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MANEUVERABILITY ASSESSMENT FOR FAULTY AIRPLANE BY IFS WITH SIMULTANEOUS MODEL-MATCHING FOR GUST AND HANDLING RESPONSES

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Abstract

The research on fault tolerant flight control has been increasingly conducted over the last two decades. However, it has not been fully cleared that stability as well as maneuverability must be recovered, or at least maneuverability should be recovered. To investigate this issue, we realize the situation in which gust response characteristics as well as handling response characteristics of other airplane are simultaneously mimicked by an In-Flight Simulator (IFS), and examine the maneuverability assessment of the airplane under the conditions that its Dutch-roll mode is marginally stable or sufficiently stable. The flight tests confirm that i) a faulty airplane with its Dutch-roll mode being marginally stable is controllable by manual pilot inputs as long as control devices are operative, and ii) there is a maneuverability problem even for an aircraft with sufficiently stable Dutch-roll mode if control device authority is severely deteriorated. This consequently verifies that maneuverability recovery should be the primal requirement in fault tolerant flight controller design.

1 Introduction

It is well known that one of the saddest aircraft accidents in the world is Japan Airlines Flight 123 accident with over 500 casualties. The official investigation reports have been issued [1, 2]. Those reports identified that this tragedy was caused by the loss of aerodynamic control devices, i.e. ailerons, rudders, elevators, spoilers, etc., and this full loss of control devices was driven by the loss of hydraulic pressure due to the destruction of the rear pressure bulkhead in the fuselage. Due to the loss of aerodynamic control devices, not only the maneuverability but also the stability of aircraft motions were severely deteriorated at the same time. Thus, the damping of oscillatory motions, e.g. Phugoid mode and Dutch-roll mode, became drastically decreased, and the uncomfortable motions continued until the crash of the airplane [1, 2].

In the researche on so-called "Propulsion Controlled Aircraft" (in short "PCA") [3], it has been well demonstrated that it is possible to control the faulty airplane with only thrust. This fact indicates that there might be a (*small but not zero*) possibility that the number of casualties in Japan Airlnes Flight 123 accident was decreased by using the onboard multiple operative engines. However, in those researches apart from the case of using F15 [3], the decrease of the stability of airplane motions was not realized but only aerodynamic control devices were supposed to be inoperative; that is, the very low damping oscillatory motions excited by wind gust were not realized[1].

[1] The damping of the oscillatory motions of F15 without flight control was very low; however, the damping of the oscillatory motions of MD-11 was moderately kept because there was no damage on its fuselage. This is a sharp contrast to Japan Airlines Flight 123 accident in which the vertical tail fin broken up and this damage introduced the very low damping of Dutch-roll mode.

Fig. 1 In-Flight Simulator (IFS) MuPAL-α

Fault tolerant flight control and fault detection/diagnosis have been recognized as the promising tools to diminish such tragedies as Japan Airlines Flight 123 accident, and there have been many reports on this topic over the last two decades, e.g. [4, 5, 6, 7, 8, 9]. In those papers, fault tolerant control is designed to recover control performance (such as, tracking performance with respect to manual pilot input) under supposed faulty situations. Though, it has not been fully cleared that control performance related to stability as well as maneuverability must be recovered, or at least control performance related to maneuverability should be recovered.

From the research background above, by using one of JAXA's research airplane MuPAL-α [10] shown in Fig. 1, we investigate the maneuverability assessment for marginally stabilized and sufficiently stable lateral-directional motions with IFS (In-Flight Simulator [11]) functionality of MuPAL-α. The objective of this investigation is as follows.

- Confirmation of the fact that airplanes even with severely deteriorated stability are controllable by pilot input as long as the control devices are operative.

To this end, we implement the flight controller used in [12] to MuPAL-α, and we realize the situations in which the gust response as well as the handling response of a Boeing 747 model with marginally stable or sufficiently stable Dutch-roll mode are mimicked. (In this paper, we use a Boeing 747 model with landing configuration [13] as the model.) Using this MuPAL-α, we conducted flight tests for the maneuverability assessment with the faulty or normal Boeing 747 model under real environment. The flight tests confirm that, even in the situation that Dutch-roll damping is severely deteriorated, controllability is kept and a faulty airplane is controlled by manual pilot inputs as long as control devices are operative. Thus, it is consequently verified that maneuverability recovery is the primal design requirement in fault tolerant flight controller design.

