# Means for Flying Qualities Improvement in Piloting Tasks Required Extremely High Accuracy

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**There are considered the results of ground based simulation of spot landing tasks required high accuracy: extremely short and carrier landing tasks. The problems of manual control (reversal performance situation, high pilot workload, possibility to loose the visual contact with touchdown point) are discussed. The head up display displaying additional information (projection of velocity on ground or sea surface and glide slope), direct lift control, auto throttle, regulation of outside TV camera zoom, and their integration were investigated to define the best way to solve the problem.**

## Nomenclature

| | | |
|---|---|---|
| $K_c$ | = | gain coefficient in DLC channel |
| $K_V$ | = | gain coefficient of auto throttle proportional law |
| $L$ | = | distance between aircraft and touchdown point |
| $M$ | = | aerodynamic pitching moment applied to aircraft |
| $M_q$ | = | $(1/I_y)(\partial M/\partial q)$ |
| $M_\alpha$ | = | $(1/I_y)(\partial M/\partial \alpha)$ |
| $M_{\delta_e}$ | = | $(1/I_y)(\partial M/\partial \delta_e)$ |
| $M_{\delta_D}$ | = | $(1/I_y)(\partial M/\partial \delta_D)$ |
| $PR$ | = | pilot rating |
| $PR_\theta$ | = | pilot rating of longitudinal flying qualities |
| $PR_\varphi$ | = | pilot rating of lateral flying qualities |
| $PR_\Sigma$ | = | pilot rating of aircraft flying qualities in multichannel task |
| $T$ | = | aircraft engine thrust |
| $T_e$ | = | time constant of engine aperiodic dynamics |
| t | = | time variable |
| Z | = | aerodynamic normal force applied to control element |
| $Z_\alpha$ | = | $(1/mV_0)(\partial Z/\partial \alpha)$ |
| $X_{th}$ | = | throttle deflection |
| $V_0$ | = | longitudinal component of trim translational velocity of aircraft |
| $V_i$ | = | calibrated airspeed |
| $1/T_{h1}$ | = | zero of transfer function $\gamma(s)/\delta_e(s)$ in phugoid motion |
| $h$ | = | altitude perturbation |
| $q$ | = | pitch rate perturbation |
| $\alpha$ | = | angle of attack |

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| | | |
|---|---|---|
| $s$ | = | Laplace operator |
| $\varepsilon$ | = | aiming angle $\varepsilon = \gamma + (h/L)$ |
| $\gamma$ | = | path angle |
| $\xi_{sp}$ | = | damping ratio for short period motion |
| $\omega_{sp}$ | = | short period frequency |
| $\sigma_x$ | = | mean square error of longitudinal touchdown point coordinate |
| *AI* | = | additional indication |
| *DLC* | = | direct lift control |
| *ESL* | = | extremely short landing |
| *HUD* | = | head up display |

## I. Introduction

The manual control of aircraft with unsatisfactory flying qualities and requirement of precise control may lead to the flight safety problem (for example to the pilot induced oscillations[1]). Such conditions of flight control are typical for the spot landing tasks such as carrier landing or extremely short landing (ESL). In these tasks pilot doesn't have necessary visual cues to close appropriate feedbacks. The ESL might be fulfilled in case of absence (or out of order) radio navigation ground landing system when pilot doesn't have any information about aircraft position relatively the glide slope and its derivative too. More then this, low landing speeds are typical for ESL and are accompanied by increase of angle of attack. It can lead to the loss of visual contact with the touchdown point and requires to develop the special means transmitted visual information in the cabin. In case of carrier task pilot has the discrete information about aircraft position relatively glide slope. Is doesn't allow him to estimate the derivative of position. In the both tasks the manual control is characterized by performance reversal situation when the zero $1/T_{h1}$ of transfer function $\gamma(s)/\delta_e(s)$ in phugoid motion becomes negative. It takes place because of high angle of attack at the spot landing speeds accompanied by the considerable increase of drag[2].

