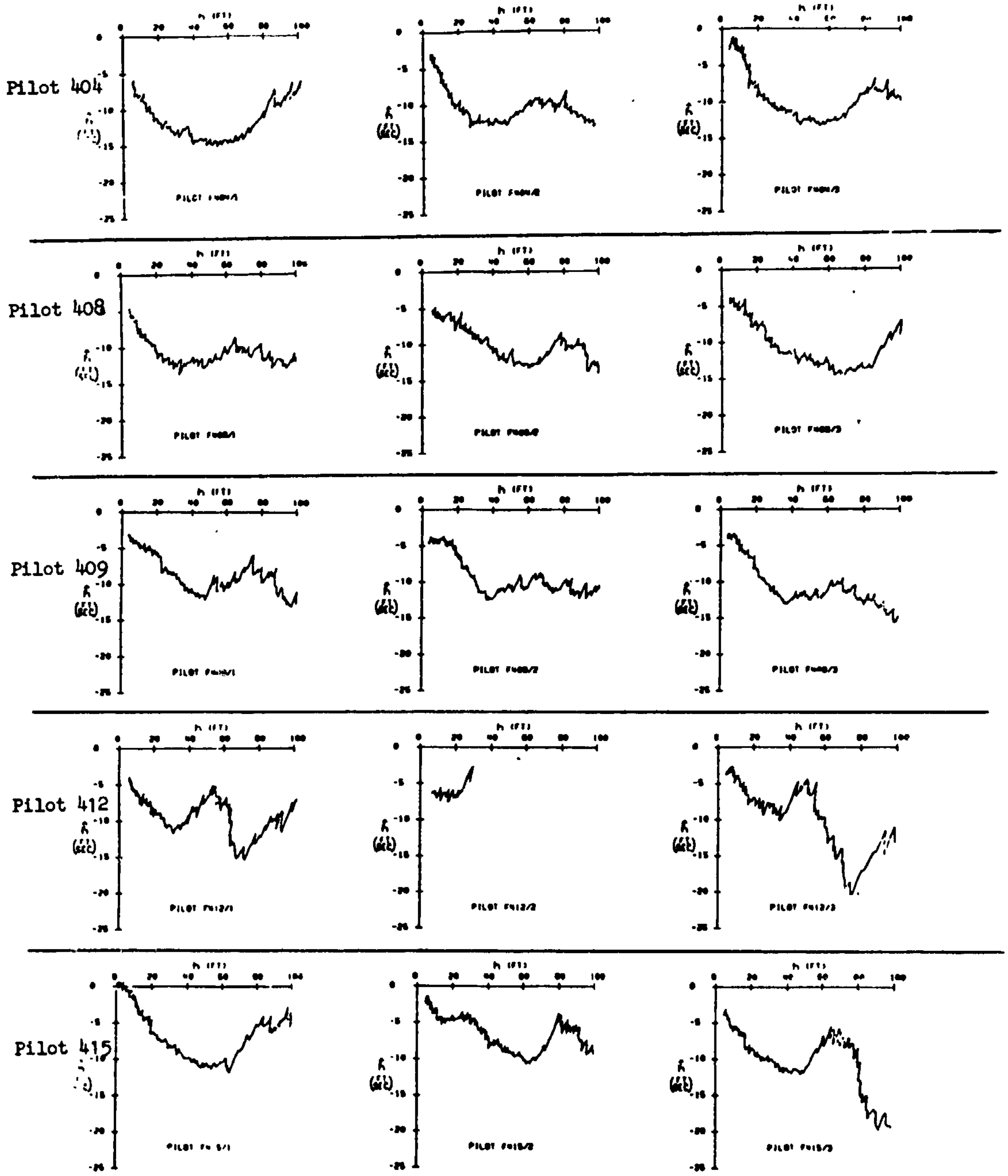

Figure 2. Samples of Landing Trajectory Phase Planes from Actual Landings (three check-ride landings for five of the 13 flight-trained pilots)

