IN-FLIGHT SIMULATOR CONTROLLER DESIGN AND EXPERIMENTAL RESULT

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Keywords: *In-Flight Simulator, inverse system, flight test*

Abstract

This paper describes the flight controller design for an experimental aircraft Multi-Purpose Aviation Laboratory-α (MuPAL-α) to be an In-Flight Simulator (IFS), and the primitive experimental results using our designed controllers to verify the possibility of MuPAL-α as an IFS for the handling quality check of aircraft which will be developed in the future.

1 Introduction

Since 1940s, the effectiveness of In-Flight Simulators (IFSs) for the evaluation of handling qualities of newly developed aircraft has widely been recognized. This has led to many IFSs [1], and the Japan Aerospace Exploration Agency (JAXA) has also developed an IFS, Multi-Purpose Aviation Laboratory-α (MuPAL-α) depicted in Fig. 1. In 2007, Mitsubishi Heavy Industries, Ltd. (MHI) announced a plan to develop a new regional jet aircraft, Mitsubishi Regional Jet (MRJ). Under these backgrounds, we verify whether or not MuPAL-α can be really used for the evaluation of handling qualities of aircraft which will be developed in the future.

This paper reports the flight controller design for MuPAL-α to be an IFS, and the results of primitive flight experiments, which were conducted around Noto airport in Japan in November 2009, using our designed controllers. The main purpose of the experiments is to verify the applicability of MuPAL-α as an IFS, not the pilot evaluation of handling qualities of the target aircraft model[1].

Fig. 1 MuPAL-α

2 Flight Controller Design

The block diagram for designing flight controllers of MuPAL-α is shown in Fig. 2. Our task is to design the feedback and feedforward controllers which realize the handling characteristics of the target aircraft model denoted as "Model" in Fig. 2. Most of the existing papers addressing the flight controller design for IFSs, e.g. [2, 3, 4, 5], use feedback controllers as well as feedforward controllers. However, feedback controllers change the gust characteristics, i.e. the responses driven by wind gust, of IFSs; that is, MuPAL-α with some feedback controllers might have completely different gust characteris-

[1] In this paper, we call the model whose handling characteristics are to be realized with MuPAL-α as the target aircraft model.

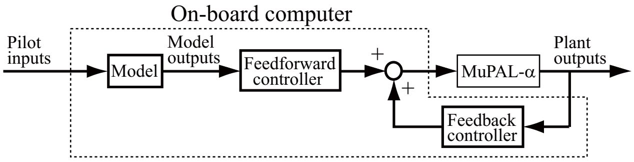

Fig. 2 Block Diagram

tics from the original ones. If this happens, the pilot might not be able to evaluate the handing qualities of the target aircraft model. One of the promising methods to prevent such troubles is realize handling characteristics of the target aircraft model with only feedforward controllers.

In general, feedforward controllers have no robustness against the uncertainties of the plant, e.g. modeling errors, uncertain delays of onboard systems, etc. However, we have already confirmed that appropriately designed feedforward controllers can realize handling characteristics of the target aircraft in [6], where only simple feedback controllers are used to reduce the initial trim errors that inevitably exist for flight tests. As the onboard actuator systems were renewed from the paper, in this paper, we newly design flight controllers of MuPAL-α, which have the same controller structure as in [6], and conduct the primitive flight experiments to verify the applicability of MuPAL-α as a tool for the evaluation of handling qualities.

2.1 Design Method

As mentioned above, feedforward controllers play a key role to make MuPAL-α be an IFS in our design. We use inverse systems as the feedforward controller, similarly to [6]. The detailed descriptions for designing inverse systems using H_∞ control problem is given in [6], we briefly review the method in the sequel.