This peculiarity requires using two effectors: stick and throttle simultaneously in longitudinal channel[3]. Such type of control increases pilot workload and deteriorates his subjective rating of flying qualities. Requirement of high accuracy in the landing causes the pilot's stress, which can lead to the accident. Except the performance reversal situation the altitude aircraft transfer function $h(s)/\delta_c(s)$ is characterized by the second order of pole. It requires generating pilot high lead compensation and is accompanied by deterioration of accuracy. All these peculiarities require to define the best ways for the automation simplifying the process of piloting and providing the necessary accuracy. There are considered below some means for solution of the problem.

## II. Alternative Means of Aircraft Automation

There are considered below mainly the means allowed to improve the flying qualities at the landing in short period motion and to suppress the performance reversal situation too.

One of them is the additional indication (AI) of flight path vector and glide slope angle on head up display (HUD). The potentiality of AI was considered for the both spot landing tasks. The second mean investigated in carrier landing task was flight control system design based on use of direct lift control (DLC). The auto throttle was considered in carrier landing for comparison of its efficiency with DLC. This mean was the basic in ESL. In the both spot landing tasks it was investigated the potentiality of integration of different means too. For ESL it was investigated the possibility to carry out the precise landing task with information about the touchdown point transmitted by the TV camera installed at outside part of aircraft on display with variable zoom.

### A. Additional Information Generated by HUD

The additional symbols generated by HUD are the following:

Symbol 1 (immovable metric) corresponds to the required glide slope, $\gamma_c$. It might be generated by pilot at the initial stage of landing when he sees the stable green line of optical landing system and (or) when dissent rate and speed define the desired glide path angle.

Symbol 2 is the projection of velocity vector on ground (or sea) surface. Its position relatively to touchdown point corresponds to the angle, $\varepsilon = \gamma + h/L$. For high distance between aircraft and touchdown point the controlled element dynamics $\varepsilon(s)/\delta_c(s)$ is close to transfer function, $\gamma(s)/\delta_c(s)$, $\varepsilon(s)/\delta_c(s) \cong \gamma(s)/\delta_c(s)$. The decrease of $L$

transforms the dynamics to the following, $\varepsilon(s)/\delta_c(s) = M_\delta (s + V/L) / s^2 (s^2 + 2\xi_{sp}\omega_{sp} s + \omega_{sp}^2)$. In any case such dynamics requires lower pilot lead compensation then the dynamics corresponding to $h(s)/\delta_c(s)$.

A coincidence of the metrics $\gamma_c$ and $\varepsilon$ with the touchdown point located on carrier deck (carrier landing task) or on runway (ESL) was pilot's task. These symbols generated on HUD in carrier landing task are shown on Figure 1. The symbols allow to get the information about the angle of attack. The situation when the symbol 2 is below symbol 1 means that angle of attack is higher then programmed angle of attack. In that case pilot has to increase the velocity (increase a thrust) to restore angle of attack and visa versa. In case when the symbol 1 is below the selected point of touchdown, pilot has to increase path angle $\gamma$ by the stick deflection. The coincidence of both metrics with selected point of touchdown provides the aircraft motion along the glide slope with the required velocity.

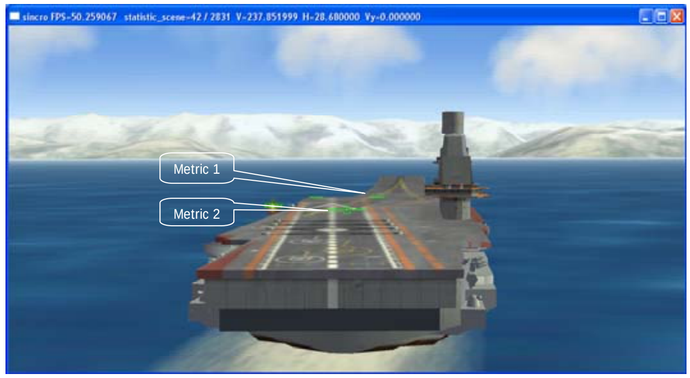

**Figure 1. Metrics generated on HUD for carrier task**

### B. Use of Direct Lift Control (DLC)

Use of direct lift control allows to realize the new dynamic modes, in particular flight with variable pitch angle and constant angle of attack. The flight with constant angle of attack suppresses the problem of performance reversal situation. Except it this mode allows to improve the controlled element dynamics in path short period motion. It can be shown by the following short period motion equations written in suggestion that pitch moment from DLC surface and lift force from elevator deflections are small, $M_{\delta_D} \cong Z_{\delta_e} \cong 0$.

$$q(s) - \alpha(s) Z_\alpha = Z_{\delta_D} W_1(s)\delta_c$$

$$q(s)(s - M_q) - \alpha(s) M_\alpha = M_{\delta_e} W_2(s)\delta_c$$

$W_1(s)$ - filter which output is the command signal for the DLC surface deflection,

$W_2(s)$ - filter which output is the command signal for the elevator deflection.