This paper is organized as follows: Section 2 briefly reviews MuPAL-α and the implemented flight controller with its performance verification (the details for designing the flight controller can be found in [12]); Section 3 shows the flight tests with the Boeing 747 model with well stabilized Dutch-roll mode but reduced controllability, and with the Boeing 747 model with marginally stabilized Dutch-roll mode; and finally Section 4 gives concluding remarks.

2 In-Flight Simulator MuPAL-α

From [11], "IFS" represents an aircraft which has an ability to mimic other aircraft motions. The *similarity* for mimicking other aircraft motions heavily depends on the number of the implemented control devices. For example, Total In-Flight Simulator (TIFS), which has already retired, was implemented with Direct Lift Control (DLC) surfaces and side force generator fins. Thus, TIFS had an ability to mimic six-degree freedom motions of other aircraft thanks to those two additional control devices [14, 15]. In contrast to TIFS, MuPAL-α has been implemented with DLC flaps only, thus MuPAL-α mimics five-degree freedom motions of other aircraft; that is, three variables in longitudinal motions and two variables in lateral-directional motions.

In 2000, MuPAL-α was developed as an IFS based on Do228-202 [10]. It has been used as a testbed for demonstrating up-to-date control techniques, e.g. [12, 16, 17], guidance methods, etc. Although there inevitably exist some un-

certainties related to onboard actuator systems, the linearized airplane motion models at certain equilibrium points faithfully represent the motions of MuPAL-α, as demonstrated in several papers [18, 12, 17].

2.1 Flight Controller

In this paper, the flight controller is required to simultaneously mimic the handling response and the gust response of Boeing 747 models with marginally stable or sufficiently stable Dutch-roll mode. From the theoretical viewpoint, as demonstrated in [18], it is possible to design a flight controller which realizes the gust response of the Boeing 747 models; however, several trial-and-errors indicate that an appropriate longitudinal flight controller for realizing the gust response of the Boeing 747 models cannot be designed. This comes from that the aerodynamic characteristics of MuPALα are far from those of the Boeing 747 models. We thus adopt the same controller designed in [12] in this paper; that is, the flight controller in [12] which simultaneously realizes gust suppression and handling responses for a variety of models without controller re-design is adopted.

In this case, gust response of MuPAL-α is suppressed as much as possible, and thus an additional scheme to realize gust response of the Boeing 747 models should be implemented. By supposing that wind gust is precisely measured by the difference between airspeed and inertial speed, it is possible to calculate the motions of the Boeing 747 models driven by the measured wind gust and pilot handling input, because the gust effect to MuPAL-α is suppressed. (See the block diagram of the implemented flight controller in Fig. 2, where M, FF, P, and FB respectively denote the Boeing 747 model, feedforward controller, MuPAL-α's dynamics, and feedback controller.) Thus, the B747 model motions affected with pilot handling input as well as wind gust are realized with the flight controller in [12].

The details for designing the flight controller are omitted, because they are given in [12].

The variables mimicked by MuPAL-α are

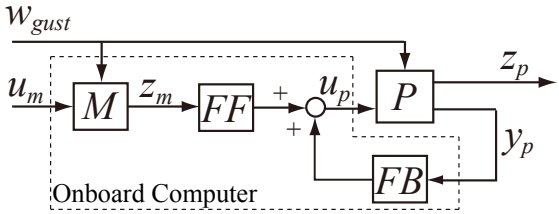

Fig. 2 Block diagram of implemented flight controller

forward-backward airspeed u_a [m/s], upward-downward airspeed w_a [m/s] and pitch angle θ [deg] in longitudinal motions, and bank angle ϕ [deg] and yaw rate r [deg/s] in lateral-directional motions.