Suppose that the linearized motion model of MuPAL-α at some equilibrium point is given as P, the linearized model of onboard actuators is given as P_a, and appropriately designed stabilizing feedback controller is given as K. Using P, P_a and K, the augmented stabilized motion model of MuPAL-α is supposed to be given as G. Furthermore, an appropriately set stable diagonal weighting function W, which in general has large gain in the low frequencies, is given. Under these preliminaries, if $\overline{G}$ is designed as a stable system which satisfies (1), then the $\overline{G}$ almost works as an inverse system of G in the low frequencies.

$$\|W(s)\left[G(s)\overline{G}(s)-\mathbf{I}\right]\|_\infty < 1, \qquad (1)$$

where $G(s)$, $\overline{G}(s)$ and $W(s)$ respectively denote the transfer functions of G, $\overline{G}$ and W, $\mathbf{I}$ denotes an identity matrix with compatible dimensions, and $\|X(s)\|_\infty$ denotes the H_∞ norm of the transfer function $X(s)$.

To be more precisely, the system $\overline{G}$ has the following inverse performance [6].

$$\begin{array}{l} |P_{o_{ll}}(j\omega)-1| < 1/\zeta(\omega),\ \forall l \\ |\angle P_{o_{ll}}(j\omega)| < \arcsin 1/\zeta(\omega),\ \forall l \\ |P_{o_{lm}}| < 1/\zeta(\omega),\ \forall l,m\ l\neq m \end{array} \qquad (2)$$

where $\zeta(\omega)(>1)$ denotes the minimum gain of W at frequency ω, and $P_{o_{lm}}$ denotes the (l,m) entry of the cascaded system of G and $\overline{G}$, i.e. $P_o = G\overline{G}$.

Obtaining a stable $\overline{G}$ which satisfies (1) is just solving an H_∞ control problem, which is easily done with the aid of some software, such as, LMI Control Toolbox® [7].

Thus, our design procedures are summaries as follows.

1. Design feedback controllers which are only for stabilizing the linearized motion model of MuPAL-α at the design point,
2. then set a weighting function $W(s)$ so that design specifications for inverse systems are satisfied, and
3. finally solve an H_∞ control problem for satisfying (1) and obtain $\overline{G}$.

2.2 Controller Design for MuPAL-α

We design flight controllers for MuPAL-α under the following flight conditions.

Approach and landing phase Steady descending flight at TAS = 59.8 [m/s] and H = 61.0 [m] with angle of descent $\gamma = -3$ [deg].

Table 3 Variable Definitions

u_i	inertial forward-backward velocity
u_g	forward-backward gust velocity
u_a	forward-backward airspeed
v_i	inertial side velocity
v_g	side gust velocity
v_a	side airspeed
w_i	inertial vertical velocity
w_g	vertical gust velocity
w_a	vertical airspeed
p	roll rate
q	pitch rate
r	yaw rate
ϕ	roll angle
θ	pitch angle
τ	engine torque
δ_e	elevator deflection
δ_{DLC}	Direct Lift Control (DLC) flap deflection
δ_{pl}	power lever deflection
δ_a	aileron deflection
δ_r	rudder deflection

Cruise phase Steady straight and level flight at TAS = 75.4 [m/s] and H = 1520 [m].

Note that, in cruise phase, only a longitudinal flight controller is designed.

The state variables, control input, etc., are summarized in Tables 1 and 2, which are at the top of the next page. The variables used in Tables 1 and 2 are given in Table 3.

The onboard actuator dynamics are modeled as follows.

$$\left\{\begin{array}{lcl} \delta_e & = & \frac{k_e}{0.02s+1}e^{-0.21s}\delta_{e_c} \\ \delta_{DLC} & = & \frac{0.94}{0.05s+1}e^{-0.13s}\delta_{DLC_c} \\ \delta_{pl} & = & 0.98e^{-0.13s}\delta_{pl_c} \end{array}\right. \qquad \left\{\begin{array}{lcl} \delta_a & = & \frac{0.67}{0.12s+1}e^{-0.23s}\delta_{a_c} \\ \delta_r & = & \frac{k_r}{0.07s+1}e^{-0.13s}\delta_{r_c} \end{array}\right. \tag{3}$$

where the variables with subscript "c", e.g. δ_{e_c}, denote the commands of the related variables. Here, k_e and k_r are given as follows.