Realization of mode $\Delta\alpha = 0$ and $q = \mathrm{var}$ might be achieved when

$$\begin{vmatrix} 1 & Z_{\delta_D} W_1(s) \\ s - M_q & M_{\delta_e} W_2(s) \end{vmatrix} = 0$$

In case when $W_1(s) = K_C$ there is possible to get $\theta(s)/\delta_c(s) = \gamma(s)/\delta_c(s) = K_C (s + V/L) / s^2 (s - M_q)$.

For high values of parameter $L$ the transfer function $W_c(s) = \gamma(s)/\delta_c(s)$ becomes close to $W_c(s) = K_c/s$. Such dynamics allows to decrease pilot lead compensation and to improve accuracy.

### C. Auto Throttle Control

Such mean was investigated for comparison its efficiency with the results obtained in experiments with the considered above means. The auto throttle was considered with the simple proportional law. Engine dynamics was simulated by aperiodic law: $T_e\, dT/dt + T = T_{\max} \overline{X}_{th}$, where $T_e$ =0.6 s, $T_{\max}$ - maximum engine thrust.

## III. Results of Experimental Research

Experiments were fulfilled on MAI simulator with computer generated visual system. There were simulated some dynamic configurations, part of them was corresponded to Have PIO data base[4]. For each configuration there were fulfilled from 10 up to 20 trials. It allowed to estimate mean square error of longitudinal and lateral coordinate of touchdown point and other variables too. After each experiment pilot gave Cooper Harper and PIO ratings.

### A. Carrier Landing

The task performances were defined before the fulfillment of experiments. Their values are given in Table 1.

Experiments demonstrated that indication of additional information (AI) on HUD leads to decrease of mean square error in 1.5 ÷ 4 times in longitudinal channel and in 1.5 ÷ 3 times in lateral channel The typical experimental results of touchdown point for one of configuration are shown on fig. 2 Except it the accuracy of glide stabilization was improved up to 2 times. Cooper Harper pilot subjective ratings were improved in 1.5 ÷ 4 units for the different pilots (Figure 3). The use of DLC allowed to improve the performances even more. In particular longitudinal mean square error $\sigma_x$ of touchdown point decreases up to 4.5 ÷ 5 times and pilot rating up to 3.5 ÷ 4 units. In case of DLC pilot doesn't change practically the position of throttle lever (Figure 4). This result demonstrates the suppression of reversal control. Simultaneous use of DLC and AI on HUD allows to improve the mean square error of longitudinal coordinate of touchdown point up to 20% and pilot rating up to 1 unit additionally (Figure 5 and Figure 6). Use of auto throttle allows to get approximately the same accuracy as use of DLC during the glide path stabilization. However the integration of auto throttle and HUD indication did not lead to the additional improvement of pilot rating. As for touchdown point variability the use of auto throttle with AI on HUD did not lead to improvement of accuracy.

**Table 1. Task performances in carrier landing task.**

| Desired performance | Adequate performance |
|---|---|
| Deviation from glide path | |
| Inside 3 colors | Inside 5 colors |
| Deviation from touchdown point | |
| Longitudinal coordinate: touchdown between 2nd and 3rd arresting wires | Longitudinal coordinate: touchdown between 1st and 4th arresting wires |
| Lateral coordinate: ±1,5 m | Lateral coordinate: ±2,5 m |
| Landing velocity: $V_l$ = 240 - 250 km/h | Landing velocity: $V_l$ = 235 - 260 km/h |