2.2 Verification of Implemented Flight Controller

The control performance with respect to gust suppression and handling response characteristics has already been confirmed in [12]; however, the control performance with respect to handling response and gust response characteristics under gust suppression has not yet been confirmed. Thus, this performance is first evaluated with Hardware-In-the-Loop Simulations (HILS).

Since the reproduction of handling response of model motions of M has already confirmed in flight tests [12], the main concern to be examined is the reproduction of model motions of M driven by wind gust.

In this HILS, not only the main Fly-By-Wire (FBW) computer but also the onboard actuators are used. Thus, the effect of the uncertainties related to the onboard actuators can be also examined.

Fig. 3 shows one of the HILS results for the Boeing 747 model with yaw Stability Augmentation System (SAS) being implemented. In this case, the authority for pilot input (denoted by "pilot input authority") is fully secured, *viz.*, the pilot input (u_m in Fig. 2) is fully implemented to the Boeing 747 model. Similarly, the authority for the estimated wind gust (denoted by "gust input authority") is fully secured, *viz.*, the

estimated gust (W_{gust} to model M in Fig. 2) is fully implemented to the Boeing 747 model. The wind gust is implemented from 140 [s] to 340 [s]. Although there exist discrepancies in forward-backward speed (u_a) and pitch angle (θ), they are mainly caused by the initial elevator deflection, which is due to the lack of aerodynamic force to elevator in HILS. Other variables well match the corresponding ones of the Boeing 747 model.

Next, Fig. 4 shows one of the HILS results for the faulty Boeing 747 model. In this case, "pilot input authority" is set as 100%; however, "gust input authority" varies to prevent too much discrepancy between the motions of the Boeing 747 model and MuPAL-α. The wind gust is implemented from 60 [s] to the end. Since the marginally stable Dutch-roll motions are realized with the implemented flight controller, the reproduction of model motions driven by wind gust is confirmed. On the other hand, in the longitudinal motions, the effect from the lateral-directional motions inevitably exists and is relatively large. The implemented flight controller was designed for the longitudinal motion control and the lateral-directional motion control independently, the interaction between two linearized motions thus cannot be eliminated completely.

In summary, the motions driven by wind gust and pilot handling input are well realized with the flight controller in [12] under the implementation framework shown in Fig. 2.

3 Flight Test with IFS MuPAL-α

Using MuPAL-α with the controller in [12] being implemented, we examined the following in flight tests:

- Under the reduced lateral-directional motion stability, is it possible to control the airplane appropriately with the normal control devices?

To this end, we conducted two tests; a) controllability check with a sufficiently stable Boeing 747 model with various pilot input authority, and b) controllability check for a Boeing 747 model whose Dutch-roll mode is marginally stable with various pilot input authority.

By considering that it is rationally expected that the controllability for the sufficiently stable Boeing 747 model is guaranteed if the controllability for the marginally stable Boeing 747 model is ensured, the possible conclusions are the following two ones:

1. If the controllability is confirmed in both cases when pilot input authority is assured, then the primal design requirement in fault tolerant flight control is the maneuverability recovery.

2. If the controllability is confirmed only in case a) when pilot input authority is assured, then the design requirement in fault tolerant flight control is not only the maneuverability recovery but also the aircraft motion stability.

We show typical flight test results in the below, and derive our conclusion.

3.1 Boeing 747 Model with Yaw SAS

Fig. 5 shows the flight test result for the Boeing 747 model with sufficiently stable Dutch-roll mode. The pilot task in this flight test is to make 30 degree turns with 10 degree roll angles while pilot control authority changes without the notice to the pilot. This result confirms that the variables to be mimicked (u_a, w_a and θ in longitudinal motion, and ϕ and r in lateral-directional motion) indeed match the corresponding ones of the B747 model under pilot handling input and wind gust input.

The pilot comment is as follows:

- The controllability is normal and it is possible to keep 10 [deg] bank angle until the wheel reaches its hardware limit. Due to this hardware stop, it is impossible to control the airplane properly anymore.

Therefore, the controllability for the sufficiently stable Boeing 747 model is guaranteed as long as the control device are operative, which is a natural and reasonable conclusion.