$$k_e = \begin{cases} 0.70 \text{ (Approach and landing phase)} \\ 0.65 \text{ (Cruise phase)} \end{cases} \quad k_r = \begin{cases} 0.76 \text{ (Approach and landing phase)} \\ 0.72 \text{ (Cruise phase)} \end{cases} \tag{4}$$

As the linearized motion models of the longitudinal motions are stable in both approach and landing phase, and cruise phase, no feedback controllers are designed. However, the linearized motion model of the lateral-directional motions in approach and landing phase is unstable, the following feedback controller is implemented to stabilize it.

$$\delta_{a_c} = 0.3\phi \tag{5}$$

The weighting functions for designing inverse systems are set as follows.

$$W(s) = \begin{cases} \frac{6.1}{s+0.3} I_3 \text{ (Longitudinal motions)} \\ \frac{7.1}{s+0.35} I_2 \text{ (Lateral – directional motions)} \end{cases} \tag{6}$$

where I_3 and I_2 respectively denote identity matrices of order 3 and 2.

The weighting functions (6) produce inverse systems which have inverse performance given in Tables 4 and 5, which are on the next page. In other words, roughly speaking, our designed controllers realize the handling characteristics of the target aircraft model within about 30 [%] error under 2 [rad/s].

After descritizing the obtained inverse systems using Tustin transformation with 0.02 [s], we implement them to the onboard computer of MuPAL-α.

3 Experimental Results

Using our controllers, we conducted flight experiments around Noto airport in Japan in November 2009.

As we designed two flight controllers for two different flight conditions, we conducted two applicability experiments, i.e. handling quality check in approach and landing phase, and that of climbing-up supposed to be caused by Airborne Collision Avoidance System (ACAS) resolution advisory was issued.

Table 1 Variables for MuPAL-α's Longitudinal Motion

state	$[u_i\,[\mathrm{m/s}]\ w_i\,[\mathrm{m/s}]\ q\,[\mathrm{rad/s}]\ \theta\,[\mathrm{rad}]\ \tau\,[\%]]^T$
gust	$[u_g\,[\mathrm{m/s}]\ w_g\,[\mathrm{m/s}]]^T$
control input	$[\delta_e\,[\mathrm{rad}]\ \delta_{DLC}\,[\mathrm{rad}]\ \delta_{pl}\,[\mathrm{mm}]]^T$
controlled output	$[u_a\,[\mathrm{m/s}]\ w_a\,[\mathrm{m/s}]\ \theta\,[\mathrm{deg}]]^T$
measurement output	$[u_a\,[\mathrm{m/s}]\ w_a\,[\mathrm{m/s}]\ q\,[\mathrm{rad/s}]\ \theta\,[\mathrm{rad}]]^T$

Table 2 Variables for MuPAL-α's Lateral-Directional Motion

state	$[v_i\,[\mathrm{m/s}]\ p\,[\mathrm{rad/s}]\ \phi\,[\mathrm{rad}]\ r\,[\mathrm{rad/s}]]^T$
gust	$v_g\,[\mathrm{m/s}]$
control input	$[\delta_a\,[\mathrm{rad}]\ \delta_r\,[\mathrm{rad}]]^T$
controlled output	$[\phi\,[\mathrm{deg}]\ r\,[\mathrm{deg/s}]]^T$
measurement output	$[v_a\,[\mathrm{m/s}]\ p\,[\mathrm{rad/s}]\ \phi\,[\mathrm{rad}]\ r\,[\mathrm{rad/s}]]^T$

Table 4 Guaranteed Performance by W in (6) (Longitudinal Motions)

Frequency [rad/s]	$1/\zeta(\omega)$
0 – 0.05	< 0.05
0.05 – 0.5	< 0.1
0.5 – 1.1	< 0.2
1.1 – 2.0	< 0.34

Table 5 Guaranteed Performance by W in (6) (Lateral-Directional Motions)

Frequency [rad/s]	$1/\zeta(\omega)$
0 – 0.06	< 0.05
0.06 – 0.6	< 0.1
0.6 – 1.3	< 0.2
1.3 – 2.0	< 0.3

3.1 Approach and landing phase

Before conducting the pilot evaluation of the applicability of MuPAL-α, we conducted flight experiments in which controller performance was to be checked.

