A Thrust-only Flight-control System as a Backup for Loss of Primary Flight Controls

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If all control surfaces of an aircraft become inoperative, only the engine thrust can change the pitching and rolling moment balance to allow the aircraft to fly stably and land safely. In an effort to actualize such aircraft control while providing as normal an operating feel as possible, Mitsubishi Heavy Industries, Ltd. (MHI) developed a thrust-only flight-control system consisting of a flight-control law based entirely on increases/decreases in thrust, an automatic-landing control law, and a pilot interface. This system was tested and evaluated by a pilot in a domed simulator to ensure that the aircraft would be able to fly and land safely, even if all control surfaces become inoperative. The results of this test indicate the possibility of improving aircraft safety and increasing the survivability of crews and passengers in the event of loss of primary flight controls.

1. Introduction

An aircraft-control system is designed to lower the probability of losing the aircraft through a multiplex redundant system. Failure of the control system, however, has occurred in past. In 1974, Turkish Airlines Flight 981 experienced a collapse of the aft cargo compartment floor associated with losing the cargo door. This damaged the control cables and made the aircraft uncontrollable. The aircraft crashed a minute later, claiming the lives of all on board. In 1989, United Airlines Flight 232 lost flight control because the hydraulic pressure for the control surfaces was lost due to the dispersion of engine parts while in flight. However, an off-duty pilot who had studied the throttle-only flight-control technique was on board, and with his help, the aircraft reached an airport. The aircraft lost balance just before touchdown, causing the aircraft to break apart and catch fire when a wing tip crashed into the runway, but more than half the people on board survived, and the worst-case scenario was avoided. Although these accidents indicate that a malfunction of the surface control system is fatal to flight control, there is a chance of being able to control the aircraft using only the engine throttles. However, such control is a special technique requiring exceptional piloting skills, and it takes considerable training time to learn. Even if the control technique is learned during training, if it is applied during an actual emergency situation, the workload on the pilot at that time will be at a maximum level. Hence, achieving a safe landing by controlling the aircraft as intended using only the engine throttles up until the moment of touchdown is extremely difficult.

Considering these issues, MHI is aiming to establish “thrust-only flight-control technology,” i.e., the technology to control the attitude of an aircraft by increasing or decreasing the engine thrust in response to the pilot’s intended operation even after the loss of primary flight controls.[1-4] Establishment of this technology will allow a pilot to operate an aircraft to the nearest airport and land on a runway through normal operation of a control terminal, even in an emergency situation after losing the primary flight controls, and thus enhance overall aircraft safety.

This paper describes the thrust-only flight-control system that was recently developed and the results of a system evaluation conducted by a pilot in a domed simulator.

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2. Development of a thrust-only flight-control system

This section describes the core factors of the developed thrust-only flight-control system (**Figure 1**): the thrust-only control law, automatic-landing control law, and pilot interface. In developing the thrust-only flight-control system, we considered a Boeing 747-400 because (1) the engine layout is suitable for thrust-only flight control, (2) it is an in-service aircraft, and (3) engineering data are available from plenty of open references.

