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FLIGHT TESTS ON FAULT-TOLERANT AUTOPILOT CONTROL LAWS IN LABORATORY AIRCRAFT CITATION II

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Abstract: The Delft University laboratory aircraft Cessna Citation II has the capability to implement and test new auto pilot control laws. The aircraft is equipped as a Fly-By-Wire testbed, that enables the user to control the aircraft through an experimental computer and directly have control over the control surfaces. An extra control stick is mounted on the right-hand side in the cockpit from where the aircraft can be controlled in a closed loop. The gains can be adjusted in-flight. An experimental display in the cockpit showed the setpoints for the rate and direct control in pitch and roll.

The control laws that were tested are developed by the department of aircraft systems dynamics of the German Aerospace Center together with Delft University of Technology. The control laws are based on Incremental Nonlinear Dynamic Inversion (INDI). INDI uses synchronized measurements or estimations of (angular) accelerations and control surface deflections. This way it is not dependent on an airplane model, but it is able to automatically adapt flight control laws to changing dynamic behavior of the aircraft, even in case of major system failures or damage to the airframe. The INDI controller directly controls the current to the control surface actuators.

This paper treats the execution of the test flights.

1 INTRODUCTION

The development of fault tolerant control laws based on Incremental Non-Linear Dynamic Inversion INDI is promising. INDI is a very elegant control method that is sensor based instead of model based. Model based control laws have the inherent disadvantage that solutions to system uncertainties and failures have to be foreseen. INDI is inherently reacting to the aircraft response on control surface deflection, and is able to adapt making it more fault tolerant to unexpected failures.

The German Aerospace Centre DLR is currently performing research to create certifiable INDI control laws in close cooperation with Delft University of Technology DUT.

The DUT operates a Cessna Citation research aircraft with a certified Fly-by-Wire FBW capability that enables flight testing of new control laws. INDI controllers have been tested on UAV's and this paper describes the flight testing of INDI controllers on the FAR/CS25 Cessna Citation aircraft.

First the setup and certification of the Fly-By-Wire capability on the Cessna Citation II is treated. Then the implementation of the INDI controllers and the actual execution of the test flights.

2 EQUIPMENT DESCRIPTION

2.1 Research Aircraft

Delft University of Technology operates a Cessna citation II as a flying testbed. This aircraft, powered by two Pratt & Whitney JT15D-4 turbofan engines, has a ceiling of 43,000ft, and has a speed range between 100kts IAS and Mach 0,705. The aircraft is used for research test flights and is also used as a flying classroom during the curriculum of the aerospace students of the faculty of aerospace engineering.

The aircraft is especially suited for installation of all kinds of test equipment in the cabin, a dedicated electrical instrumentation bus is available to provide power to the experimental installation. The cabin can accommodate up to 8 persons, with all seats removed there is a space of approximately 3.45 m available for experiment mounting and observer seating. Also a few already certified outside installations are available, such as a nose boom with an alpha and beta vane, and a roof rack for installation of up to 20 antennas.



Figure 1. Delft University laboratory aircraft.

2.2 Avionics and additional sensors

The aircraft is fitted with Pro Line 21 cockpit, with a UNS 1Fw SBAS enabled FMS. The ARINC 429 databus can be accessed through the Integrated Avionics Processor System (IAPS) and the aircraft has two separate Attitude Heading Reference Systems (AHRS).

Specialized on-board sensors and synchro's provide status information about the aircraft's primary and secondary controls and control surfaces. A number of extra parameters are available, for example the deflection of the control surfaces, deflection of the elevator trim tab, control force, and flap setting, wheel speed and speed brake setting. Engine parameters, such as N1, N2, ITT, oil pressure and oil temperature and fuel flow are available for