3.2 Boeing 747 Model with Reduced Stability

Fig. 6 shows the counterpart result of Fig. 5 for the B747 model with reduced lateral-directional motion stability. The following are confirmed from this figure.

Phase I: In $0 \sim 65\,[\mathrm{s}]$, the marginally stable Dutch-roll mode is excited due to wind gust.

Phase II: In the period of $[65, 140]\,[\mathrm{s}]$, the gust input authority is set as 30% to keep the amplitude of roll angle and yaw rate.

Phase III: Pilot is asked to recover from the oscillatory motions to level flight from $95\,[\mathrm{s}]$; however, the pilot cannot recover from the oscillatory motions until $110\,[\mathrm{s}]$. That is, the airplane is uncontrollable with *low* pilot input authority and *moderate* gust input authority.

Phase IV: After pilot input authority is increased to $20\,[\%]$ at $110\,[\mathrm{s}]$, the oscillatory motions are mitigated with appropriate pilot input in $[110, 125]\,[\mathrm{s}]$. That is, the airplane is controllable with *moderate* pilot input authority and *moderate* gust input authority.

Phase V: The pilot input authority is decreased to $5\,[\%]$ at $125\,[\mathrm{s}]$ and the gust input authority is increased to $100\,[\%]$ at $140\,[\mathrm{s}]$, then the amplitude of oscillatory Dutch-roll mode motions begin to increase again in $[140, 160]\,[\mathrm{s}]$. That is, the airplane is uncontrollable with *low* pilot input authority and *high* gust input authority.

Phase VI: The oscillatory motions begin to decrease with pilot input after the pilot input authority is increase to $40\,[\%]$. That is, the airplane is controllable with *moderate* pilot input authority and *high* gust input authority.

The results in Phase III and V indicate that the airplane is not controllable if control devices are not properly operative, and the results in Phase IV and VI indicate that the airplane is controllable as long as control devices are operative even if the gust effect is relatively large.

In summary, the controllability is guaranteed even for the marginally stable Boeing 747 model as long as the control devices are properly operative.

From the both results shown in Fig. 5 and Fig. 6, our conclusion is the first one in the list of possible conclusions; that is, the primal design requirement in fault tolerant flight control is the maneuverability recovery.

4 Summary

In this paper, we investigate the maneuverability assessment for a faulty airplane model by using an In-Flight Simulator (IFS) MuPAL-α. The objective of this investigation is to confirm that airplane even with severely damaged stability is controllable as long as the control devices are properly operative, *viz.*, the response of pilot manual inputs is properly ensured. The flight tests clearly indicate the above, and thus it is also confirmed that maneuverability recovery is the primal design requirement in fault tolerant flight controller design.