The results are shown in Figs. 3 and 4.

In Fig. 3, the pilot task is as follows.

1. Keep level flight,
2. pitch up for a prescribed angle Δ_θ and keep the pitch angle,
3. recover the initial pitch angle and keep it,
4. pitch down for Δ_θ and keep it,
5. pitch up for $2\Delta_\theta$ and keep it, and
6. finally pitch down for $2\Delta_\theta$ and keep it.

In Fig. 4, the pilot task is as follows.

1. Keep level flight,
2. right bank for a prescribed angle Δ_ϕ and keep the bank angle,
3. recover the level flight and keep it,
4. right bank for $2\Delta_\phi$ and keep it,
5. recover the level flight and keep it,
6. left bank for Δ_ϕ and keep it,
7. recover the level flight and keep it, and
8. finally left bank for $2\Delta_\phi$ and keep it.

As our controllers have neither servo mechanism nor tracking mechanism, the discrepancies of the controlled outputs do not converge to zeros. However, Figs. 3 and 4 demonstrate that our designed controllers almost realize the handling characteristics of the target aircraft model.

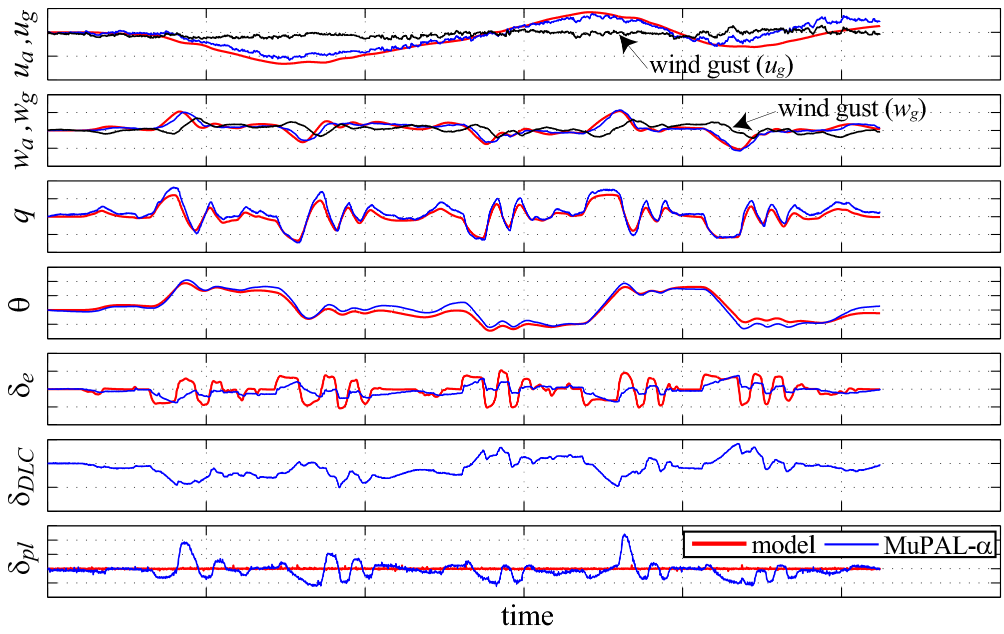

Fig. 3 Time History (Longitudinal Motions)

As our designed controllers have satisfactory performance as IFS's flight controllers, we next verify the applicability of MuPAL-α as a tool for the evaluation of handling qualities in approach and landing phase.