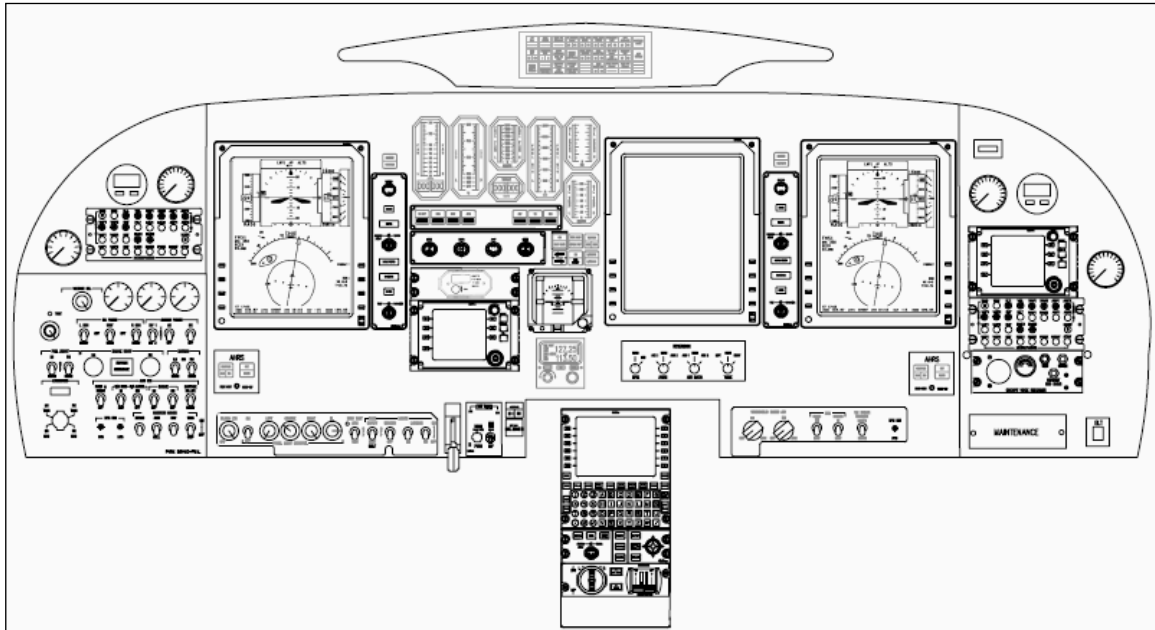


Figure 2. Pro Line 21 cockpit layout.

datalogging.

2.3 Flight Test Instrumentation System

The Flight Test Instrumentation System (FTIS) consists of a data acquisition computer and a signal conditioning unit and is powered by the electrical instrumentation bus onboard of the aircraft. The FTIS is connected to all information sources, such as both AHRSs and the IAPS to access the ARINC 429 both high speed and low speed data labels and the signal conditioning unit SCU.



Figure 3. Flight Test Instrumentation System



The SCU conditions the analogue signals coming from the sensors and synchros. It filters and samples that data at an adjustable rate and bandwidth. FTIS provides timestamps and is able to accurately log parameters real time at a high sample rate (up to 1000hz).

2.4 Control system

The flight controls of the Citation consist of conventional control columns, connected by cables to the control surfaces. The aircraft is equipped with an auto pilot that is controlled by the flight control computer FCC. The FCC controls both the electric circuits for the control law and the servo amplifiers. It uses multiple information sources (e.g. AHRS, Navigation data, air data information, etc.) and provides current signals to the servo amplifiers. The servo amplifiers are rendering the amplified current signals to the actuators that deflect the control surfaces. The actuators are mechanically connected through a drum and a friction clutch to the cable system. This clutch provides protection as a torque limiter and may be overpowered by the pilot when an unwanted command is given by the FCC.

2.5 Fly-By-Wire system

In 2012 a Fly-by-wire capability was certified and installed in the aircraft (see [1]). The Fly-By-Wire system is based on the standard FCC for this Cessna Citation aircraft. An extra FCC was acquired, modified and can be swapped with the standard FCC in the nose of the aircraft. The modified FCC has a breakout box to connect to an experimental FBW computer to gain access to the actuators directly. With this experimental FBW computer it is possible to control the aircraft using your own developed logic. The safety solutions (friction clutch) of the control mechanism is still available using the experimental FBW computer. Unwanted commands of the experimental FBW computer can be overpowered or the autopilot could be disconnected returning a normal fly by hand aircraft to the safety pilot. This safety feature also accelerated the certification process and is further explained in chapter 3.