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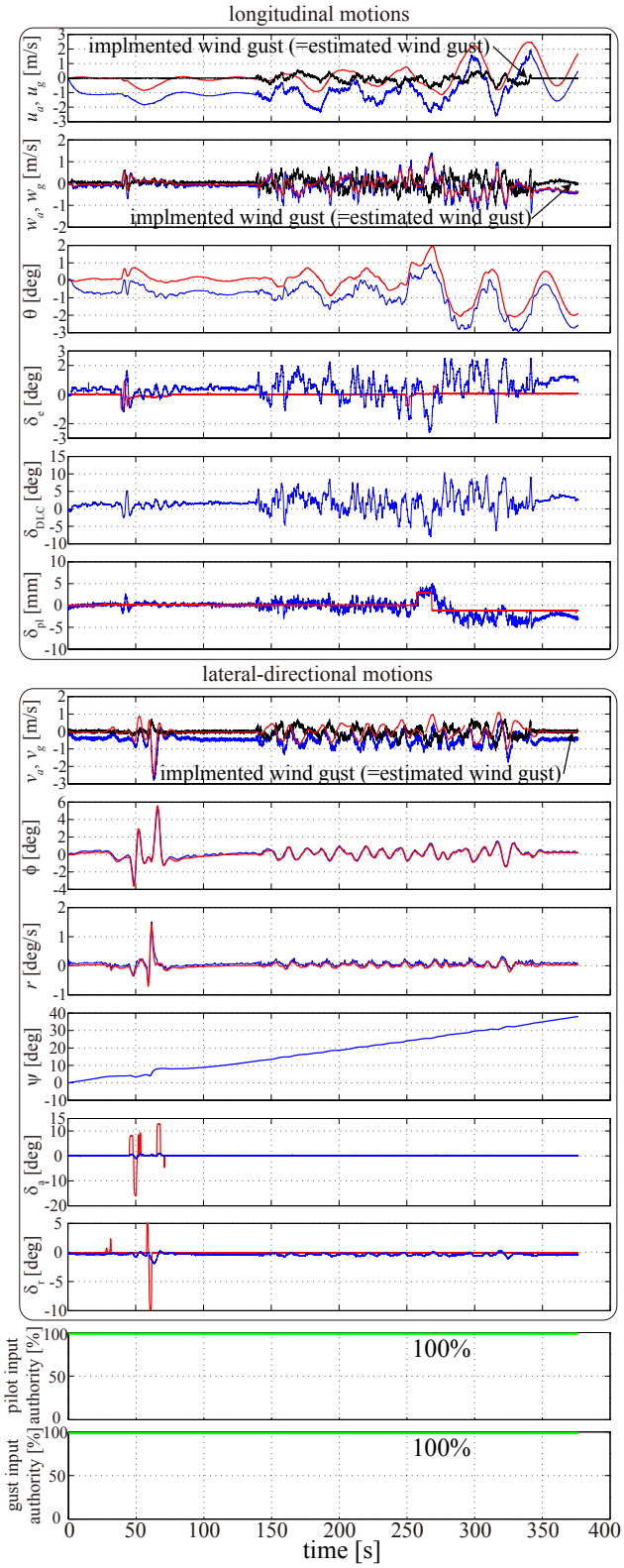

Fig. 3 HILS result for normal B747 model with Yaw-SAS (red lines: Boeing 747 model, blue lines: MuPAL-α)