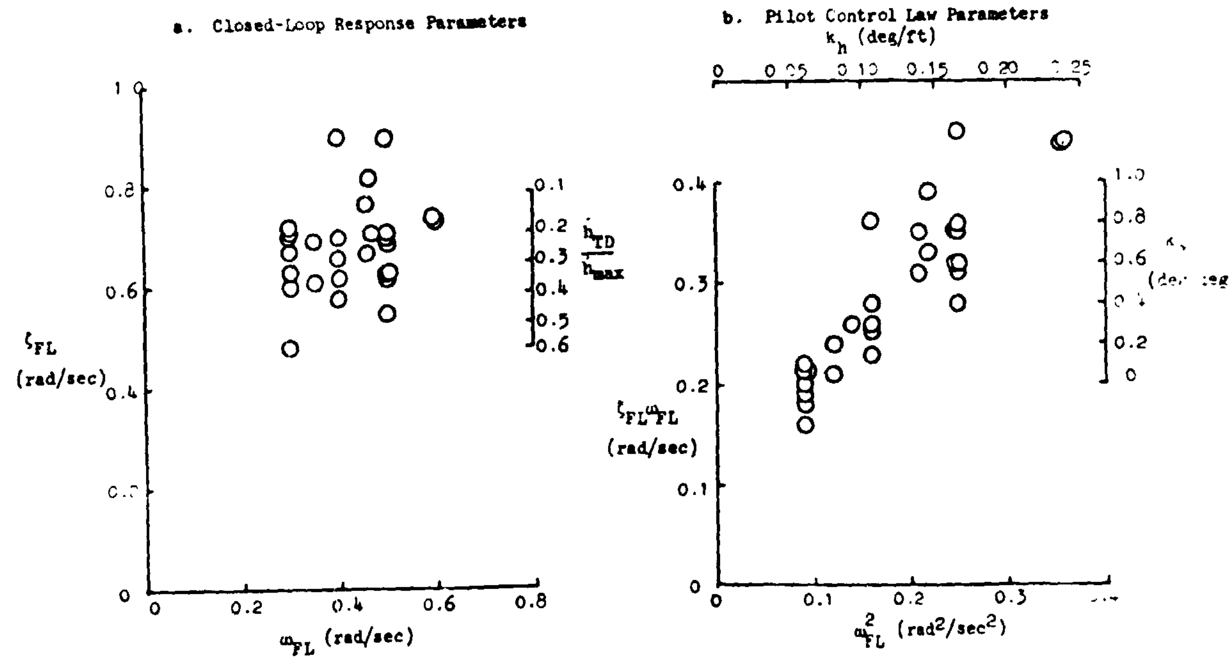

Figure 3. Closed-Loop Flare Parameters Representative of Skilled Pilots in Flight

TABLE 1. AVERAGE PILOT BEHAVIOR IN FLIGHT — PILOTING TECHNIQUE

Features Of Maneuver and Pilot Behavior	Parameters	Flight-Trained Pilots Exhibiting Good Landings*	Remarks
Control of touchdown sink rate	ζ_{FL} $\dot{h}_{TD}/\dot{h}_{max}$	0.68 ± 0.09† 0.25 ± 0.14	Effective reduction in sink rate
Abruptness of flare maneuver	ω_{FL} (rad/sec) ω_{c_h} (rad/sec)	0.42 ± 0.09 0.28 ± 0.06	Bandwidth high enough to precede airspeed decay (about 0.1 rad/sec) and low enough to accommodate lag in pitch attitude command (about 1 rad/sec)
Height Feedback	ω^2_{FL} (rad²/sec²) k_h (deg/ft)	0.19 ± 0.08 0.13 ± 0.05	Consistent with flight manual — about 3.5 deg attitude change over the final 30 to 40 ft
Direction-of-flight feedback	$\zeta_{FL}\omega_{FL}$ (rad/sec) k_γ (deg/deg)	0.29 ± 0.08 0.45 ± 0.35	Significant feedback of direction-of-flight or its equivalent

* $|\dot{h}_{TD}| < 3$ ft/sec, no floating (Group FA).

† Mean ± standard deviation.

final reduction in sink rate. In fact the duck-under maneuver fitted the phase plane trajectory of the flare itself, i.e., the same pilot control law generated both maneuver segments as shown in Fig. 4. Furthermore the initiation of the duck-under ranged even greater in height than did the flare, per se.