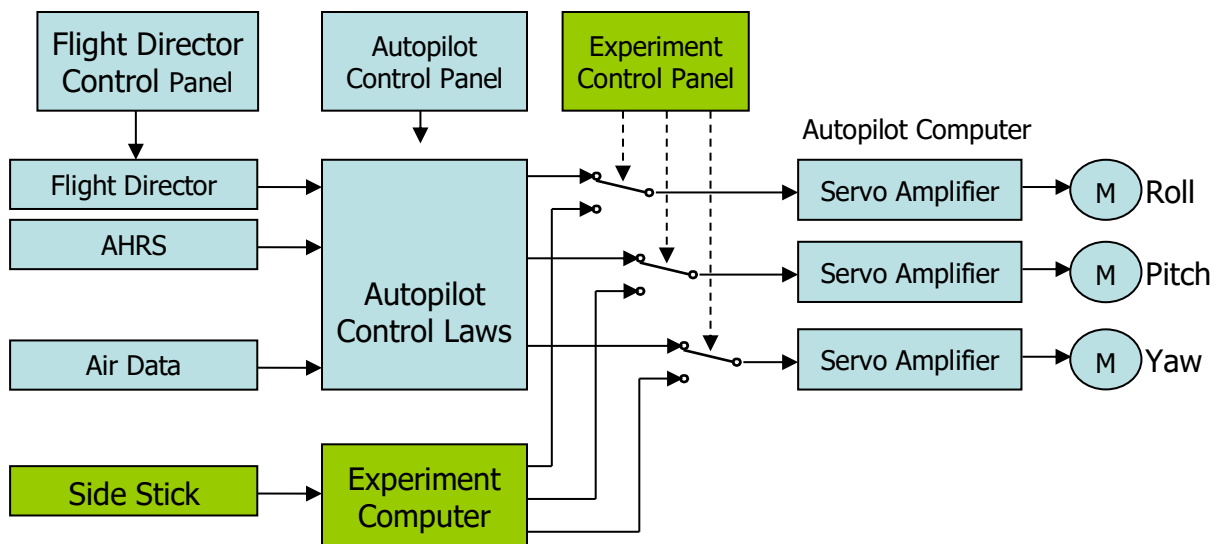


Figure 4. FBW system layout.

2.6 Fly-By-Wire pilot interfaces

In the cockpit there are two pilot interfaces to the FBW system: a FBW control panel and a fixed force side stick. The control panel is located in the pedestal next to the control display unit CDU of the FMS. On the control panel switches for each channel (Roll, Pitch and Yaw) are available to the pilots and can be selected separately. Only the selected channels are controlled by the experimental FBW computer, the other channels are subject to the original

autopilot control laws. Note that when using the pitch channel, it is not possible yet to control the automatic elevator trim by the experimental FBW computer. During flights tests it is possible to disable the automatic elevator trim.

When the appropriate channels are selected, the experimental FBW computer has to be engaged to get control over those channels. This is the fourth switch on the FBW control panel: EC engaged.

This ensures that pilots are always aware of the exact moment that the aircraft is controlled by the experimental FBW computer when pressing that switch.



Figure 5. FBW Control Panel

A fixed force side stick is installed on the right-hand side of the cockpit, to perform pilot in the loop research. The side stick can be used only for Pitch and Roll commands, a pilot yaw control (e.g. experimental rudder pedals) are not implemented.



Figure 6. Experimental fixed force side stick.

2.7 Fly-by-Wire control software

The software used on the experimental FBW computer is the inhouse developed DUECA, Delft University Environment for Communication and Activation. This middleware layer, synchronizes with FTIS and runs on multiple research platforms in the university, e.g. The fixed based simulator (HMI Laboratory) and the full flight simulator (SIMONA), but can also

be run on a single PC. It is possible to test the software on those platforms before using it in the aircraft and compare the results.