Fig. 5 shows the time histories of the flight experiment, in which the pilot task is to keep MuPAL-α on ILS course. Fig. 6 shows the time histories of the flight experiment, in which the pilot task is to keep the prescribed offset for localizer (LOC) and glide slope (GS) indicators for a prescribed interval then converge those to zeros with appropriate pilot control inputs.

In both experiments, our lateral-directional flight controllers have satisfactory performance. On the other hand, our longitudinal flight controllers have some discrepancies. However, the pilot evaluates that MuPAL-α can be used as a tool for the evaluation of handling qualities.

3.2 Cruise phase

Similarly to the previous experiments, we first conducted flight experiments in which controller performance was to be checked.

As the airspeed of the target aircraft model is almost double as that of MuPAL-α, the vertical speed w_a driven by pilot inputs becomes very large for the target aircraft model even with a small change of pitch angle. Considering this property, we multiplies the vertical speed of the target aircraft model with 0.1 in order to disregard the realization of the vertical speed.

After the above revision, we conducted flight experiments in which the controller performance was checked. Fig. 7 shows the result. Although as the realization of the vertical speed is disregarded, there is a large discrepancy between w_a of MuPAL-α and that of the target aircraft model, MuPAL-α almost realizes the forward-backward speed and the pitch angle of the target aircraft.

Next, we verify the applicability of MuPAL-α as a tool of the evaluation of handling qualities in sudden climbing-up situations from the steady cruise flight, in which it is supposed that ACAS resolution advisory is issued. The result is shown in Fig. 8. As MuPAL-α almost realizes the forward-backward velocity and the pitch angle of the target aircraft model, we conclude that MuPAL-α can in part work as an IFS even if the supposed flight conditions of the target aircraft model is much different from those of MuPAL-α.

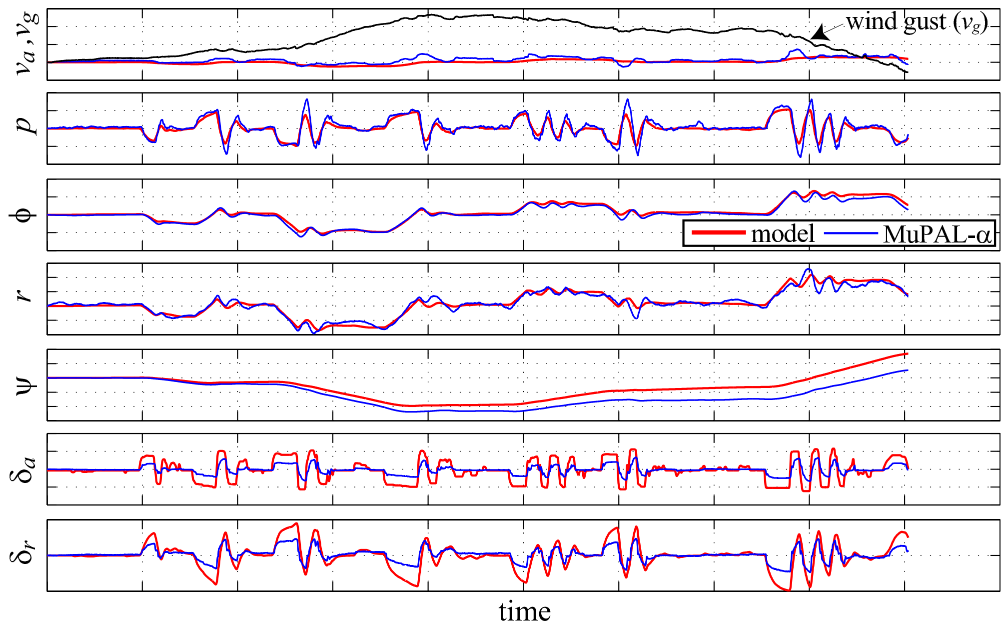

Fig. 4 Time History (Lateral-Directional Motions)

However, the experiments also conclude that MuPAL-α has some limitations as an IFS for checking the handling characteristics of target aircraft models; that is, MuPAL-α cannot be fully used as an IFS for target aircraft which are in much different flight conditions.