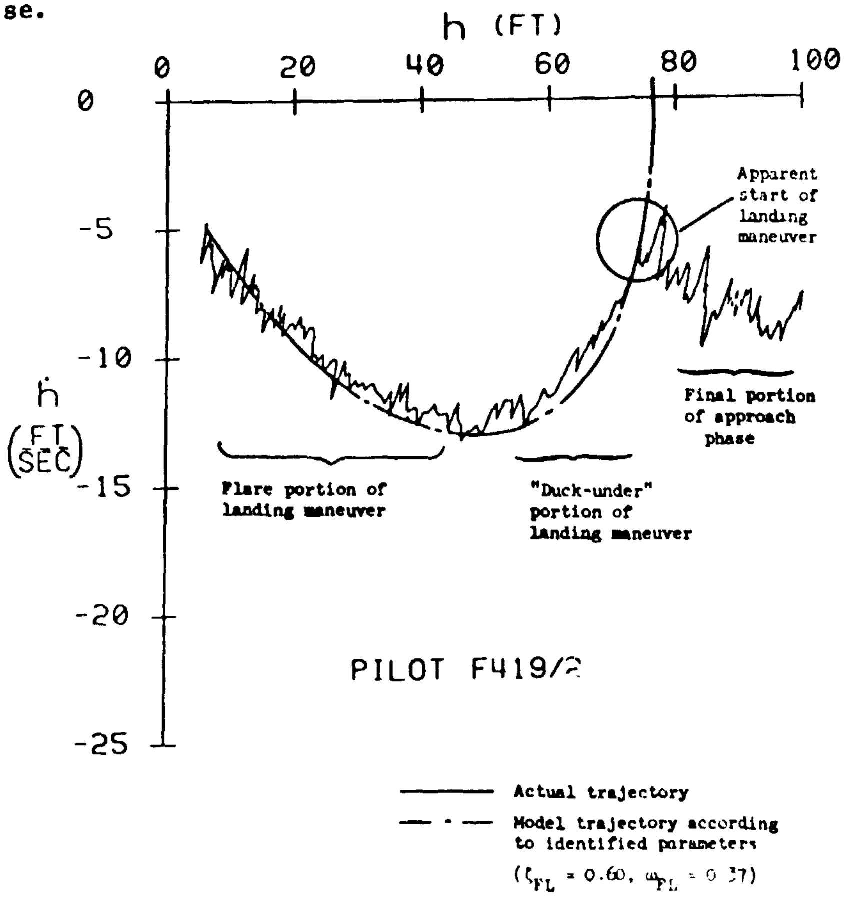

Figure 4. Typical Landing Maneuver Performed in the Actual Aircraft

A NASA research pilot observed that the combined duck-under and flare was a natural action aimed at adjusting touchdown point along the runway. A normal electronic glide slope may intercept the runway at a conservative distance from the runway threshold. Thus at some judicious point prior to flare the pilot may elect to transition from the electronic glide slope to a lower approach slope. The data suggest that this final adjustment is integrated with the flare and that the height of that adjustment corresponds to how large a change is desired in the nominal touchdown point. Hence "flare height" or "landing initiation height" should not be regarded as a constant. Rather it is a "control" used to alter the point of touchdown along the runway.

Landings in the Simulator

Substantially different average landing behavior was observed in the simulator. The same analysis procedure was applied, i.e., identification of landing maneuver parameters from phase plane trajectories. A summary of results is given in Table 2.

TABLE 2. AVERAGE PILOT BEHAVIOR IN FLIGHT AND IN THE SIMULATOR — SIMULATOR FIDELITY

Features of Maneuver and Pilot Behavior	Parameters	All Flight-Trained Pilots in Flight	All Pilots in Flight	All Pilots in the Simulator	Remarks
Control of touchdown sink rate	ζ_{FL}	0.68	0.67	0.58	Harder landings in the simulator
	$\dot{h}_{TD}/\dot{h}_{max}$	0.25	0.27	0.42	
Abruptness of flare maneuver	ω_{FL} (rad/sec)	0.40	0.37	0.36	No difference
	ω_{c_h} (rad/sec)	0.27	0.25	0.27	
Height Feedback	ω_{FL}^2 (rad²/sec²)	0.17	0.13	0.15	No difference
	k_h (deg/ft)	0.11	0.08	0.10	
Direction-of-flight or sink rate feedback	$\zeta_{FL}\omega_{FL}$ (rad/sec)	0.28	0.25	0.20	Direction-of-flight loop lacking in the simulator
	k_γ (deg/deg)	0.40	0.25	0	

The most obvious difference between simulator and flight was in the firmness of landings. This is reflected in the ratio of sink rate decay, $\dot{h}_{TD}/\dot{h}_{max}$, and the effective damping ratio, ζ_{FL}. At the same time the abruptness of the flare maneuver and corresponding height feedback were comparable between simulator and flight.

One important piloting technique implication from the above observations is that the effective direction-of-flight or sink rate feedback is inadequate in simulator landings. A further implication is that a cue deficiency exists. The exact nature of that cue was, however, not clear from the data although visual perception of sink rate is suspected.