For the INDI trials, the main development of the controllers was done by DLR in a Simulink® environment. Using MATLAB®'s Real Time Workshop software package, the model was transcribed into C-code, which is then parsed into the DUECA environment. Since the FTIS can connect to the TU Delft network through wifi when installed in the aircraft, this whole process takes just minutes. Especially during the ground testing phase, this proved a valuable time saver.

2.8 WIFI

In 2016 an isolated onboard wifi network was developed and certified in the aircraft. Real time information gathered by FTIS is made available on board. This feature opened up a lot of possibilities.

Through wifi it is possible to connect any tablet or (any) experimental FBW computer and have all parameters at hand to compute for example a new control command. The FTIS hosts all communications and sends the applicable data to the modified FCC that will in turn send current signals to the servo amplifiers.

Because all data of the aircraft is available through the wifi connection, it may also be displayed on a tablet. These tablets can be used by observers present in the cabin but also as a fully functional experimental cockpit display used by the pilots during the experiment without further need to modify the cockpit instruments or displays, see Figure 7.



Figure 7. Examples of tablet display.

3 FBW CERTIFICATION PROCESS

Unlike many other research aircraft, the Delft University of Technology Citation does not have an experimental certificate of airworthiness, but a full normal category certificate (large aircraft). This allows the aircraft to be used on international campaigns without having to apply for ferry permits. Furthermore, the aircraft can thus be used for student educational flights. In order to maintain this fully certified status, each major modification to the airframe or its components has to be approved through a supplemental type certificate (STC).

Normally, when certifying an autoflight system, a large amount of time and effort is spent testing the control laws in various operating conditions. Of course, the whole point of designing the experimental FBW system is to provide a testbed for newly developed, untested control software. This means that the system had to be certified *without* any control software. This was made possible by incorporating a number of hardware precautions that guarantee the system can be switched off and disconnected from the control surfaces at all times, before structural damage or a hazardous aircraft attitude can develop.

From a certification point of view, the system is regarded to be a modified flight control computer rather than a fly-by-wire control system. The conventional control columns are left in place, as is the flight director. The only modified component is the FCC, which now has extra connections to directly receive steering commands from an experimental source (i.e. non-certified), such as a research computer or a sidestick. Items such as the control surface actuators, the servo clutches and disconnect switches could be carried over from the existing autopilot system.

Because of these prerequisites, the certification centered around the effect on the airplane of uncommanded step inputs, so-called ‘actuator hardovers’, and the ability for the flight crew to disconnect the system, revert to manual control, and recover the aircraft to a normal flight attitude. The latter requirement was readily satisfied by leaving the existing servo clutches and autopilot disconnect switches intact. To satisfy the certification requirement that a servo hardover may not result in a dangerous flight attitude or overstress the airframe, a certification test program was developed.

In the original autopilot design, the roll, pitch, and yaw channels are completely separated in the hardware, allowing certification based on single channel hardovers. The FBW design introduces a new failure mode where all channels could command a full deflection because of a single point failure in, for example, the software. Offline simulations indicated that the greatest deviations from an initial condition could be expected from a simultaneous hardover on all three channels, with yaw and roll in the same direction and pitch down. Furthermore, airspeed and altitude excursions were found to be minor as were the expected g levels. The simulations proved that for the worst-case condition the pilot would have sufficient time to detect the hardover and recover the aircraft. The results were used to setup the certification flight test program.

3.1 Certification Flight Test Program

A flight test program was designed to validate the simulation results and to demonstrate to the certifying authorities that the aircraft can indeed be safely flown in this configuration. Using a build-up approach compliance was shown for a simultaneous hardover on all three channels in all aircraft configurations, throughout the entire airspeed/altitude flight envelope, resulting in the issuance of the STC.

4 FBW USE-CASE: INDI-CONTROLLER

Delft University of Technology (DUT) and DLR are both researching the use of INDI in fly-by-wire systems and autopilot control laws. In February 2017, both institutions executed a flight campaign to validate the use of INDI controller in a FAR/CS 25 aircraft.