4 Summary

This paper reports the flight controller for our experimental aircraft MuPAL-α to be an In-Flight Simulator (IFS). The controller is composed of simple stabilizing feedback controllers and inverse systems as the feedforward controller. Using our flight controllers, we conducted flight experiments to verify the applicability of MuPAL-α as an IFS. The experiments confirm that MuPAL-α with our designed controllers can be used as an IFS in approach and landing phase; however, they also reveal that it is difficult to use MuPAL-α as an IFS for target aircraft under much different flight conditions.

5 Acknowledgement

The authors really appreciate Mitsubishi Heavy Industries, Ltd. for the kind supply of aircraft dynamics model. They are also indebted to invaluable supports of Ms. Iida, Mr. Okada, Mr. Masui, and Mr. Funabiki.

References

[1] Weingarten N. C. History of in-flight simulation at General Dynamics. *Journal of Aircraft*, Vol. 42, No. 2, pp. 290–298, 2005.

[2] Motyka P. R., Rynaski E. G. and Reynolds P. A. Theory and flight verification of the TIFS model-following system. *Journal of Aircraft*, Vol. 9, No. 5, pp. 347–353, 1972.

[3] Komoda M., Kawahata N., Tsukano Y. and Ono T. VSRA in-flight simulator—its evaluation and applications. *AIAA Flight Simulation Technologies Conference*, Atlanta, Georgia, AIAA Paper 88-4605-CP, 1988.

[4] Hanke D. and Lange H. H. Flight evaluation of the ATTAS digital fly-by-wire/light flight control system. *Proceedings of ICAS 16th Congress*, Jerusalem, Israel, pp. 866–876, 1988.

[5] Sato M. and Satoh A. Simultaneous Realization of Handling and Gust Responses: In-Flight Simulator Controller Design. *Journal of Guidance, Control, and Dynamics*, Vol. 31, No. 6, pp. 1545–1560, 2008.