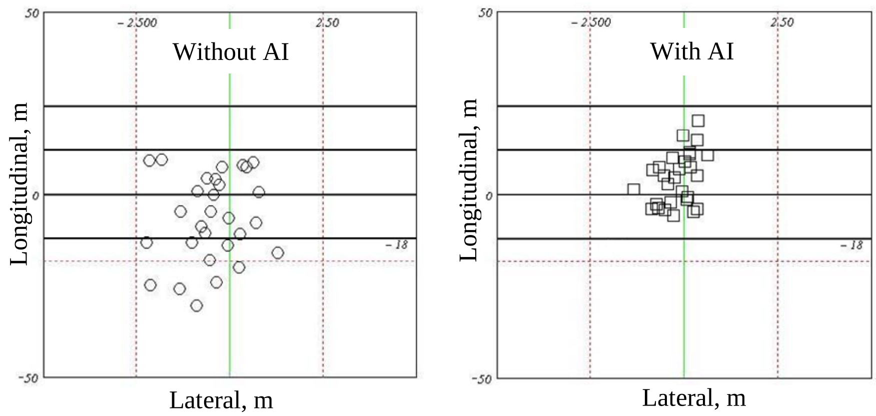


**Figure 2. Touchdown point variability.**

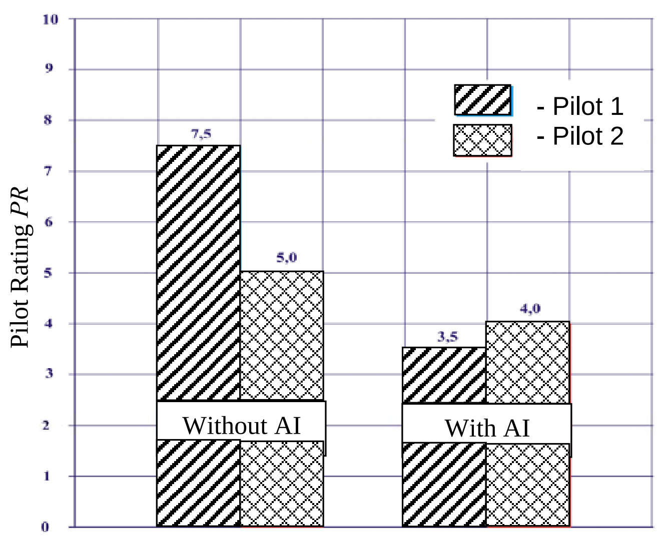


**Figure 3. Influence of AI on pilot rating.**

## B. The Extremely Short Landing (ESL)

The ESL with low speeds is characterized by a number of manual control problems especially in case when radio navigation ground landing system is out of order. There are the following:

- Absence of glide path information;
- Absence of visual contact with ground in case when the landing speed is about $V_l$ = 180 km/h and angle of attack $\alpha$ >20 deg;
- Reversal path control;
- Considerable deterioration of flying qualities in lateral channel as a result of bank and yaw coupling.

The experiments were fulfilled in two phases. During the first, preliminary stage, there were defined the means of automation provided the possibility to carry out the landing with the preliminary defined task performances. At the second stage there were made more precise requirements to these means with task performances defined more accurately after the first stage. The experiments were fulfilled on the same simulator, which was used for the carrier landing research with computer generated image corresponding to the investigated task. Pilots had to evaluate the flying qualities in both channels for a number of configurations. Except ratings of flying qualities in longitudinal ( $PR_{\vartheta}$ ) and lateral ( $PR_{\varphi}$ ) channels, pilot evaluated the total pilot rating $PR_{\Sigma}$ . The analysis of the results demonstrated that total pilot rating in landing task is defined by pilot according to the rule:

$$PR^{*}_{\Sigma} = \max(PR_{\theta}, PR_{\gamma})$$

Such way of definition of total pilot rating gave excellent agreement with $PR_{\Sigma}$ (figure 7)

The desired and adequate task performances are given in Table 2.