4.1 INDI fault tolerant control laws

INDI uses synchronized measurements or estimations of angular accelerations and control surface deflections. As such, it is not dependent on an aircraft dynamic model, but it depends

on feedback of the reaction of the aircraft to incremental commands. The fundamental difference between INDI and traditional Nonlinear Dynamic Inversion (NDI) is that only partial knowledge of the system dynamics is required as the resulting control law only depends on the control effectiveness. INDI is subsequently less sensitive to model mismatches. However, additional feedback signals are required in the form of state derivatives and the input signals. In addition, the controller should be discretized with a sufficiently high sampling rate (100 Hz in this application). Finally, it should be noted that synchronization between the input and state derivative is required as the calculated control increment is based on a linearization around a specific point in time.

Because these characteristics, INDI-based flight control laws are able to cope with large changes in the dynamic behavior of the aircraft, even in case of major system failures or damage to the airframe. Thus, INDI can provide a good basis for fault-tolerant control strategies.

5 EXECUTION OF THE TEST FLIGHTS

The objective of the test campaign was to validate the performance of the INDI-controller in FAR/CS 25 aircraft, as all flight applications so far had been limited to UAVs.

5.1 Flight test preparation

Before implementation on the actual FBW computer in the aircraft, the controller was tested on an "iron bird" hardware-in-the-loop simulation. In this step the actual hardware of the aircraft is placed in the control loop, in particular the FBW system components. Successful implementation subsequently cleared the controller for implementation on the actual aircraft. Before the flight test several ground tests were performed to check the correct functionality of the controller. With the FBW system engaged, the responses of the control surfaces were assessed for correctness to manual inputs on the angle of attack and angle of sideslip sensors. In addition, the controller response at initialization was assessed.

5.2 Flight test campaign

Over the course of five days, three successive test flights have been performed to validate the incremental controller. All flights departed from and terminated at Amsterdam Airport Schiphol (AMS) and the experiments were executed in designated military training areas within Dutch airspace.

The experiments focused on a series of pitch and roll captures of varying magnitude and rate. In addition, a number of simulated engine failures were executed. Some turbulent air layers were encountered during the flight tests and were used to evaluate the controller response to turbulence. Finally, the incremental controller was used during an instrument approach and was active down to an altitude of 2000 ft.

During the flight, different versions of the control software could be loaded and tested. Furthermore, parameter gains could be changed without shutting down the FBW-system, using a graphical interface on the experiment controller's laptop, see Figure 8.

The figure consists of two screenshots of the DLR FBW ECI software interface.

Top Screenshot: Controller Tab

- Switches:**
 - ☐ INDI on/off
 - ☐ IBS on/off
 - ☐ PCH Inner on/off
 - ☐ PCH Outer on/off
 - ☐ C* on/off
 - ☐ Act Model INDI on/off
 - ☐ Act Model PCH on/off
 - ☐ β Est on/off
 - ☐ α Vane on/off
 - ☐ IBS Outer Loop on/off
 - ☐ AA on/off
 - ☐ Do Turn Comp
 - ☐ Do β -Roll
 - ☒ Open Loop on/off
 - ☐ Force Control on/off
 - ☒ Lon Cmd on/off
 - ☒ Lat Cmd on/off
 - ☒ Aero CG on/off
 - ☒ Do Limit
- Reference/command:**
 - ω_{roll} [rad/s]: 1.3600
 - ζ_{roll} [-]: 0.8949
 - ω_{pitch} [rad/s]: 2.4000
 - ζ_{pitch} [-]: 0.8000
 - $k_{the_F3_c*}$ [rad/s]: 4.0000
 - k_{c*} [-]: 1.0000
- Aero model gains:**
 - $k_{ContEff_de}$ [-]: 1.0000
 - $k_{ContEff_da}$ [-]: 1.0000
 - $k_{ContEff_dr}$ [-]: 1.0000
- Stick:**
 - $k_{stick_x_cl}$ [deg/s / N]: 0.2870
 - $k_{stick_y_cl}$ [deg/s / N]: 0.0573
 - k_{stick_nz} [g/N]: 0.0143
 - k_{stick_a} [deg/N]: 0.11
 - stick deadzone [N]: 2.50
- Deflection limits:**
 - de_limit [deg]: 2.0
 - da_limit [deg]: 5.0
 - dr_limit [deg]: 2.0
- Delays:**
 - actuator delay [-]: 5
 - sync delay [-]: 88
 - aa delay [-]: 15
- Payload configuration:**
 - payload [0-10]: 8
- Buttons:** Apply, Undo, Select nominal set, Select conservative set