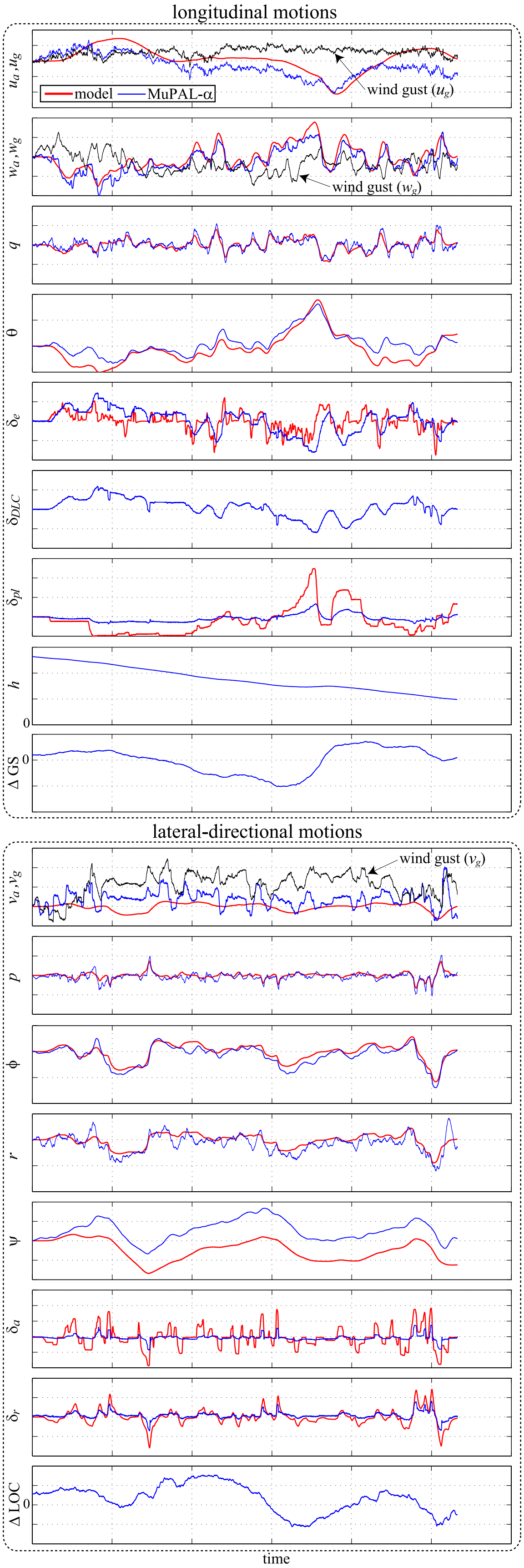

Fig. 5 Time History (ILS Approach)

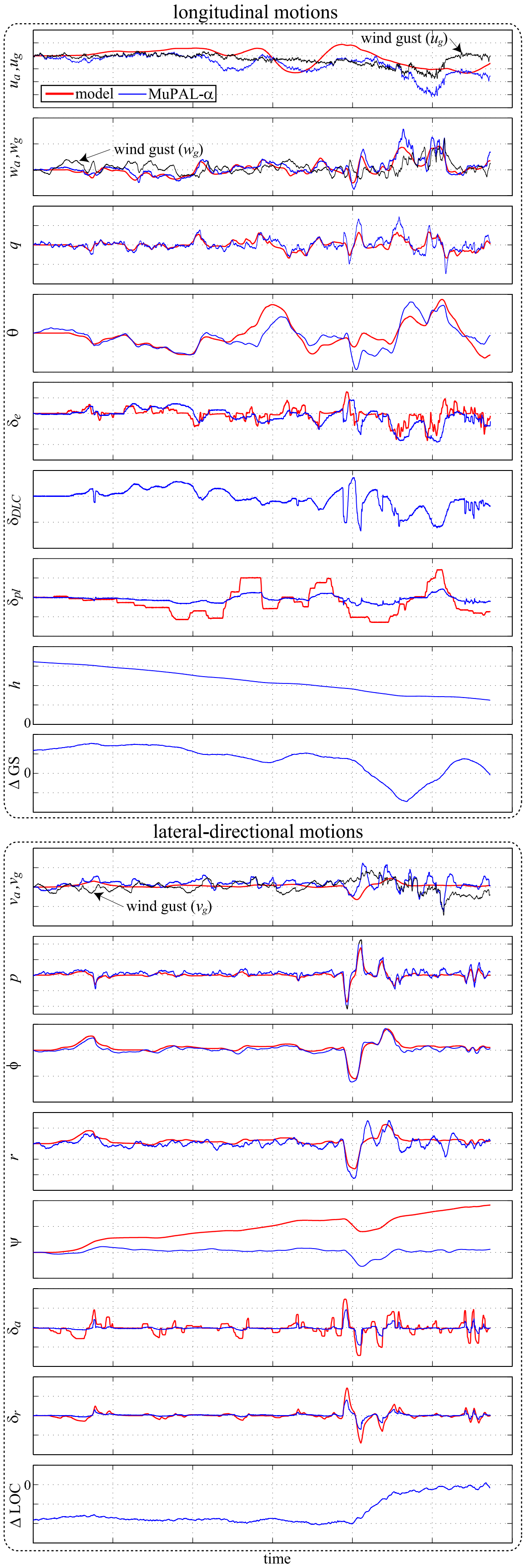

Fig. 6 Time History (ILS Offset Approach)