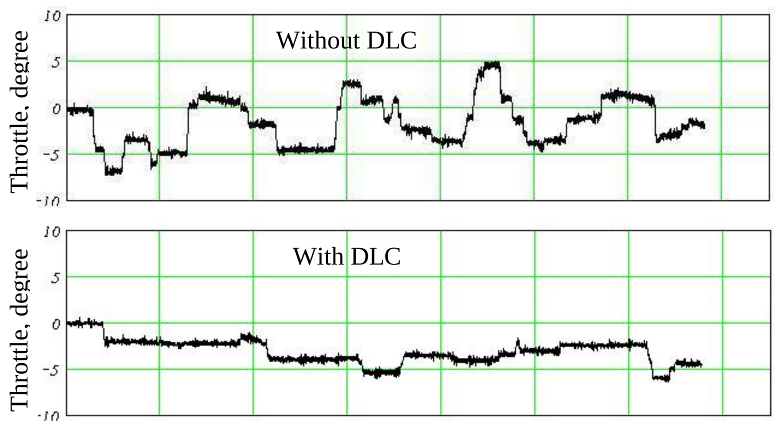


**Figure 4. Deflection of throttle in landing.**

In case of landing with high angle of attack ( $\alpha$ >20 deg) the visual information of aircraft position relatively the runway pilot may receive by installation of TV camera at the fuselage and transmission of the signal to the HUD. Except such visual information the additional information has to be generated on the same screen: projection of velocity vector and glide slope angle. Such visual information allows pilot to carry out landing. The use of auto throttle improves the accuracy of the ESL considerably even for small gain coefficient ( $K_v$ = 0.05). The following increase of this gain up to $K_v$ = 0.1 leads to decrease of mean square error of longitudinal touchdown coordinate up to 3.5-3.8 m (instead of 16 m corresponds to the landing without auto throttle, Figure 8). The influence of zoom and automation in lateral channel was investigated at the second phase. Because of the modern cameras have the potentiality to change zoom automatically it was investigated the influence of gain coefficient of transmitted picture $K_m$ (the last is the ratio of TV camera angle of view to HUD angle of view). It was shown that in case of small value of $K_m$ ( $K_m$ = 0.7) pilot had problems to recognize the touchdown point for considerable distance from it. Increase of $K_m$ from $K_m$ =0.7 up to 1 led to decrease of $PR_{\theta}$ up to 2.5 units during the approach and up to 2 units during the final stage of approach. The pilot ratings of flying qualities in lateral channel improved up to 1 unit too. More detail investigations of zoom's gain coefficient demonstrated the necessity

**Table 2. Task performances in ESL.**

| Parameter | |
|---|---|
| Longitudinal touchdown point | Desired ±10 m<br>Adequate ±20 m |
| Lateral touchdown point | Desired ±1.5 m<br>Adequate ±7 m |
| Dissent rate | Desired 3 - 4 m/s<br>Adequate 2.5 – 4.5 m/s |
| Glide path accuracy | Desired ±0.5 of indicator metric<br>Adequate ±1 of indicator metric |
| Variability of velocity | Desired ±5 km/h<br>Adequate ±8 km/h |

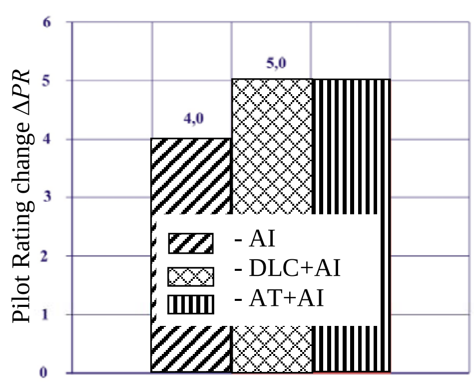


**Figure 5. Influence of integration of AI with DLC or AT on Pilot rating.**

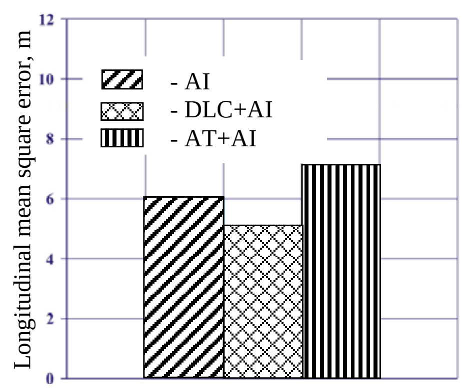


**Figure 6. Influence of integration of AI with DLC or AT on accuracy of landing.**

to change $K_m$ discretely. At the distance equals 1 km from touchdown point it might be decreased from $K_m$ =1.25÷1.5 up to $K_m$ = 1. Such law of gain $K_m$ regulation improves the pilot rating up to 1 unit approaching the pilot ratings to the ratings of flying qualities obtained in landings fulfilled with higher velocity ($V_l$ = 250 km/h). Improvement of flying qualities in lateral channel may be achieved by use of bank angle feedback. Such feedback leads to decrease of $PR_\gamma$ up to 1 unit.