Bottom Screenshot: FBW Tab

- Autopilot status:**
 - ☐ AP enable
 - ☐ AP enabled
 - ☐ AP engaged
 - Normal (dropdown)
 - ☐ Watchdog OK
 - ☐ TCS Selected
 - ☐ EC engaged
 - ☐ Inhibit Watchdog (test)
- TU Delft control tuning:**

	Kp	K _{ff}	K _{ffq}	K _{ffv}	V/tgt out
roll	150.0	0.00	0.00	0.00	0.00
pitch	150.0	0.00	0.00	0.00	0.00
yaw	100.0	0.00	0.00	0.00	0.00
- DLR control tuning:**

	Kp	Ki	Kd	Kff
roll	180.0	600.00	0.00	3.8500
pitch	90.0	300.00	0.00	6.4100
yaw	150.0	600.00	0.00	0.00
- channel selection and status:**

	DLR	enable	match?	init?	override init
roll	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
pitch	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
yaw	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
- Buttons:** plot roll, plot pitch, plot yaw, raw synchro
- Plot legend:**
 - * orange: target [deg]
 - * black: drum delta [deg]
 - * red: motor current [A]
 - * blue: surface delta (synchro) [deg]

Figure 8. Experiment Control Interface.

5.3 Results

This first flight test campaign was mainly used for proof of concept purposes. Both the NDI and INDI controllers functioned satisfactory and showed similar performance, proving that INDI provides a feasible control strategy for aircraft control of FAR/CS 25 aircraft.

The controllers were tested using both the aircraft AHRS and a dedicated experimental AHRS running at a much higher update rate. As expected the higher rate AHRS generated better performance, but satisfactory control behavior was achieved using the aircraft's AHRS.

The full results of the performance evaluation of the controllers can be found in [2].

Furthermore, the ability to connect individual control channels (pitch, roll and yaw) to the experimental FBW computer, leaving the remaining channels connected to the aircraft's

autopilot, proved extremely useful during the experiment. This allowed the testing and tuning of the pitch and roll channels one by one.

The ability to adjust the parameter gains of the controllers in real-time in flight without having to disconnect the FBW system greatly reduced the time required to fine tune the different controllers.

An approximately 10 Hertz noise in the alpha and beta signals was traced to the eigenmode of the air data boom. To better filter out this noise in the future, plans are made to install accelerometers in the nose of the air data boom.

6 CONCLUSIONS

This flight test campaign was the first implementation of an INDI-controller in a FAR/CS 25 aircraft. The results indicate that INDI is a very promising technique for aircraft control design.

The fly-by-wire testbed on the Cessna citation laboratory aircraft has proven to be a very efficient platform for testing new fly-by-wire and auto pilot control laws. The fact that there is no requirement to certify the control software, allows new control laws to be developed off site, tested and quickly implemented in the aircraft.

7 FUTURE PLANS

Next to further research into INDI and general fault tolerant control, currently research is focusing on using the FBW capability on developing a variable stability demonstrator. Expectations are to be able to demonstrate different static and dynamic stability characteristics by changing directly the stability derivatives of the aircraft's software model. Changes in stability characteristics can then be demonstrated in-flight by varying influencing parameters, for example the location of center of gravity of the aircraft. Variable stability demonstrations are not limited to the pilots in the cockpit, observers in the cabin with a wifi connected tablet are able to follow the cockpit instruments, as well as relevant flight data parameters, increasing their understanding of aircraft stability as well.

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