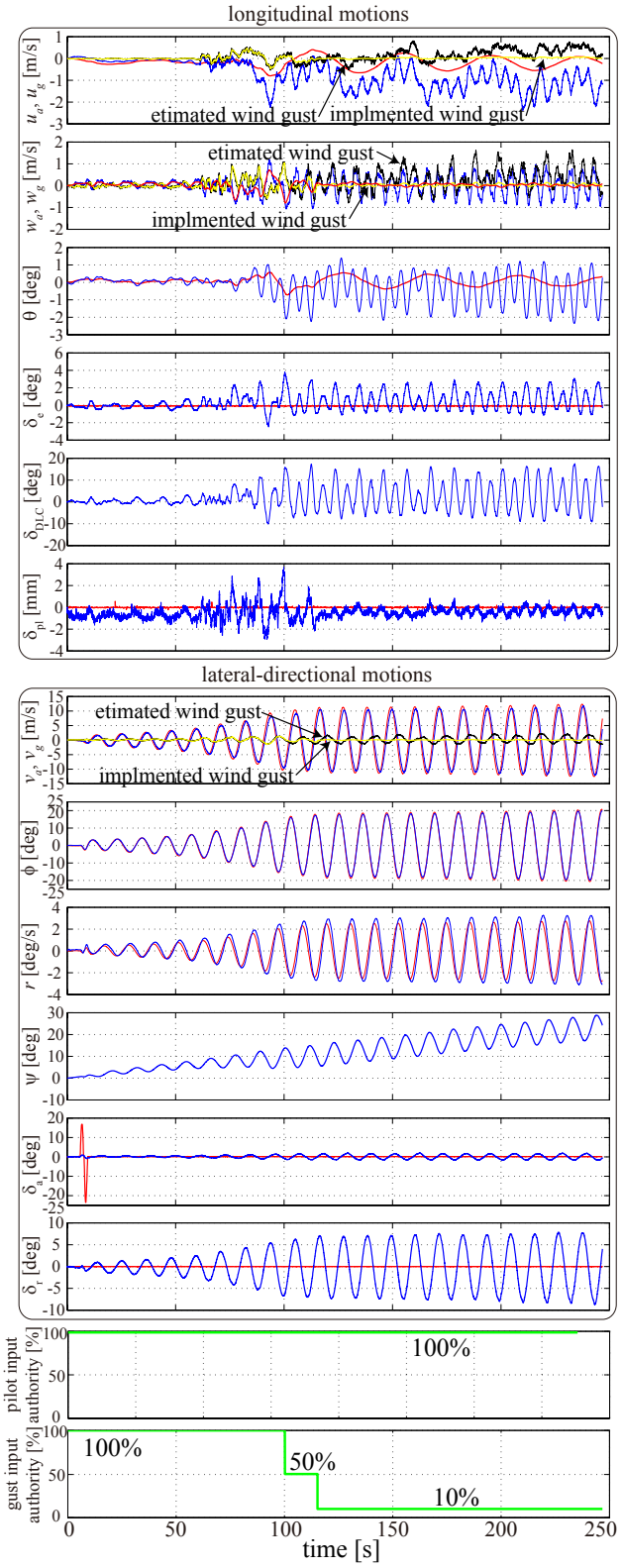

Fig. 4 HILS result for B747 model with reduced lateral-directional stability (estimated wind gust is denoted by black lines and implemented wind gust is denoted by yellow lines)