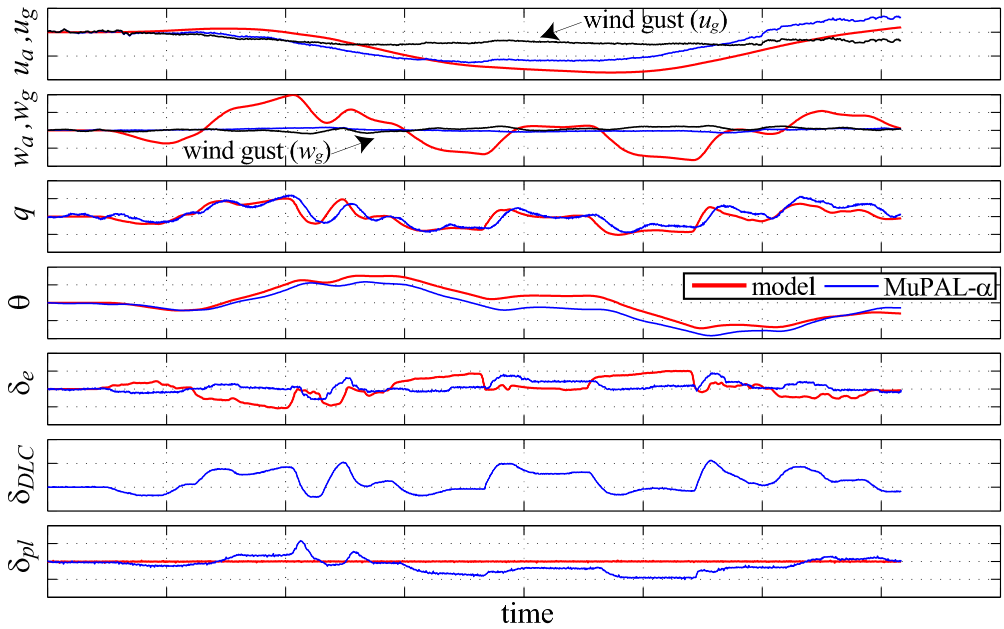

Fig. 7 Time History (Longitudinal Motions)

[6] Sato M. Flight test of model-matching controller for in-flight simulator MuPAL-α. *Journal of Guidance, Control, and Dynamics*, Vol. 29, No. 6, pp. 1476–1481, 2006.

[7] Gahinet P., Nemirovskii A., Laub A. J. and Chilali M. *LMI Control Toolbox User's Guide*. The Math Works Inc., Natick, MA, 1995.

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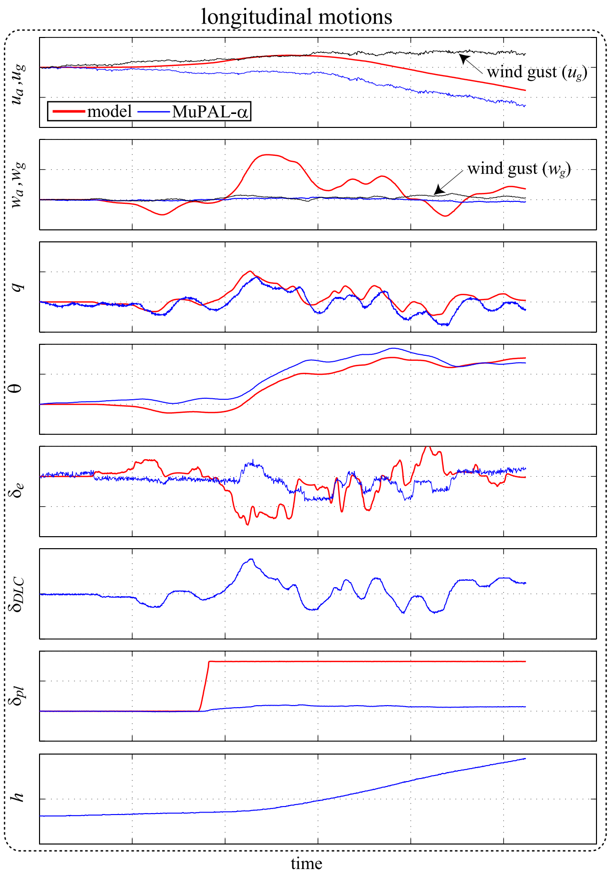

Fig. 8 Time History (Sudden Climbing-Up)