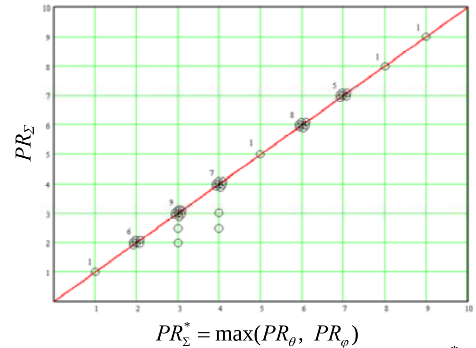


**Figure 7. Correlation between $PR_\Sigma$ and $PR_\Sigma^*$.**

For the both spot landing tasks all pilot gave the comments that increase of PIO tendency took place when they tried to coincide the projection of velocity vector with aiming touchdown point at small distance $L$. Such event is explained by the considerable influence of $h(s)/L$ on transfer function $W_c = \varepsilon(s)/\delta_c(s) = (\gamma(s) + h(s)/L)/\delta_c(s)$. Decrease of parameter $L$ leads to influence of path motion on this transfer function and deterioration of flying qualities.

It was developed the piloting technique for suppression of PIO tendency. According to it at the final stage of landing (2 - 3 s before touchdown) pilot has to change the strategy and instead of to control the angle $\varepsilon$ he has to coincide the symbols of projection of velocity vector and required path angle. In that case controlled element dynamics is defined by path angle which is not depended on parameter $L$. Such piloting technique allowed to avoid PIO tendency and to keep high accuracy.

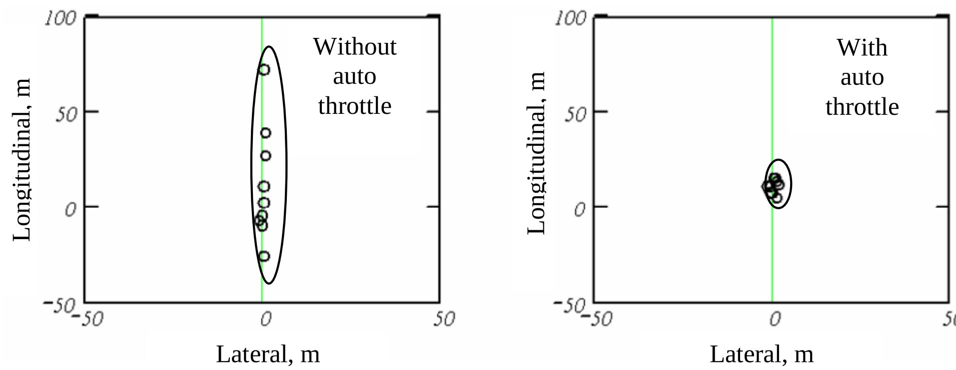


**Figure 8. Variability of touchdown point.**

## IV. Conclusion

Usage of additional information about the projection of velocity vector and glide slope allowed to improve accuracy of landing in the both spot landing task. Simultaneous usage of DLC allowed to improve accuracy, pilot ratings and to suppress performance too. The successful fulfillment of ESL requires usage of auto throttle and installation of outside TV camera with variable zoom to restore the visual contact with ground surface in case of landing with high angle of attack

## References


[1]*Aviation Safety and Pilot Control. Understanding and Preventing Unfavorable Pilot-Vehicle Intrgration*, National Academy Press, Washington DC, 1997.

[2]McRuer, D., Ashkenas, I., and Graham, D., *Dynamics and Automatic Control*, Princeton University, Princeton, 1973.

*Periodicals*

[3]McRuer, D., and Ashkenas, I., "A Theory of Handling Qualities Derived from Pilot-Vehicle System Consideration," *Aerospace Engineering*, Vol. 21, No. 2, 1982.

[4]Bjorkman, E. A., Eidsaune, D. W., Wilkinson, O. C., Bennett, R. L., and Miyahoto, S., "NT33 Pilot Induced Oscillation Evaluation," USAF TPS-TR-85B-S4, June, 1986.