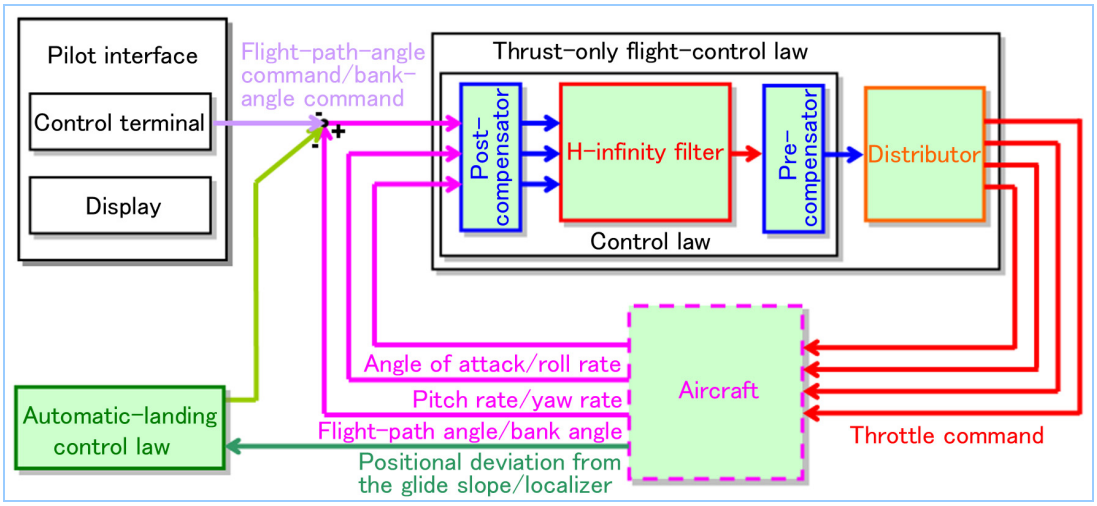

Figure 1 Block diagram of the thrust-only flight-control system

2.1 Development of a thrust-only flight-control law and an automatic-landing control law

(1) Selection of control variables

To control an aircraft using control surfaces, state variables such as normal acceleration, pitch rate for longitudinal motion, and roll rate or sideslip angle for lateral-directional motion are commonly defined as the control variables. However, as the control response characteristics using thrust are quite different from those using control surfaces, these state variables are not necessarily appropriate as control variables for a thrust-only flight-control law. Accordingly, we considered control variables appropriate for thrust-only flight control by using a mathematical model of the target aircraft. We selected the control variables from state variables that respond dynamically to engine thrust within a bandwidth in which engine can respond. Through this process, the flight-path angle and bank angle were selected as control variables for the longitudinal motion and lateral-directional motion, respectively. The flight-path angle and bank angle commands are inputted by the pilot control terminal.

(2) Design of the thrust-only flight-control law

We designed the thrust-only flight-control law consisting of a control law to calculate the angular acceleration command and a distributor to provide optimal distribution of the manipulated variables to actualize the angular acceleration. This made it possible to use the thrust of four aircraft engines independently and appropriately in response to flight conditions and the pilot's input. The study and development of a thrust-only flight-control law using such a design has no precedent in the world and is one of the major characteristics of this thrust-only flight control system. We applied a loop-shaping design procedure consisting of a pre-compensator, a post-compensator, and an H-infinity filter when designing the control law. The feedback variable/signal consisted of the flight-path angle, angle of attack, and pitch rate for longitudinal motion and the bank angle, roll rate, and yaw rate for lateral-directional motion. The thrust-only flight-control law generated appropriate throttle commands to each of the four engines.

(3) Design of the automatic-landing control law

We adopted an automatic-landing control law to mitigate the enhanced workload on the pilot when approaching and landing on the runway. We designed it using a proportional–integral–derivative (PID) controller as an outer-loop controller, in contrast to the thrust-only flight-control as an inner-loop controller. We defined the feedback variable/feedback signal as the positional deviation from the glide slope for longitudinal motion and positional deviation from the localizer for lateral-directional motion. We designed the automatic landing control law to allow the pilot to override commands even after engaging the autopilot. This was achieved by adding the flight-path angle and bank-angle commands, which are generated by the automatic-landing control law, to those inputted by the pilot through the control terminal and then inputting them to the thrust-only flight-control system.

2.2 Development of the pilot interface

(1) Control terminal

The control terminal is an important factor in the development of a thrust-only flight-control system because it serves as the interface between the pilot and the thrust-only flight-control law. Improper settings not only make it difficult for the pilot to operate the aircraft but also have the potential to bring about hazardous oscillatory aircraft motion such as pilot-induced oscillations because aircraft control based only on increasing or decreasing the engine thrust has a slow response speed compared with normal aircraft control. Taking this into consideration, we aimed to establish a thrust-only flight-control system that was also applicable to a broad range of existing and future aircraft. We prepared two types of control terminals, a column-wheel type and a trim-switch type, based on those in general use in aircraft, and selected the one best suited for thrust-only flight-control after evaluating them in the domed simulator. **Figure 2** (a) shows an outline view of the two control terminals that were considered.

(2) Display

We considered the Boeing 747-400 aircraft when we developed our thrust-only flight-control system. Based on the instrument panel display of this airplane, with additional indications thought to be effective for thrust-only flight control, we developed a primary flight display (PFD) and an engine indication and crew alerting system (EICAS). They had the following new features:

- The command variable for the longitudinal and lateral-directional motion generated by the trim switch operation is displayed.
- The reference velocity vector is displayed as a pilot-support indicator for runway approach.
- The target N1 (revolution ratio) is displayed as a pilot-support indicator for aircraft control by throttle operation.

Figure 2(b) shows the PFD and the EICAS display.