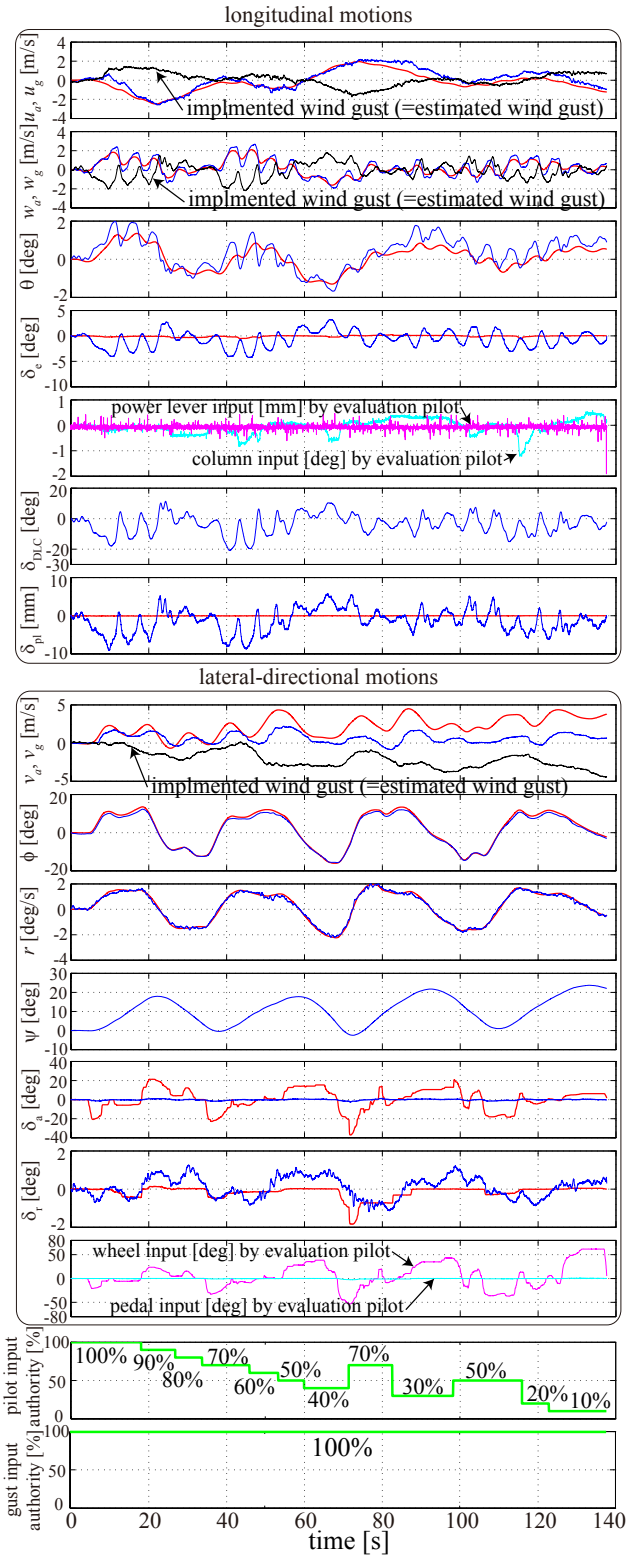

Fig. 5 Flight test result for normal B747 model with Yaw-SAS

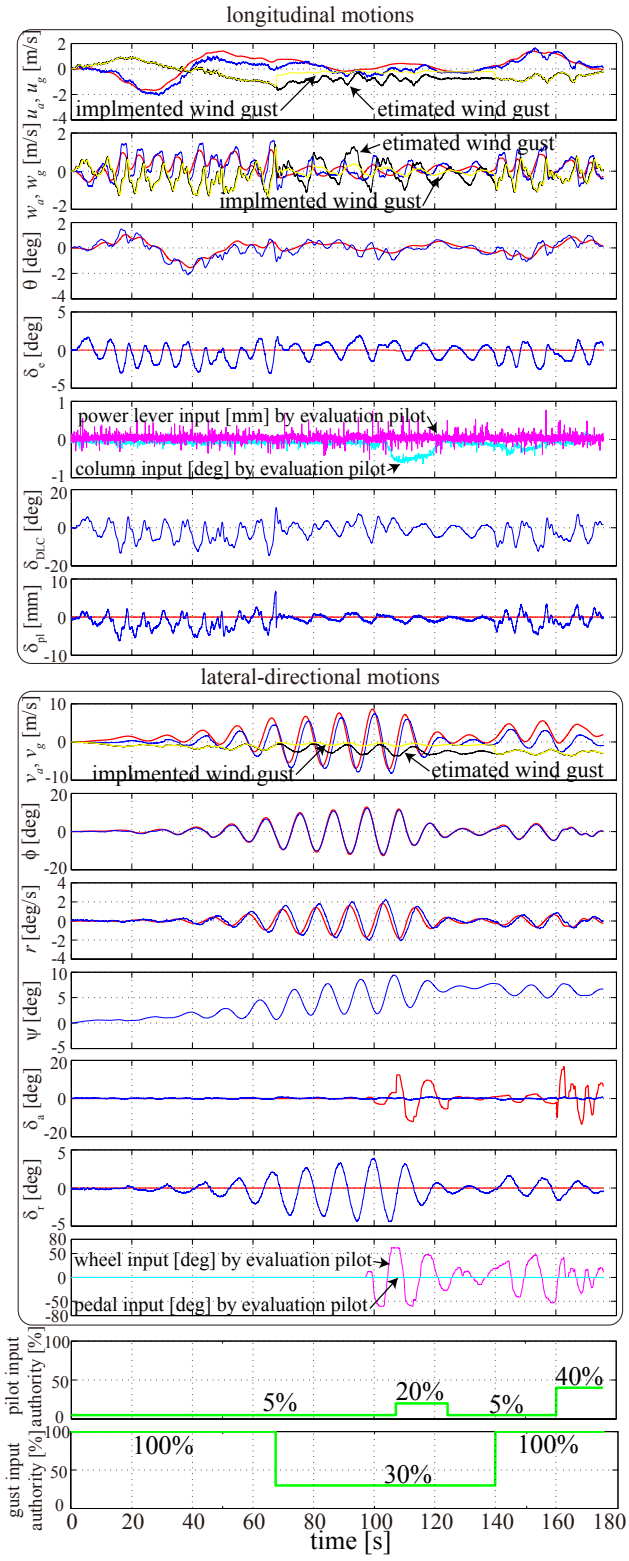

Fig. 6 Flight test result for B747 model with reduced lateral-directional stability (estimated wind gust is denoted by black lines and implemented wind gust is denoted by yellow lines)