An additional feature of the simulator data was that there was an absence of the initial duck-under maneuver which was so prominent in the flight data. This could be interpreted as either the absence of a runway distance cue or a different approach geometry which made a duck-under unnecessary.

As suggested in Ref. 4 the fidelity of the simulator can be judged on the net difference in piloting technique exhibited in the simulator compared to actual flight. Therefore, for the case reported here, one could question the fidelity of the essential sink-rate or direction-of-flight cues as well as distance along the runway. At the same time it is not clear, without further experimentation, what the specific origins of these difficulties were in engineering terms used to specify simulator components.

CONCLUDING REMARKS

The airline landing data analyzed yielded a rich variety of results with implications in several areas including quantification of piloting technique and the fidelity of an airline training simulator for the landing maneuver. Besides providing important quantification in these various areas, the data have also provided the basis for a revised analytical model of the flare maneuver. In fact the model developed provides a useful bridge between the raw data collected and the ensuing interpretations of those data.

Several metrics have evolved with regard to describing the landing maneuver. The first metric is the phase plane representation to characterize the flare maneuver, not only in terms of the ultimate landing performance but also how that performance was achieved: whether it was the result of a last-minute abrupt pull-up leaving no room for error or misjudgment, or whether it was the result of an exceedingly gentle decay in sink rate which might be accompanied by a large loss of airspeed prior to touchdown. The phase plane also, of course, shows where there were dangerously high sink rates at low altitudes or if there was a floating or ballooning tendency.

Two metrics which bear a direct dependence upon the effective closed-loop parameters are the inferred pilot-vehicle loop gains, namely the height gain and the direction-of-flight gain. The height gain was shown to be dependent upon the closed-loop natural frequency and the true airspeed. The direction-of-flight gain was shown to be a function of the product of damping ratio and natural frequency along with the basic vertical response lag for the aircraft.

An important aspect of the analysis performed here is the quantification of the landing maneuver as it is performed on the actual aircraft. This provides an important baseline for examining simulator fidelity. Without this description of piloting technique, we would have to rely far more heavily upon terminal landing performance (i.e., scoring of the touchdown sink rate or distance along the runway) or on strictly subjective judgments.

There are indications in the closed-loop pilot-vehicle response parameters that the fidelity of the training simulator used in this study was deficient in at least one modality. The outside visual scene is most suspect; but the simulator motion system cannot be ruled out without further investigation nor, for that matter, can the simulator model implementation.

REFERENCES

1. Heffley, Robert K., Schulman, Ted M., Clement, Warren F., and Randle, Robert J., Jr., An Analysis of Airline Landing Data Based on Flight and Training Simulator Measurements, Systems Technology, Inc., Technical Report No. 1172-1 (forthcoming NASA CR), June 1981.

2. Randle, Robert J., Jr., Tanner, Trieve A., Hamerman, Joy A., and Showalter, Thomas H., The Use of Total Simulator Training in Transitioning Air-Carrier Pilots: A Field Evaluation, NASA TM 81250, January 1981.

3. McRuer, D. T., and Krendel, E. S., Mathematical Models of Human Pilot Behavior, AGARD-AG-188, January 1974.

4. Heffley, Robert K., Clement, Warren F., Ringland, Robert F., et al., Determination of Motion and Visual System Characteristics for Flight Simulation, Systems Technology, Inc., Technical Report No. 1162-1, April 1981.

5. Key, David L., (Ed.), Fidelity of Simulation for Pilot Training, AGARD Advisory Report No. 159, October 1980.

6. Smith, Jon M., Mathematical Modeling and Digital Simulation for Engineers and Scientists, John Wiley and Sons, New York, 1977, pp. 195-199.

7. White, Maurice D., Proposed Analytical Model for the Final Stages of Landing a Transport Airplane, NASA TN D-4438, April 1968.

8. Hoh, Roger H., Craig, Samuel J., and Ashkenas, Irving L., Identification of Minimum Acceptable Characteristics for Manual STOL Flight Path Control. Volume III: Detailed Analyses and Tested Vehicle Characteristics, FAA-RD-75-123, III, June 1976.

9. Bray, Richard S., A Piloted Simulator Study of Longitudinal Handling Qualities of Supersonic Transports in the Landing Maneuver, NASA TN D-2251, April 1964.

10. McRuer, Duane, Ashkenas, Irving, and Graham, Dunstan, Aircraft Dynamics and Automatic Control, Princeton University Press, Princeton, New Jersey, 1973.