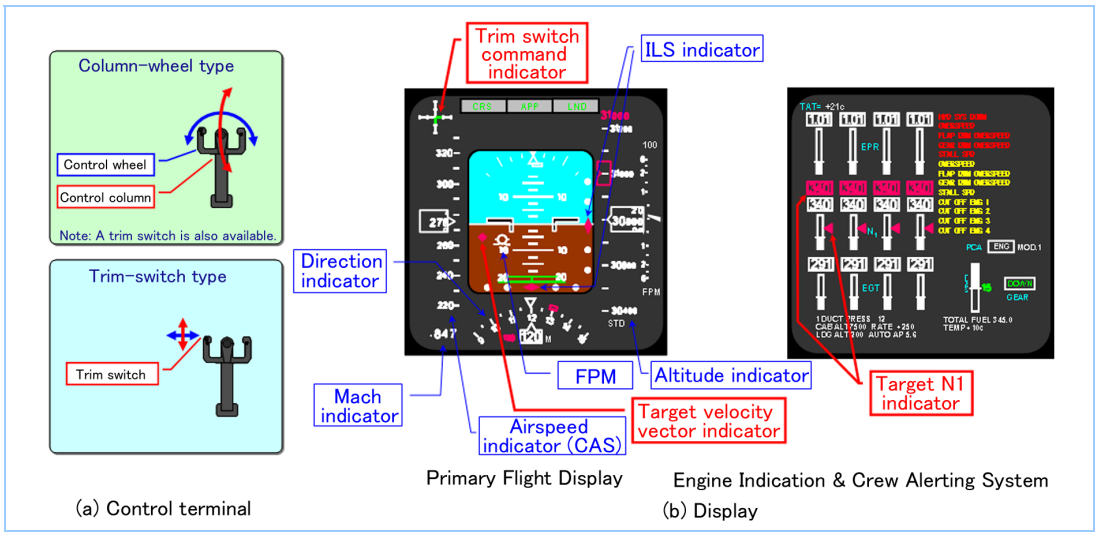

Figure 2 Outline of the pilot interface

3. Pilot evaluation of the thrust-only flight-control system

A piloted simulation test was conducted using the thrust-only flight-control system, including the thrust-only flight-control law, automatic-landing control law, and pilot interface. This section describes the test outline, test case, and one example of the results.

3.1 Test outline

The piloted simulation test was conducted as follows:

(1) Date : December 1 and 2, 2010
(2) Place : Domed simulator at MHI
(3) Operator : A pilot who works for a Japanese airline
(4) Subject of test : An evaluation of various prepared control systems (**Table 1**).

Details of the test case are given in the following section.

Table 1 Control modes evaluated during the piloted simulation test

	Control mode	Outline
Conventional control system	Conventional	Control by throttle operation
Control system developed in this study	PCA Mode 1	Control by throttle operation (with pilot support indicator)
	PCA Mode 2	Control through thrust-only flight-control system (column-wheel type)
	PCA Mode 3	Control through thrust-only flight-control system (trim-switch type)
	PCA Mode 4	Control through thrust-only flight-control system (column-wheel type) plus automatic-landing control law (with automatic flare)
	PCA Mode 5	Control through thrust-only flight-control system (column-wheel type) plus automatic-landing control law (without automatic flare)

3.2 Test case

We set up the following test case for our piloted simulation test under the assumption that all the control surfaces were locked at the trim surface deflection for cruise due to the failure of the surface control system during cruise flight. In this case, the flaps and gear are supposed to be operable through an emergency alternate mechanism (electrical or mechanical).

(1) Flight-path change during cruise

The controllability for emergency descent and change of direction was evaluated using each control mode based on the assumption that the aircraft can descend and change direction only by increasing or decreasing the engine thrust, with all control surfaces locked, to reach to an airport for an emergency landing.

(2) Flight-path maintenance at approach

The controllability for a follow-up to the glide slope and localizer was evaluated using each control mode based on the assumption that the aircraft can approach the runway only by increasing or decreasing the engine thrust with all control surfaces locked.

(3) Landing touchdown-point and sink-rate control

The controllability for touchdown-point and sink-rate control were evaluated for each control mode based on the assumption that the aircraft can land on the runway only by increasing or decreasing the engine thrust with all control surfaces locked.

(4) Automatic landing

The follow-up performance to the glide slope and localizer, touchdown-point and sink-rate control response, and controllability after the pilot overrides the system were evaluated for two control modes based on the assumption that the aircraft can approach and land on the runway using the automatic-landing control law with all control surfaces locked.

3.3 Test results and evaluation

Figure 3 shows the flight path for each type of operation during approach, representative of the aircraft-motion time histories obtained from the piloted simulation test. This figure reveals that control through the thrust-only flight-control system (PCA Modes 2 and 4) has advanced controllability, with better follow-up to the glide slope and localizer than a conventional control mode.

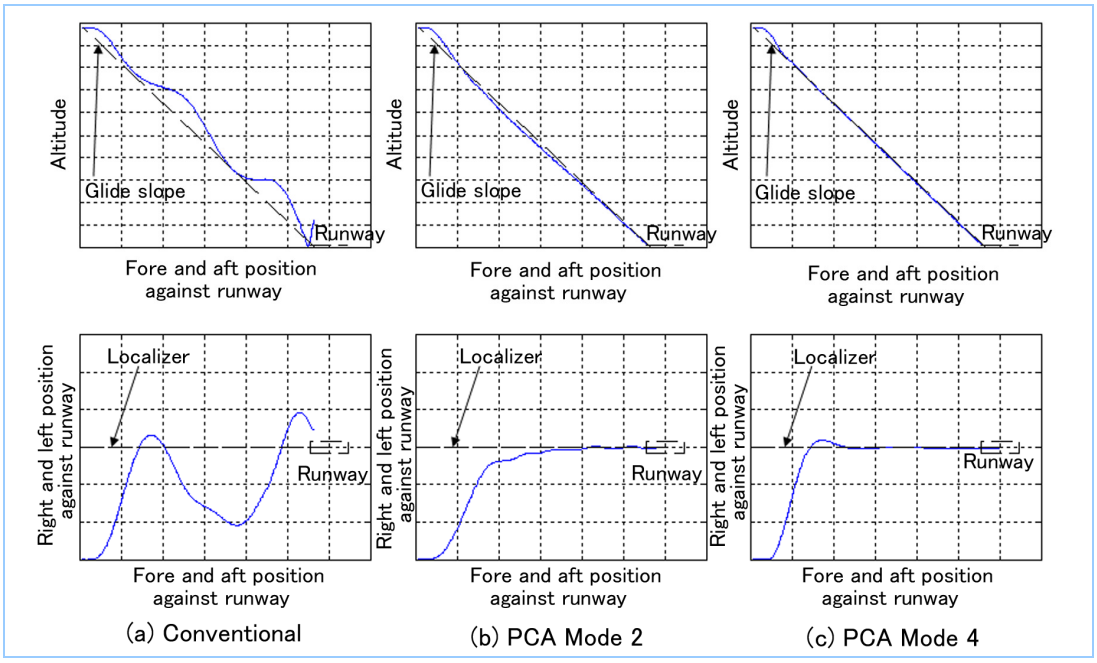

Figure 3 Flight path using each control system

Table 2 shows the major pilot comments received during the test. PCA Modes 2 and 3, which were controlled using the thrust-only flight-control system, had remarkably better controllability than a conventional control mode and PCA Mode 1, which were controlled through throttle operation. PCA Mode2, with a column-wheel control terminal, showed more positive results; thus, a column-wheel control terminal was deemed suitable for thrust-only flight control. For the automatic-landing control law, PCA Mode4, which performed the flare automatically, was more desirable compared with PCA Mode 5, which required the pilot to override the system and perform the flare manually.

The test cases demonstrated that the controllability of the thrust-only flight-control system was remarkably enhanced compared with conventional systems and was effective as an alternate flight-control means after the loss of primary flight controls.

Table 2 Pilot comments

	Control mode	Pilot comments
Conventional control system	Conventional	Unworthy of evaluation. Uncontrollable.
Control system developed in this study	PCA Mode 1	• I could only operate the throttle to follow the target N1 indication. • Follow-up to the glide slope could be done successfully compared with a conventional control system, but I cannot evaluate in terms of whether to implement the task.
	PCA Mode 2	• This mode is effective, with much better controllability compared with a conventional control system and PCA Mode 1. • Unique indication of the trim-switch command level is a useful reference.
	PCA Mode 3	• This mode is effective, with much better controllability compared with a conventional control system and PCA Mode 1. • This mode needs a little getting used to compared with PCA Mode 2.
	PCA Mode 4	The automatic-landing control law is dependable and can be trusted.
	PCA Mode 5	PCA Mode 4 which makes the flare maneuver automatically is more dependable and preferable.
General		• It is impossible to carry out landing through throttle operation. • The thrust-only flight-control system is very useful and practical because it can even conduct landing operations. • As long as the aircraft is equipped with this system, I will choose to head to an airport for landing even after the loss of primary flight controls.

4. Conclusion

We developed a thrust-only flight-control system consisting of a thrust-only flight-control law, an automatic-landing control law, and a pilot interface and conducted a pilot evaluation in our domed simulator. We received high acclaim, such as “the developed thrust-only flight-control system is very useful and practical enough for real emergency situations.” If this system can be demonstrated in actual aerodynamic circumstances, such as during a flight demonstration with a small experimental airplane or an actual airplane, the system will be considered more practical. Therefore, we are working on this project continuously.

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